PocketProfessional™ Series

EE•*Pro*®

A software Application
On TI-89 and TI-92 Plus

User's Guide

June 1999

Rev. 1.0

da Vinci Technologies Group, Inc.
1600 S.W. Western Blvd
Suite 250
Corvallis, OR 97333

www.dvtg.com

Notice

We welcome your comments on the software and the manual. Forward your comments, preferably by e-mail to da Vinci at support@dvtg.com.

Acknowledgements

The EE•*Pro* software was developed by Dave Conklin, Casey Walsh, Michael Conway and Megha Shyam with the generous support of TI's development team. The user's guide was developed by Michael Conway and Megha Shyam. Many helpful comments from the testers at Texas Instruments and other locations during β testing phase is gratefully acknowledged.

Table of Contents

Part I: Analysis

Part II: Equations

Part III: Reference

Appendix

Chapter 1 Introduction to EE•*Pro*

Thank you for your purchase of EE•*Pro,* a member of the PocketProfessional® Pro software series designed by da Vinci Technologies to meet the computational needs of students and professionals in the engineering and scientific fields. Many long hours and late nights have been spent by the designers of this software to compile and organize the subject material in this software. We hope you enjoy EE•*Pro* and that it serves as a valuable companion in your electrical engineering career.

Topics in this chapter include:

- Key Features of EE•Pro
- Download/Purchase Information
- Manual Ordering
- Memory Requirements
- Differences between the TI 89 and TI 92 plus.
- Beginning EE•Pro
- Manual Organization
- Summary

1.1 Key Features of EE•*Pro*

The manual is organized into three sections representing the main menu headings of EE•*Pro.*

Analysis	**Equations**	**Reference**
AC Circuits	Resistive Circuits	Resistor Color Chart
Polyphase Circuits	Capacitors and Electric Fields	Standard Component Values
Ladder Network	Inductors and Magnetism	Semiconductor Data
Filter Design	Electron Motion	Boolean Expressions
Gain and Frequency	Meters and Bridges	Boolean Algebra
Fourier Transforms	RL and RC Circuits	Transforms
Two-Port Networks	RLC Circuits	Constants
Transformer Calculations	AC Circuits	SI Prefixes
Transmission Lines	Polyphase Circuits	
Computer Engineering	Electrical Resonance	
Error Functions	Operational Amplifier Circuits	
Capital Budgeting	Solid State Devices	
	Linear Amplifiers	
	Class A, B, & C Amplifiers	
	Transformers	
	Motors and Generators	

These main topic headings are further divided into sub-topics. A brief description of the main sections of the software is listed below:

Analysis-(Chapters 2-14) *Analysis* is organized into 12 topics and 33 sub-topics. The tools in this section incorporate a wide variety of analysis methods used by electrical engineers. Examples include evaluation of AC circuit performance characteristics, designing signal filters, building and computing ladder network properties, plotting transfer functions, estimating transformer and transmission line characteristics, performing binary arithmetic operations, and estimating pay-back returns for different projects in capital budgeting. Many sections in analysis can perform calculations for numeric as well as symbolic entries.

Equation Library (Chapters 15-31) This section contains over 700 equations organized under 16 topics and 105 subtopics. In any sub-topic, the user is able to select a set of equations, enter known values and compute results for unknown variables. The math engine is able to compute multiple or partial solution sets. A built-in unit management feature allows for the entry and expression of values in SI or other established measurement systems. Descriptions of each variable, unit selection, and appropriate diagrams are included in this section of the software.

Reference (Chapters 32-41) The *Reference* section of EE•*Pro* contains tables of information commonly found in electrical engineering handbooks. Topics include physical and chemical properties of common semiconductor materials, a list of fundamental constants commonly used by electrical engineers, tables of Fourier, Laplace, and z-transforms, and a list of Boolean algebraic expressions. Added features are the ability to perform simple computations, such as estimating standard (or preferred) manufacturer component values for inductors, resistors, and capacitors, in addition to a resistor color chart guide which can compute resistance and tolerance from a resistor's color band sequence.

1.2 Purchasing, Downloading and Installing EE•*Pro*

The EE•*Pro* software can only be purchased on-line from the web store at Texas Instruments Inc. at *http://www.ti.com/calc*. The software can be installed directly from your computer to your calculator using TI-GRAPH LINK™ hardware and software (sold separately). Directions for purchasing, downloading and installing EE•*Pro* software are available from TI's website.

1.3 Manual Ordering Information

Chapters and Appendices of the manual for EE•*Pro* can be downloaded from TI's web store and viewed using the free Adobe Acrobat Reader which can be downloaded from *http://www.adobe.com* (it is recommended that you use the latest version of the Acrobat reader and use the most updated driver for your printer). Printed manuals can be purchased separately from da Vinci Technologies (see address on cover page or visit da Vinci's website *http://www.dvtg.com/ticalcs/docs*).

1.4 Memory Requirements

The EE•*Pro* program is installed in the system memory portion of the flash ROM, which is separate from the RAM available to the user. EE•*Pro* uses RAM to store some of its session information, including values entered and computed by the user. The exact amount of memory required depends on the number of user-stored variables and the number of session folders designated by the user. To view the available memory in your TI calculator, use the [VAR-LINK] function. It is recommended that at least 10K of free RAM be available for installation and use of EE•*Pro*.

1.5 Differences between TI-89 and TI-92 plus

EE•*Pro* is designed for two models of graphing calculators from Texas Instruments, the TI-92 Plus and the TI-89. For consistency, keystrokes and symbols used in the manual are consistent with the TI-89. Equivalent key strokes for the TI-92 plus are listed in Appendix D.

1.6 Beginning EE•*Pro*

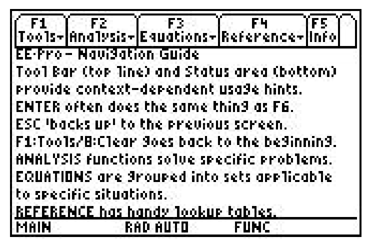
- To begin EE•*Pro*, start by pressing the [APPS] key. This accesses a pull down menu. Use the ⊝ key to move the cursor bar to **EE Pro Elec. Eng**. and press [ENTER]. Alternatively, enter **[A]** on *TI-89*, or [A] key on *TI-92 Plus* to get to the home screen of EE•*Pro.*

(Pull down Menu for [APPS]
EE•Pro option is further down the list)

Pull down Menu on for [APPS]
(EE•Pro at the end of the list)

The EE•*Pro* home screen is displayed below. The tool bar at the top of the screen lists the titles of the main sections of EE•*Pro* which can be activated by pressing the function keys.

- [F1] **Tools:** Editing features, information about EE•*Pro* in **A:About**
- [F2] **Analysis-**Accesses the ***Analysis*** section of the software
- [F3] **Equations-**Accesses the ***Equations*** section of the software.
- [F4] **Reference-**Accesses the ***Reference*** section of the software.
- [F5] **Info-**Helpful hints on EE•*Pro.*



A selection on any menu can be entered by moving the highlight bar to the item with the arrow key ⊝ and pressing [ENTER] (alternatively, the number or letter of the selection can be typed in). The **Analysis, Equation** and **Reference** menus are organized in a directory tree of topics and sub-topics. The user can return to a previous level of EE•*Pro* by pressing [ESC]. EE•*Pro* can be exited at any time by pressing the [HOME] key. When EE•*Pro* is restarted the software returns to it's previous location.

1.7 Manual Organization

- The five sections in the manual, *Introduction, Analysis, Equations, Reference,* and *Appendix,* have separate page numbering systems. The manual section, chapter heading and page number appear at the bottom of each page.
- The first chapter in each of the *Analysis, Equations* and *Reference* sections (Chapters 2, 15, and 32) gives an overview of the succeeding chapters and introduces the navigation and computation features common to each of the main sections. For example, Chapter 2 explains the basic layout of the *Analysis* section, menu navigation principles, and gives general examples of features common to all topics in *Analysis*. The chapters which follow are dedicated to the specific topics in each section. The titles of these chapters

correspond to the topic headings in the software menus. The chapters list all the equations used and explains their physical significance. These chapters also contain example problems and screen displays of the computed solutions.

- The Appendices contain trouble-shooting information, commonly asked questions, a bibliography used to develop the software, and warranty information provided by Texas Instruments.

1.8 Manual Disclaimer

- The calculator screen displays in the manual were obtained during the testing stages of the software. Some screen displays may appear slightly different due to final changes made in the software while the manual was being completed.

1.9 Summary

The designers of EE•*Pro* have attempted to maintain the following features:

- *Easy-to-use, menu-based interface.*
- *Computational efficiency for speed and performance.*
- *Helpful-hints and context-sensitive information provided in the status line.*
- *Advanced EE analysis routines, equations, and reference tables.*
- *Comprehensive manual documentation for examples and quick reference.*

We hope to continually add and refine the software products in the Pocket Professional series line. If you have any suggestions for future releases or updates, please contact us via the da Vinci website *http://www.dvtg.com*
or write to us at *improvements@dvtg.com.*

Best Regards,
da Vinci Technologies Group, Inc.

Chapter 2 Introduction to Analysis

The **Analysis** section of the software is able to perform calculations for a wide range of topics in circuit and electrical network design. A variety of input and output formats are encountered in the different topics of **Analysis.** Examples for each of the input forms will be discussed in some detail.

- The unit management feature in **Equations** is not present in **Analysis** due the variety of computation methods used in this section. All entered values are assumed to be common SI units (F, A, kg, m, s, Ω) or units chosen by the user (such as **len** in *Transmission Lines*).
- A feature unique to **Analysis** is the ability to perform symbolic computations for variables (with the exception of *Filter Design and Computer Engineering* and a few variables in other sections).
- An entry can consist of a single undefined variable (such as 'a' or 'x') or an expression of defined variables which can be simplified into a numerical result (such as 'x+3*y', where x=-3 and y=2).
- More information on a particular input can be displayed by highlighting the variable, press [F5] and [2]**/Type:** to show a brief description of a variable and its entry parameters.
- A variable name cannot be entered which is identical to the variable name (ie.: C for capacitance). If a symbolic calculation using the variable name, leave the entry blank.
- Variables which accept complex entries (ex: 115+23**i*) are followed by an underscore '_' (ex: **ZZ1_**).

2.1 Introduction

Analysis routines have been organized into twelve sections, each containing tools for performing electrical analysis of a variety of circuit types. One can design filters, solve two-port networks problems, calculate transmission line properties, minimize logic networks, perform binary arithmetic at bit and register levels, draw Bode diagrams, and examine capital budget constraints - all with context-sensitive assistance displayed in the status line.

2.2 Setting up an Analysis Problem

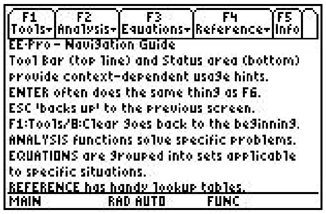
The **Analysis** section is located in the home screen of EE•*Pro*.

- To access the home screen of EE•*Pro,* start by pressing the [APPS] key. This accesses a pull down menu listing all the topics available. Use the ⊖ key to move the cursor bar to **EE Pro Elec. Eng**. and press [ENTER]. Alternatively, enter **[A]** on *TI-89*, or [A] key on *TI-92 Plus* to get to the home screen of EE•*Pro.*

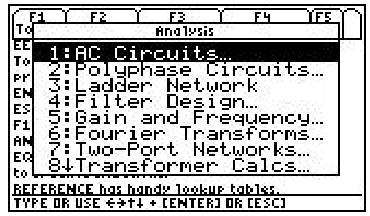
On TI -89 for (Pull down Menu On EE•Pro option is further down the list)

Pull down Menu on TI -89 for (Lower end of the list)

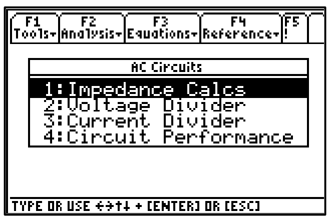
- Pressing [F2] will access the **Analysis** section of the software and display a pull down menu listing the topics available. There are 12 sections under **Analysis**. The sections are accessed by using the ⊽ key to move the highlight bar to the desired section and pressing [ENTER]. Alternatively, any section can be accessed by entering the number associated with each section. Thus pressing [1] will display a pop up menu for **AC Circuits**, while pressing [5] will list topics in **Gain and Frequency**. Analysis sections are listed and tagged with a number 1, 2, 3, etc. A down arrow (↓) beside a topic at the bottom of a menu indicates there are more choices.



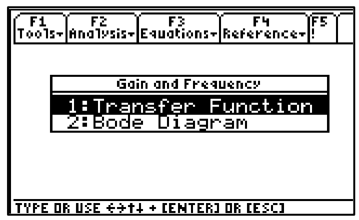
Main Screen for EE•Pro
Press [F2] for Analysis



*Pull down menu for **Analysis**; down arrow (↓) indicates that there are more items.*

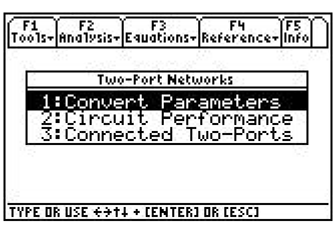


*Press [1] for topics in **AC Circuits**.*

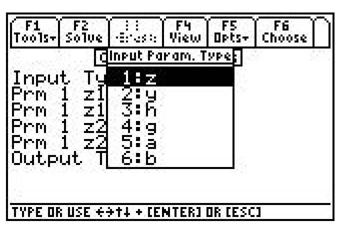


*Press [5] for topics in **Gain and Frequency**.*

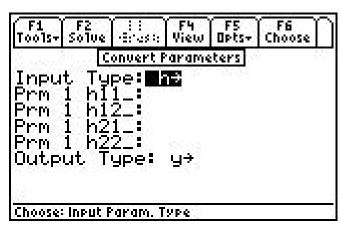
- Once an **Analysis** topic is accessed, a pop up menu lists the sub topics available for in the section. For example, when **Two-Port Networks** is selected**,** the pop up menu shows three sub topics:
  1. **Convert Parameters**
  2. **Circuit Performance**
  3. **Connected Two-Ports**.
- Each of these sub topics are tagged with a number 1, 2, 3 as shown in the screen display. These topics are accessed by using the ⊽ key to move the highlight bar to the desired choice and pressing [ENTER]. Alternatively, a section can be accessed by typing the number associated with the topic or subtopic. Thus pressing [1] will display an input screen for **Convert Parameters**.



*Pop up menu in **Two-Port Networks***



*Pop up menu for **Input Type***



Input Screen for data entry

Input Type **z**

The right arrow indicates that there are choices to be made for input type. Pressing ⊳ or [ENTER] displays a pop up menu showing the choices for **Input Type**. To select **h** parameters for input, press [3] or use the ⊽ to move the highlight bar to **h** and press [ENTER].

Prm 1: z11_	Parameter **z11_**; when **h** parameter is selected this changes to **h11_**.
Prm 2: z12_	Parameter **z12_**; when **h** parameter is selected this changes to **h12_**.
Prm 3: z21_	Parameter **z21_**; when **h** parameter is selected this changes to **h21_**.
Prm 4: z22_	Parameter **z22_**; when **h** parameter is selected this changes to **h22_**.
Output Type y ▶	The right arrow ▶ indicates additional choices for this parameter. Select this using the cursor bar. Pressing ▶ or [ENTER] displays a pop up menu showing the choices for **Output Type** the screen display shown. To select say **z** parameters for output, press [1] or use the ▼ to move the highlight bar to **z** and press [ENTER].

The input screen for **Convert Parameters** has several characteristics common to various portions of the EE•*Pro* software.

- The status line contains helpful information prompting the user for action.

Input Type z→	Choose: Input parameter type
Prm 1: z11_	Enter: P1 Impedance V1/I1 (I2=0)
Prm 2: z12_	Enter: P1 Impedance V1/I2 (I1=0)
Prm 3 z21_	Enter: P2 Impedance V2/I1 (I2=0)
Prm 4: z22_	Enter: P2 Impedance V2/I2 (I1=0)
Output Type y	Choose: Output parameter type

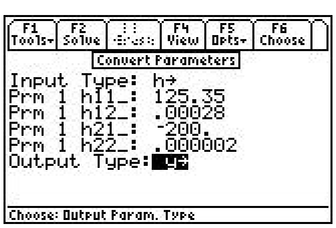
- The status line contents change if **h** parameters were chosen for **Input Type**:

Prm 1: h11_	Enter: P1 Impedance V1/I1 (V2=0)
Prm 2: h12_	Enter: P1 Parameter V1/V2 (I1=0)
Prm 3 h21_	Enter: P2 Parameter I2/I1 (V2=0)
Prm 4: h22_	Enter: P2 Admittance I2/V2 (I1=0)

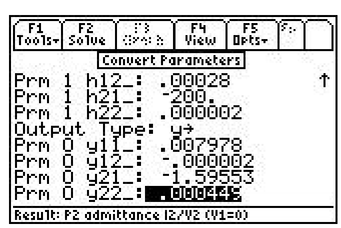
2.3 Solving a Problem in Analysis

Continuing the example of **Parameter Conversion, h** parameters are to be converted to **y** parameters.

- At the input screen choose **h** for **Input Type** and **y** for **Output type**. Move the highlight bar to **h11_** and type in a value of 125.35 and press [ENTER]**.**
- Repeat the above step entering a value of for **h12_=** .000028, **h21_= -**200 and **h22_**= 2.3E-6. The entered data can be real or complex or a variable name that is acceptable to the operating system.
- Press [F2] to solve the problem.
- The results of the computation are displayed in the result screen shown below.



Inputs entered, ready to solve.



Calculated results.

> **Note:** If the calculator is turned off automatically or manually while a results screen is being displayed, when EE•*Pro* is accessed again via the [APPS] key, the software automatically bypasses the home screen of EE•*Pro* and returns to the screen result display.

2.4 Special Function Keys in Analysis Routines

When **Analysis** functions are selected, the function keys in the tool bar access or activate features which are specific to the context of the section. They are listed in Table 2-1:

Table 2-1 Description of the Function keys

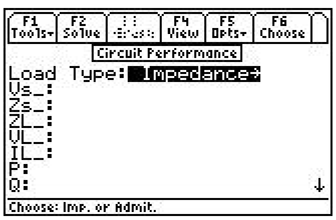
Function Key	Description
[F1]	Labeled **"Tools"** - contains all the functions available on the *TI-89* at the *Home* screen level. These functions are: 1: Open 2: (save as) 3: New 4: Cut 5: Copy 6: Paste 7: Delete 8: Clear 9: (format) A: About
[F2]	Labeled **"Solve"** - Is the primary key in various input screens. Pressing this key enables the software to begin solving a selected problem and display any resulting output to the user.
[F3]	Labeled **"Graph"** - This feature is available in input screens where the solution can be represented in graphical form. A plot can be viewed in the full screen or a split screen mode. This can be performed by pressing the [MODE] followed by [F2]. Use [2nd] and [APPS] to toggle between the data entry screen and graph window.
[F4]	Normally labeled as **"View"** - This enables the information content highlighted by the cursor to be displayed using the entire screen in *Pretty Print* format. An example of such a screen is shown in the screen displays shown. This function is also duplicated by pressing the ▶ key. If there is no contents to be viewed, then pressing the key has no effect. In some cases [F4] is labeled as **"Mode**", "**Split Screen**", **"Pict"**, **"Cash"**. • "**Mode**" is used in **Computer Engineering Applications** that displays an input screen to select binary parameters such word size, octal, binary, decimal or hexadecimal data. • "**Split Screen**" is displayed when a graphing solution is being set up. It allows the user to use the right half or the bottom half of the screen to display the graphical representations. • "**Pict**" is available when the **Polyphase Circuits** is selected, giving the user a quick glimpse of a picture of the circuit configuration. • "**Cash**" is used in **Capital Budgeting** section of the software
[F5]	Labeled "**Opts**" - This key displays a pop up menu listing the options: 1: View - allows the highlighted item to be viewed using *Pretty Print*. 2: (type) - Not active 3: Units - Not active 4: (conv) - Not active 5: Icons - presents a dialog box identifying certain Icons used by the software to display content and context of the information.

	6: (know)- Not active 7: Want - Not active
[F6]	• "**Edit**" **-** Brings in a data entry line for the highlighted parameter. • "**Choose**" in **Capital Budgeting** enabling the user to select from one of nine projects. • "**√ Check"** requesting the user to press this key to select a highlighted parameter for use in an **Analysis** computation.
[F7]	Appears only when solving problems in the **Ladder Network** section and is labeled "**Add**"; this displays the input screen allowing the user to add new elements to a ladder network.
[F8]	Appears only when solving problems in the **Ladder Network Section** and is labeled "**Del**". Pressing [F4] will delete an element from the ladder network.

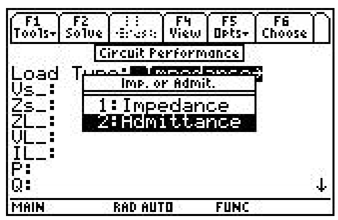
2.5 Data Fields Analysis Functions and Sample Problems

The Data Fields available to the user in the **Analysis** functions falls into four convenient categories.

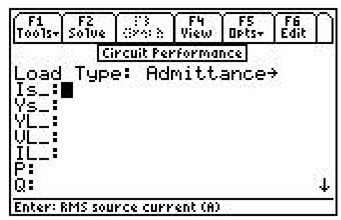
AC Circuits, Polyphase Circuits, Filter Design sections provide the first type of user interface. In these sections, a pop up menu presents the types of analysis available. Once the user has chosen a specific analysis topic, an input form is presented to the user. For example, choosing **AC Circuits** section followed by **Circuit Performance** as a topic displays a screen that has all the inputs and output variables.



Input screen for circuit. ***Impedance*** *for Load Type.*



Press [ENTER] *to display a Pop-up menu for* ***Load Type****.*

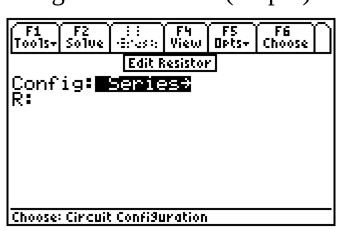


Input variables change when ***Admittance*** *is selected for Load Type.*

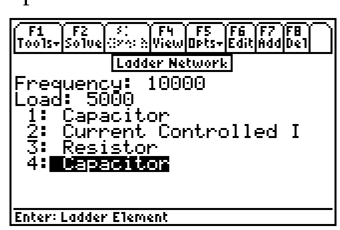
Use the cursor bar to highlight **Load Type**, press [ENTER] to display a pop up menu for *Impedance* or *Admittance* as a load type. Selecting a different load type will automatically update the variable list in the input screen as shown above.

Ladder networks presents a second type of user input interface. A ladder network consists of a load, and a series of ideal circuit elements (16 in variety) that can be added to the load as a rung or the side of a ladder. Circuit elements are added to the ladder network via the "**Add**" key (or [F7]). After selecting the proper element, enter the value for the element and press [F2]. This produces a description of the ladder as shown in the screen display. Ladder elements can be added at any location by moving the highlight bar to the element just prior to where the new element is needed and pressing [F7]. Any element can be removed from the list by pressing [F8]. The circuit elements are listed in order of appearance moving from the load (output) to the input.

Pop up menu of elements for Ladder Network

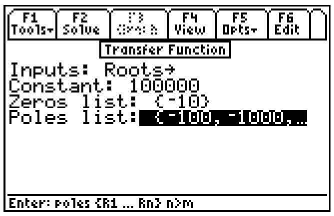


Edit Screen for Resistor in Ladder Network

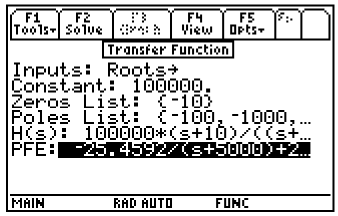


Updated component list for the Ladder Network

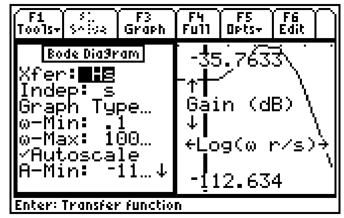
The **Gain and Frequency** section under the **Analysis** menu offers an example where a problem is set up in one topic area (**Transfer Function**) and graphed under another topic heading (**Bode Diagram**). A **Transfer Function** is set up as in the screen shown below. It is important to note that data for **Zeroes** and **Poles** is entered as a list, e.g., numbers entered within curly brackets separated by commas. Once the **Transfer Function** has been determined, it can be graphed by switching to the **Bode Diagram** topic by pressing [ESC] followed by [2]. The software takes full advantage of the graphing engine portion of the operating system of the calculator. Thus when the graphing function is executed using the [F3] key, the tool bar reflects the functions available during a graphing operation.



Input Screen for Transfer Function

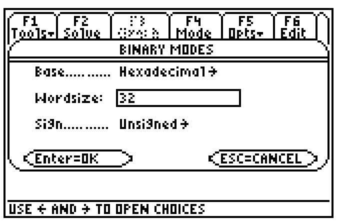


Graphing Parameters for Transfer Function

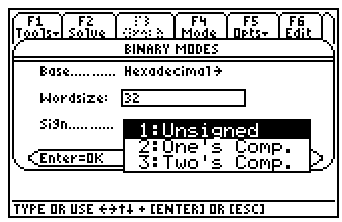


*Split Screen Display of Bode Diagram of Gain Function (**Hs**)*

The **Computer Engineering** section, under the **Analysis** menu, performs calculations involving numbers represented in binary, decimal, octal or hexadecimal formats within the constraints of parameters defined by the user. In any topic of the **Computer Engineering** section, the function key [F4] opens a dialog box allowing the user to specify parameters such as the base of a number system, its word size, arithmetic using unsigned, 1's or 2's complement methods, setting Carry and Range Flags. Examples of these screens are shown below:

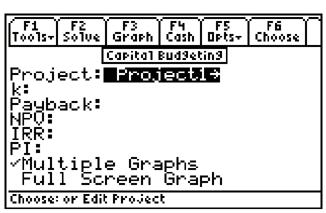


Press [F4] to access EE•Pro's MODE screen.

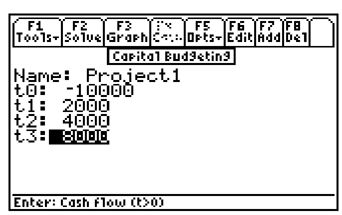


*Highlight **Sign** and press ▶ to display a pop-up menu for available options.*

Capital Budgeting represents a fourth category of an input interface where the user can compare relative financial performance of several projects with relevant data such as **interest rate or discount rate (k), IRR, NPV, Payback period**. Screen displays shown here illustrate the basic user interface.



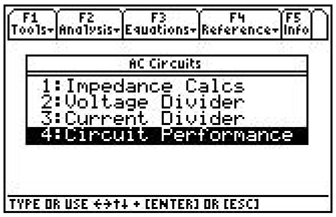
Input Screen for Capital Budgeting

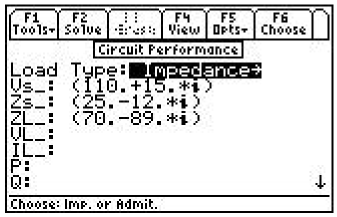


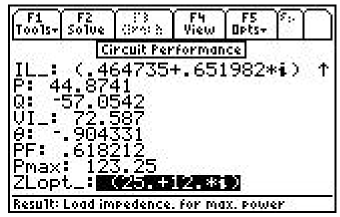
Press [F4] to display Cash Flow for 'Project 1'

Example 2.1 (Numeric Results)

Find the electrical **Circuit Performance** of an **AC circuit** consisting of a voltage source 110+15**i* volts and an impedance of 25-12**i* ohms. The load for the example is a capacitive impedance 70-89**i*.





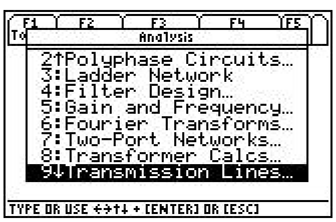


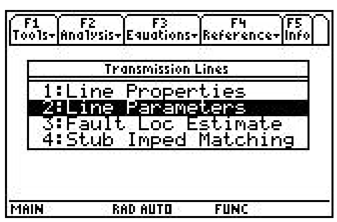
Pop up menu in AC Circuits *Input entry complete* *Computed output*

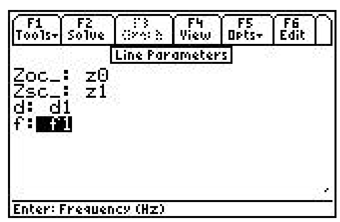
1. From the home screen of EE•*Pro* press the [F2] key labeled Analysis to display the pull down menu listing all the sections available under **Analysis.**
2. Press [1] to access **AC Circuits** section to view a pop up menu of all topics available.
3. Press [4] to enter to the input screen of **Circuit Performance**.
4. Enter the value of 110+15**i* for **Vs_**, 25-12**i* ohms for **Zs_** and 70-89**i* for load impedance **ZL_**.
5. Press the Solve key [F2]**.**
6. The results of the calculations are displayed in the data screen as shown.

Example 2.2 (Symbolic Results)

Find the parameters of a transmission line given the open circuit impedance is **Z0_**, the short circuit impedance is **Z1_**, distance is d1, and frequency of measurement is f1.

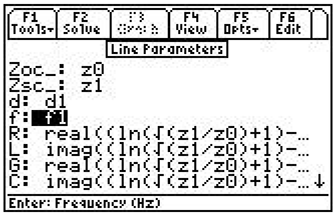




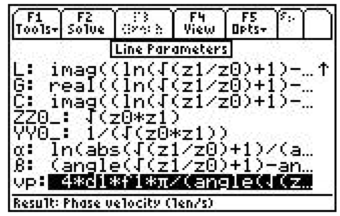


Pull down menu for Analysis *Menu for Transmission Lines* *Input for Line Parameters*

1. From the home screen of EE•*Pro* press the [F2] key labeled **Analysis** to display the pull down menu listing all the sections available under **Analysis**.
2. Press [9] to access the **Transmission Lines** section to view a pop up menu of the all available topics.
3. Press [2] to open the input screen for **Line parameters**.
4. Enter the value of z0 for **Zoc_**, z1 of **Zsc_**, d1 for **d** and f1 for **f**.
5. Press the Solve key [F2]**.**
6. The results of the calculations are displayed in the data screen as shown below.



Input entered symbolically



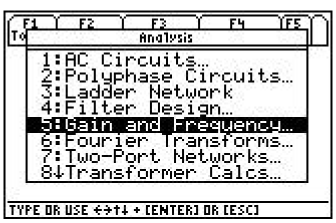
Calculated Output also symbolic

Example 2.3 (Graphical Results)

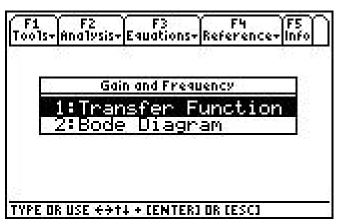
Construct a Bode diagram for a system with pole locations at 1000, 10000, 50000, a zero at 5000, and a proportionality constant of 1000000.

1. From the home screen of EE•*Pro*, press the [F2] key to display the pull down menu listing all the sections available under **Analysis**.
2. Press [5] to access the **Gain and Frequency** section to view a pop up menu of available topics.
3. Press [1] to open the input screen for **Transfer Functions**.
4. Choose Roots for **Inputs**, enter 1000000 for **Constant**, {5000} for **Zeroes List** and {1000, 10000, 50000} for **Poles List**.
5. Press the **Solve** key [F2]**.**
6. The results of the calculations are displayed in the data screen as shown.
7. Press [ESC] key to revert to the pop up display for **Gain and Frequency**, and press [2] to access **Bode Diagram** input screen.
8. Begin entering parameters for graphing the *Gain* of the *Transfer Function*. The minimum and maximum values for the horizontal axis show the default settings. Note that log (ω) is the horizontal axis.
9. Move the highlight bar to set ω**-Min** to 1, and ω**-Max** to 200000.
10. Move the highlight bar to **Auto Scale** and press [F6] to select this option.
11. Press [F3]to graph the function.

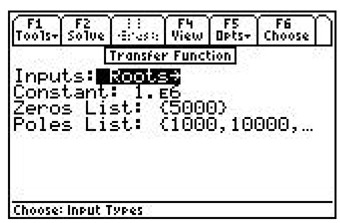
Examples of the screen display for this problem are shown here:



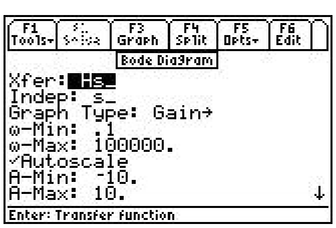
Pull down menu of



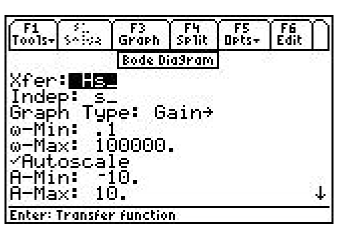
Pop up menu for Gain and Frequency



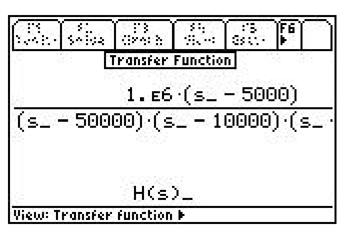
Input Screen for Analysis Function Transfer



Graphing parameters



Split Screen Graph



Partial view of Transfer function

2.6 Session Folders, Variable Names

EE•*Pro* automatically stores its variables in the current folder specified by the user in [MODE] or the HOME screens. The current folder name is displayed in the lower left corner of the screen (default is "Main"). To create a new folder to store values for a particular session of EE•*Pro*, press [F1]**:/TOOLS,** [3]**:/NEW** and type the name of the new folder (see Chapter 5 of the TI-89 Guidebook for the complete details of creating and managing folders). There are several ways to display or recall a value:

- The contents of variables in any folder can be displayed using the [VAR-LINK], moving the cursor to the variable name and pressing [F6] to display the contents of a particular variable.
- Variables in a current folder can be recalled in the HOME screen by typing the variable name.
- Finally, values and units can be copied and recalled using the [F1]**/Tools 5:COPY** and **6:PASTE** feature.

All inputs and calculated results from *Analysis* and *Equations* section are saved as variable names. Previously calculated, or entered values for variables in a folder are replaced when equations are solved using new values for inputs.

Overwriting of variable values in graphing

When an equation or analysis function is graphed, EE•*Pro* creates a function for the TI grapher which expresses the dependent variable in terms of the independent variable. This function is stored under the variable name *pro(x)*. When the EE•*Pro*'s equation grapher is executed, values are inserted into the independent variable for *pro(x)* and values for the dependent value are calculated. Whatever values which previously existed in either of the dependent and independent variables in the current folder are cleared. To preserve data under variable names which may conflict with EE•*Pro*'s variables, run EE•*Pro* in a separate folder.

Reserved Variables

There is a list of reserved variable names used by the TI operating system which cannot be used as user variable names or entries. These reserved variables are listed in Appendix F.

Chapter 3 AC Circuits

This chapter describes the software in the **AC Circuits** section and is organized under four topics. These topics form the backbone of AC circuit calculations.

- Impedance Calculations
- Voltage Divider
- Current Divider
- Circuit Performance

3.1 Impedance Calculations

The **Impedance Calculations** topic computes the impedance and admittance of a circuit consisting of a resistor, capacitor and inductor connected in Series or Parallel. The impedance and admittance values are displayed to the user in symbolic, numeric, real or complex form. As stated in Chapter 2, due to the variety of computation methods used in each topic in of *Analysis*, the unit management feature is not present. All entered values are assumed to be in common SI units (F, A, m, Ω, s, etc.). Symbolic computation is limited to single undefined terms for each entry (such as 'a' or 'x' where 'a' and 'x' are undefined) or an algebraic expression of previously defined terms which can be simplified to a numerical result upon entry (such as 1.5*x-3/y, where x=1+2****i*** and y=4).

Field Descriptions

Config: (*Circuit Configuration*)
Press [ENTER] and select **Series** or **Parallel** configuration by using ⌄ After choosing**,** press [ENTER] to display the input screen updated for the new configuration..

Elements: (*Element Combination*)
Pressing [F2] displays the following circuit elements: R, L, C, RL, RC, LC and RLC. The choice of elements determines which of the input fields are available.

fr: (*Frequency in Hz*)
Enter a real number or algebraic expression of defined terms.

R: (*Resistance in ohms - only appears if* R, RL, RC *or* RLC *is chosen in* **Elements** *field*)
Enter a real number or algebraic expression of defined terms.

L: *(Inductance in H* enry- *only appears if* L, RL, LC *or* RLC *is chosen in* **Elements** *field*)
Enter a real number or algebraic expression of defined terms.

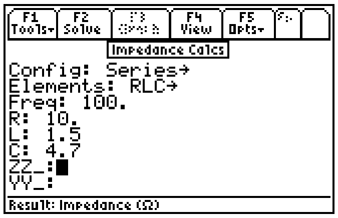
C: (*Capacitance in Farads - only appears if* C, LC, RC *or* RLC *is chosen in* **Elements** *field*)
Enter a real number or algebraic expression of defined terms.

ZZ_: (*Impedance in ohms*)
Returns a real or complex number.

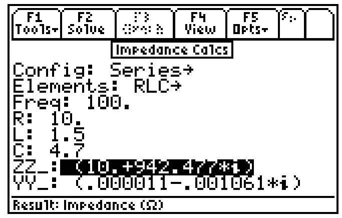
YY_: (*Admittance in Siemens*)
Returns a real or complex number.

Example 3.1

Compute the impedance of a series RLC circuit consisting of a 10 ohm resistor, a 1.5 Henry inductor and a 4.7 Farad capacitor at a frequency of 100 Hertz.

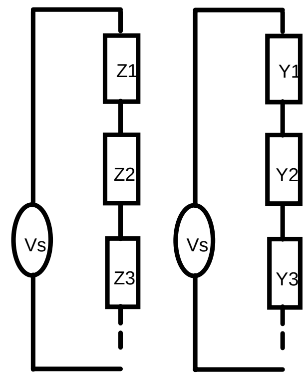


Input Screen



Output Screen

1. Choose Series for **Config** and RLC for **Elements** using the procedure described above.
2. Enter 100 for **Freq**.
3. Enter 10 for **R**, 1.5 for **L**, and 4.7 for **C**.
4. Press [F2] to calculate **ZZ_** and **YY_**.
5. The output screen shows the results of computation.



Impedance/Admittance loads in series

3.2 Voltage Divider

This section demonstrates how to calculate the voltage drop across a load connected to an ideal voltage source. The load consists of impedances or admittances in series. The software computes the current through the load and the voltage across each impedance/admittance.

Field Descriptions

Load Type: *(Type of Load)* Press [ENTER] to display the choices; Impedance **(Z)** or Admittance **(Y).**

The choice made determines whether the third field is **ZZ_** (impedance chain) or **YY_** (admittance chain) is displayed .

Vs_: (*Source Voltage in V*) Enter a real or complex number, variable name, or algebraic expression of defined terms.

ZZ_: (*Impedances in Series*) Enter a list of real or complex numbers, or algebraic expression of defined terms.

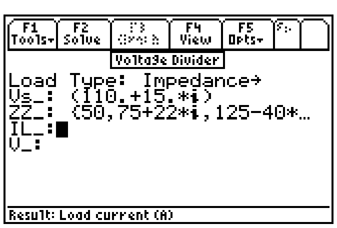
YY_: (*Admittances in Series*) Enter a list of real or complex numbers, or algebraic expression of defined terms.

IL_: (*Load Current in A*) Returns a real or complex number, variable name or algebraic expression.

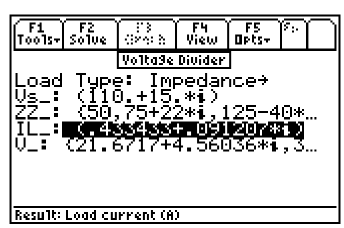
V_: (*Element Voltages in V*) Returns a list of real or complex numbers, variable names, or algebraic expressions.

Example 3.2

Calculate the voltage drop across a series of loads connected to a voltage source of (110+25**i*) volts. The load consists of a 50 ohm resistor, and impedances of (75+22**i*), and (125-40**i*) ohms.



Input Screen

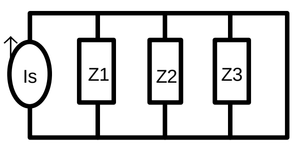


Output Screen

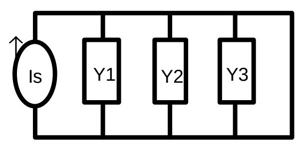
1. Choose Impedance for **Load Type**
2. Enter the value 110 + 25**i* for **Vs_**.
3. Enter {50, 75 + 22**i*, 125 - 40**i*} for **ZZ_**.
4. Press [F2] to calculate **IL_** and **V_**.
5. The results of the computation are shown in the screen display above.

3.3 Current Divider

This section demonstrates how to calculate individual branch currents in a load defined by a set of impedances or admittances connected in parallel. In addition, the voltage across the load is calculated.



Current Divider - Impedances



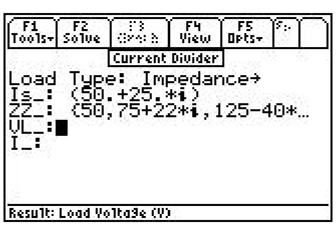
Current Divider - Admittances

Field Descriptions

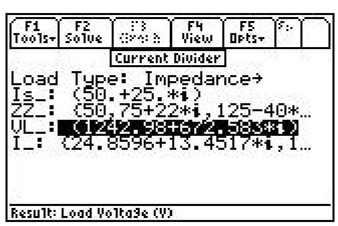
Load Type:	(*Type of Load*)	Press [ENTER] to select Impedance or Admittance. This sets the third field to be **ZZ_** (Impedances) or **YY_** (Admittances).
Is_:	(*Source Current in A*)	Enter a real or complex number, variable name or algebraic expression of defined terms.
ZZ_:	*(Impedance in ohms)*	Enter a list of real or complex numbers, or algebraic expression of defined terms.
YY_:	(*Admittances in Siemens*)	Enter a list of real or complex numbers or algebraic expressions of defined terms.
VL_:	(*Load Voltage in V*)	Returns a real, complex number or algebraic expression.
I_:	(*Currents in A*)	Returns a list of real or complex numbers or algebraic expressions.

Example 3.3

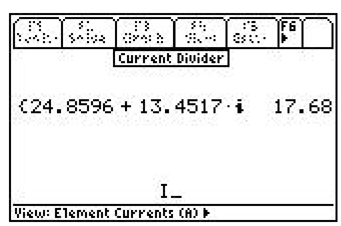
Calculate the voltage drop across impedances connected in parallel to a current source of (50 + 25**i*). The load consists of 50, 75+22*i, 125-40*I Ω.



Input Screen



Output Screen



*Partial **Pretty Print** of I_*

1. Choose Impedance for **Load Type**
2. Enter the value 50 + 25**i* for **Is_**.
3. Enter the value { 50, 75+22*i, 125-40*i } for **ZZ_.**
4. Press [F2] to calculate **VL_** and **I_**.
5. The results of the computation are displayed in the screen shown above along with a *Pretty Print* display of the expression for **I_**.

3.4 Circuit Performance

This section shows how to compute the circuit performance of a simple load connected to a voltage or current source. Performance parameters computed include load voltage and current, complex power delivered, power factor, maximum power available to the load, and the load impedance required to deliver the maximum power.

Field Descriptions - Input Screen

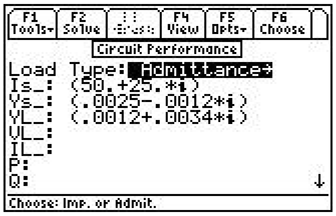
Load Type:	(*Type of Load*) Press [ENTER] to select load impedance (Z) or admittance (Y). This will determine whether the remaining fields **Vs_**, **Zs_**, and **ZL_** or **Is_**, **Ys_**, and **YL_** are displayed, respectively.	
Vs_:	(*RMS Source Voltage in V*)	A real or complex number, variable name, or algebraic expression of defined terms.
Zs_	(*Source Impedance in* Ω)	A real or complex number, variable name or algebraic expression of user-defined terms.
ZL_:	(*Load Impedance in* Ω)	A real or complex number, variable name, or algebraic expression of defined terms.
Is_:	(*RMS Source Current in A*)	A real or complex number, variable name, or algebraic expression of defined terms.
Ys_:	(*Source Admittance in Siemens*)	Enter a real or complex number, variable name, or algebraic expression of defined terms.
YL_:	(*Load Admittance in Siemens*)	Enter a real or complex number, variable name or algebraic expression of defined terms.

Field Descriptions - Output Screen

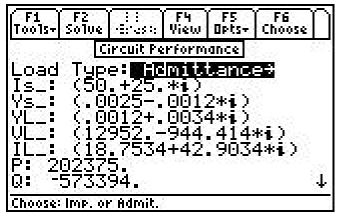
VL_:	(*Load Voltage in V*)	Returns a real, complex number or algebraic expression.
IL_:	(*Load Current in A*)	Returns a real, complex number or algebraic expression.
P:	(*Real Power in W*)	Returns a real number or algebraic expression.
Q:	(*Reactive Power in W*)	Returns a real number or algebraic expression.
VI_:	(*Apparent Power in W*)	Returns a complex number or algebraic expression.
θ:	(*pf Angle in degrees or radians. determined by the* [MODE] *setting*)	Returns a real number or algebraic expression.
PF:	(*Load Power Factor*)	Returns a real number or algebraic expression.
Pmax:	(*Maximum Power Available in W*)	Returns a real number or algebraic expression.
ZLopt_:	(*Load Impedance for Maximum Power in* Ω - *if* Impedance *is chosen for* **Load Type** *at the input screen*).	Returns a real, complex number or algebraic expression.
YLopt_:	(*Load Admittance for Maximum Power in Siemens* - *if* Admittance, *is chosen for* **Load Type** *at the input screen*)	Returns a real, complex number, or algebraic expression.

Example 3.4

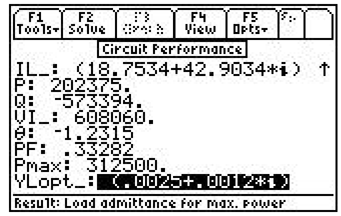
Calculate the performance parameters of a circuit consisting of a current source (10 - 5**i*) with a source admittance of .0025 - .0012*i and a load of .0012 + .0034*i.



Input Screen



Output: Upper Half



Output: Lower Half

1. Choose Admittance for **Load Type**.
2. Enter the value 10 **-** 5*i for **Is_**.
3. Enter the value .0025 **-** .0012*i for **Ys_**, and .0012 + .0034*i for a load of **YL_**.
4. Press [F2] to calculate the performance parameters.
5. The input and results of computation are shown above.

Chapter 4 Polyphase Circuits

This chapter describes Wye and Δ arrangements in **Polyphase Circuits.**

- ❖ Wye ↔ Δ Conversion
- ❖ Balanced Wye Load
- ❖ Balanced Δ Load

4.1 Wye ↔ Δ Conversion

The Wye ↔ Δ Conversion converts three impedances connected in Wye or Δ form to its corresponding Δ or Wye form, i.e., . Wye ↔ Δ or Δ ↔ Wye

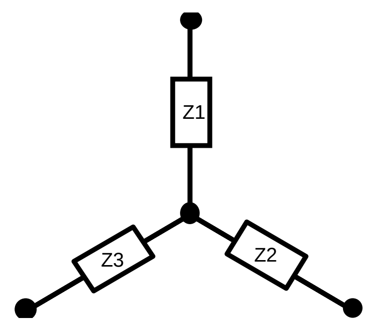


Fig. 4.1 Wye Network

Input Fields -

Input Type:	Selection choices are Δ→Wye or Wye→Δ. This determines whether the next 3 fields (input fields) accept Δ or Wye Impedances.
ZZA_: (*Δ Impedance*)	Real or complex number, variable name, or algebraic expression of defined terms.
ZZB_: (*Δ Impedance*)	Real or complex number, variable name, or algebraic expression of defined terms.
ZZC_: (*Δ Impedance*)	Real or complex number, variable name, or algebraic expression of defined terms.
ZZ1_: (*Y Impedance*)	Real or complex number, variable name, or algebraic expression of defined terms.
ZZ2_: (*Y Impedance*)	Real or complex number, variable name, or algebraic expression of defined terms.
ZZ3_: (*Y Impedance*)	Real or complex number, variable name, or algebraic expression of defined terms.

Result Fields

ZZA_: (*Δ Impedance*)	Real or complex number, or algebraic expression.
ZZB_: (*Δ Impedance*)	Real or complex number, or algebraic expression.
ZZC_: (*Δ Impedance*)	Real or complex number, or algebraic expression.
ZZ1_: (*Y Impedance*)	Real or complex number, or algebraic expression.
ZZ2_: (*Y Impedance*)	Real or complex number or algebraic expression.
ZZ3_: (*Y Impedance*)	Real or complex number or algebraic expression.

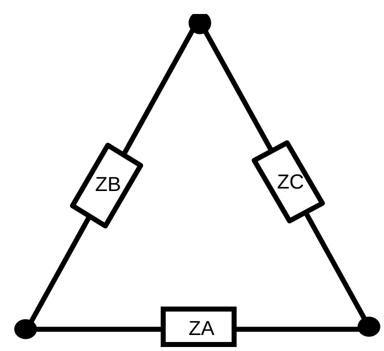
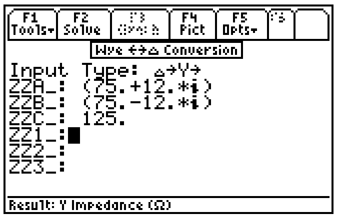


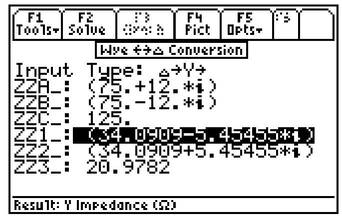
Fig. 4-2 Δ Network

Example 4.1 - Compute the Wye impedance equivalent of a Δ network with impedances 75+12**i*, 75-12**i*, and 125 ohms.

1. Select Δ →Y for Input Type. .
2. Enter the values 75+12**i*, 75 -12**i*, 125 for **ZZA_, ZZB_** and **ZZC_.**
3. Press F2 to calculate **ZZ1_, ZZ2_** and **ZZ3_.**



Input Parameters



Calculated Output

The computation results are: **ZZ1_:** 34.0909 - 5.45455·*i*
ZZ2_: 34.0909 + 5.45455·*i*
ZZ3_: 20.9782

4.2 Balanced Wye Load

A balanced Wye load refers to three identical impedance loads connected in a Wye configuration. The voltage **V12_** represents the line voltage from line 1 to line 2 and is used as the reference voltage throughout this Wye network. The voltages across lines 2 and 3, and across 3 and 1 have the same magnitude as **V12_**, but are out of phase by -120º and 120º respectively. The software computes the currents **I1_, I2_**, and **I3_** in each leg of the Wye network, the line to neutral voltage in each phase **V1N_, V2N_**, and **V3N_**, the power dissipated in each phase **P**, and the wattmeter readings **W12** and **W13** connected to the circuit as shown in the Fig 4-3.

Input Fields

Input Type:

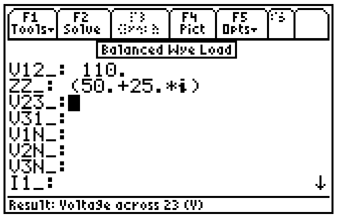
V12_:	(*Reference Voltage in V across lines 1 and 2*)	Enter a real or complex number, variable name, or algebraic expression of defined terms.
ZZ_:	(*Phase Impedance in Ω*)	Enter a real or complex number, variable name, or algebraic expression of defined terms.

Result Fields

V23_:	(*Voltage in V across lines 2 and 3*)	A real, complex number, or variable name.
V31_:	(*Voltage in V across lines 3 and 1*)	A real, complex number, or variable name.
V1N_:	(*Voltage in V across 1N*)	A real, complex number, or variable name.
V2N_:	(*Voltage in V across 2N*)	A real, complex number, or variable name.
V3N_:	(*Voltage in V across 3N*)	A real, complex number, or variable name.
I1_:	(*Line Current 1 in A*)	A real, complex number, or variable name.
I2_:	(*Line Current 2 in A*)	A real, complex number, or variable name.
I3_:	(*Line Current 3 in A*)	A real, complex number, or variable name.
P:	(*Phase Power in W*)	A real number or variable name.
W12:	(*Wattmeter reading in W across lines 1 and 2*)	A real number.
W13:	(*Wattmeter reading in W across lines 1 and 3*)	A real number.

Example 4.2 - A Wye network consists of three impedances of 50 + 25**i* with a line voltage of 110 volts across line 1 and 2. Find the line current and power measured in a two-wattmeter measurement system.

1. Select Balanced Wye Load.
2. Enter the value 50 + 25**i* for **ZZ_.**
3. Press [F2] to calculate performance characteristics of the circuit.



Input Screen

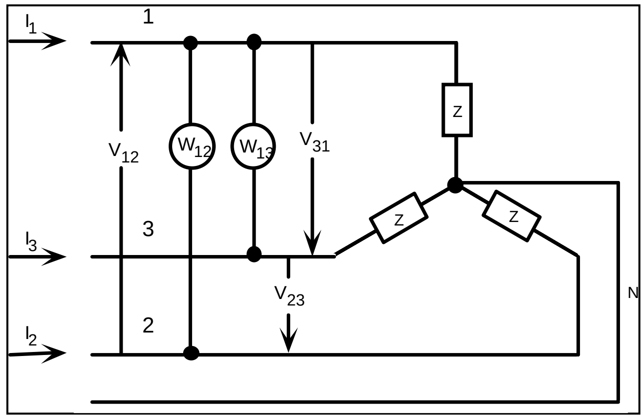
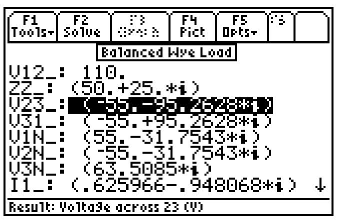
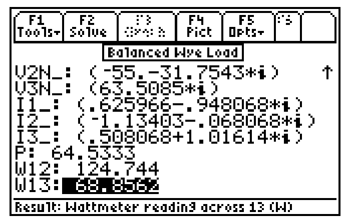


Fig. 4.3 Balanced Wye network with 2 wattmeters



Output Screen (upper half)



Output Screen (lower half)

The results of computation are listed below:

V23_:	-55 - 95.2628**i*
V31_:	-55 + 95.2628**i*
V1N_:	55 - 31.7543**i*
V2N_ :	-55 - 31.7543**i*
V3N_:	63.5085**i*
I1_:	.625966 - .948068**i*
I2_:	-1.13403 - .068068**i*
I3_:	.508068 + 1.01614**i*
P:	64.533
W12:	124.744
W13:	68.8562

4.3 Balanced Δ Load

A balanced Delta load refers to three identical impedance loads connected in a Delta configuration. The voltage **VAB_** represents the line voltage from line A to line B and is used as the reference voltage throughout this Delta network. The voltages across lines B and C, and C and A have the same magnitude as **VAB_**, but are out of phase by -120º and 120º respectively. The software computes the currents **IA_, IB_**, and **IC_** in each leg of the Delta network, power dissipated in each phase **P**, wattmeter readings **WAB** and **WAC** connected as shown in the Fig 4-4 .

Input Fields

Input Type:

VAB_: (*Reference Voltage in V across lines 1 and 2*)
Enter a real or complex number, variable name, or algebraic expression of defined terms.

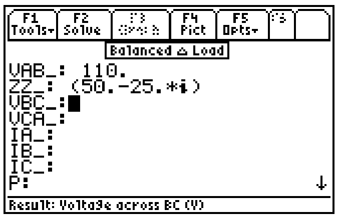
ZZ_: (*Phase Impedance in Ω*)
Enter a real or complex number, variable name, or algebraic expression of defined terms.

Result Fields

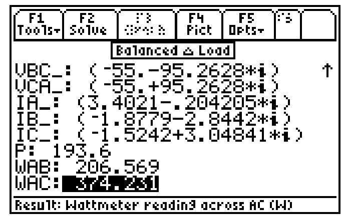
VBC_: (*Voltage in V across lines B and C*) A real or complex number, or algebraic exp.

VCA_:	(*Voltage in V across lines C and A*)	A real or complex number, or algebraic exp.
IA_:	(*Line Current A in A*)	A real or complex number, or algebraic exp.
IB_:	(*Line Current B in A*)	A real or complex number, or algebraic exp.
IC_:	(*Line Current C in A*)	A real or complex number, or algebraic exp.
P:	(*Phase Power in W*)	A real number or algebraic expression.
WAB:	(*Wattmeter reading in across lines A and B*)	A real number or algebraic expression.
WAC:	(*Wattmeter reading in W across lines A and C*)	A real number or algebraic expression.

Example 4.3 - A Delta network consists of three impedances of 50 - 25**i* with a line voltage of 110 volts across line A and B. Find the line current and power measured in a two-wattmeter measurement system.

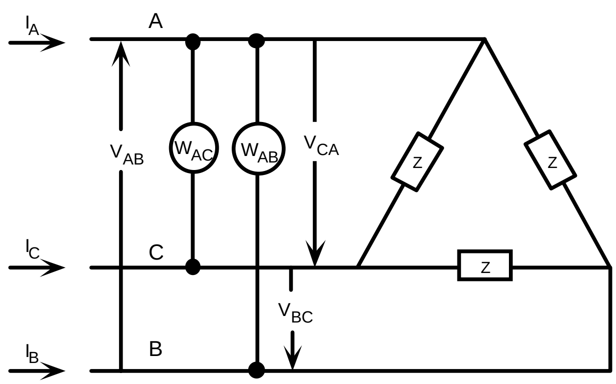


Input Parameters



Calculated Output

1. Select **Balanced Delta Load.**
2. Enter the values 50 - 25**i* for **ZZ_** and 110_V for **VAB_.**
3. Press F2 to calculate performance characteristics of the circuit.



.

Fig. 4.4 Wattmeter Measurement in a Delta Circuit

The results of computation are listed below:

VBC_:	-55 - 95.2628**i*	**IC_:**	-1.5242 + 3.04841**i*
VCA_:	-55 + 95.2628**i*	**P:**	193.6
IA_:	3.4021 - .204205**i*	**WAB:**	206.569
IB_:	-1.8779 – 2.8442**i*	**WAC:**	374.231

Chapter 5 Ladder Network

This chapter describes ladder network analysis **-** a circuit reduction method by which branches of the circuit are treated as sides (series connection) or rungs (parallel or shunt connection) of a ladder.

5.1 Elements of a Ladder Network

In the examples that follow, the left end of the ladder is the input end and the right end of the ladder is the output end, where the load is connected. The elements of the ladder (from **1** to **N**) are entered from right to left, going from output to input. The input impedance **Zin_** is calculated as if you were "looking in" to the left end of the ladder.

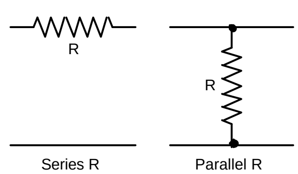
Field Descriptions - Input Screen

Frequency: (*Frequency*) Enter a real number, or algebraic expression of defined terms.
Load_: (*Initial Load*) Enter a real or complex number, variable name, or algebraic expression of defined terms.

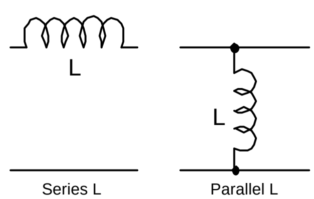
1: (*Element 1* **-** *closest to the load or output*)
...
N: (*Element N* **-** *furthest from the load or output*)

Field Descriptions - Element Screen

Sixteen different element types are available to build the ladder network. These elements can be inserted in series or parallel configuration.

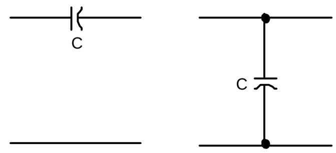


Resistor
A resistor can be added as a rung (parallel) or side (series). Choose Series or Parallel for **Config,** and enter a value for **R** in ohms.



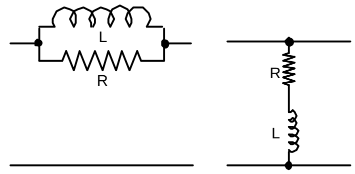
Inductor - (ideal inductor)
An inductor can be added as a rung (parallel) or side (series)). Choose Series or Parallel for **Config,** and enter a value for **L** in henrys.

Capacitor - (ideal capacitor)
A capacitor can be added as a rung (parallel) or side (series). Choose Series or Parallel for **Config,** and enter a value for **C** in Farads.



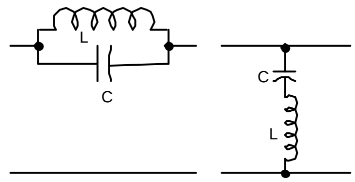
Series C Parallel C

RL
An RL series circuit can be added as a rung (parallel) or as an RL parallel circuit as a side (series). Choose Series or Parallel for **Config,** and enter a value for **R** in ohms and **L** in henrys.



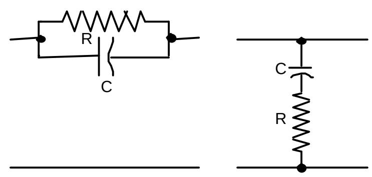
Series RL Parallel RL

LC
An LC series circuit can be added as a rung (parallel) or as an LC parallel circuit as a side (series). Choose Series or Parallel for **Config,** and enter a value for **L** in henrys and **C** in farads.



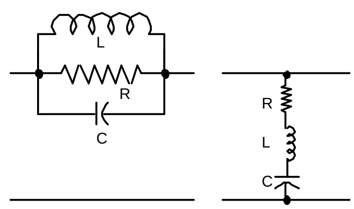
Series LC Parallel LC

RC
An RC series circuit can be added as a rung (parallel) or as an RC parallel circuit as a side (series). Choose Series or Parallel for **Config,** and enter a value for **R** in ohms and **C** in farads.



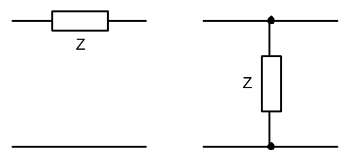
Series RC Parallel RC

RLC
An RLC series circuit can be added as a rung (parallel) or as an RLC parallel circuit as a side (series). Choose Series or Parallel for **Config,** and enter a value for **R** in ohms, **L** in henrys, and **C** in farads.



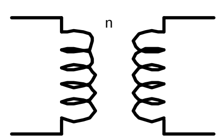
Series RLC Parallel RLC

General Impedance
An impedance can be added as a rung (parallel) or side (series). Choose Series or Parallel for **Config,** and enter a value for **Z_** in ohms.

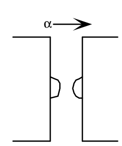


Series Impedance Parallel Impedance

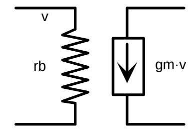
Transformer - (ideal transformer)
A transformer can be added only in cascade connection. Specify turns ratio by entering a value for **n**.



Gyrator- (synthetic inductance filter)
A gyrator can be added only in cascade connection. Specify gyrator parameter by entering a value for α.

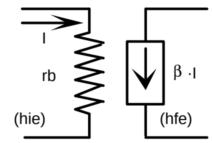


Voltage-Controlled I
A controlled voltage can be added only in cascade connection. Specify base resistance and transconductance by entering values for **rb** in ohms and **gm** in siemens.



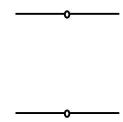
VCIS

Current-Controlled I
A controlled current can be added only in cascade connection. Specify base resistance and common base current gain by entering values for **rb** in ohms and β.

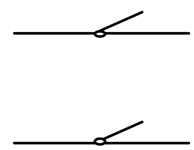


ICIS

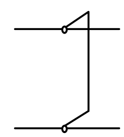
Transmission Line
A transmission line can be added only in cascade connection. Specify characteristic impedance and electrical length by entering values for **Z0** in ohms and θ**0** in radians. The variation of θ**0** with frequency is not taken into account in the ladder network calculation. **Caution-**be sure to enter a value for the electrical length θ**0** which is consistent with the chosen frequency.



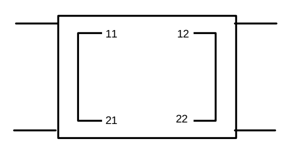
Open Circuited Stub
Can be added only in cascade connection. Specify characteristic impedance and electrical length by entering values for **Z0** in ohms and θ**0** in radians. **Caution-**be sure to enter a value for the electrical length θ**0** which is consistent with the chosen frequency.



Short Circuited Stub
Can be added only in cascade connection. Specify characteristic impedance and electrical length by entering values for **Z0** in ohms and θ**0** in radians. **Caution-**be sure to enter a value for the electrical length θ**0** which is consistent with the chosen frequency.



Two-Port Network
Can be added only in cascade connection. Choose **z, y, h, g, a,** or **b** for Input Parameters, and enter values for **..11**, **..12**, **..21**, and **..22**.



Field Descriptions - Output Screen

Zin_:	(*Input Impedance in ohms)*	Returns a real or complex number, variable name or algebraic expression.
I2/V1_:	(*Forward Transfer Admittance in Siemens)*	Returns a real or complex number, variable name or algebraic expression.
I2/I1_:	(*Current Transfer Ratio*)	Returns a real or complex number, variable name or algebraic expression.
Pout/Pin:	(*Real Power Gain*)	Returns a real or complex number, variable name or algebraic expression.
V2/V1_:	(*Forward Voltage Transfer Ratio*)	Returns a real or complex number, variable name or algebraic expression.
V2/I1_:	(*Forward Transfer Impedance in ohms)*	Returns a real or complex number, variable name or algebraic expression.

5.2 Using the Ladder Network

General instructions for entering the elements and computing the parameters of a ladder network.

1. The initial screen prompts the user for entry of values for **Frequency** and **Load**.
2. Build the ladder by adding elements to it. Press [F7] to insert the first element. Choose an element type and press [ENTER]. Enter the appropriate values. Press [F2] to update the ladder with the new element just added. A second press of the [F2] key computes the electrical performance of the circuit.
3. New elements can be added or inserted by moving the highlight bar to the location desired and pressing [F7]**.** The new element will appear after the a highlighted element.
4. A circuit element can be deleted from the ladder by moving the highlight bar to the element and pressing [F8].
5. Press [F2] to compute the overall ladder network parameters.
6. Previously calculated results are not automatically updated for new element entries; the user must press [F2] to re-solve for the circuit parameters for a new circuit configuration.

Example 5.1

What is the input impedance of the circuit shown below in Fig. 5.1 at 1 MHz and 10 MHz?

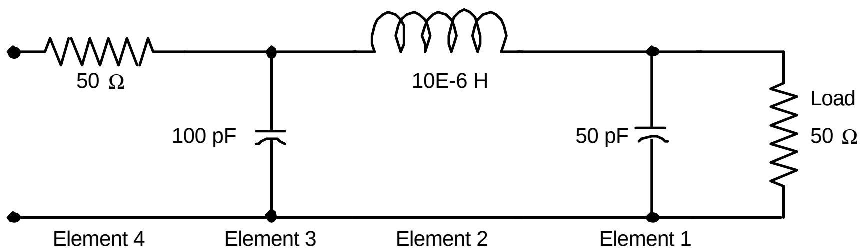
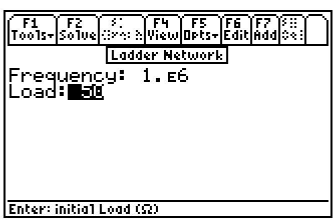
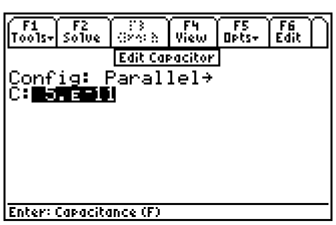


Fig. 5.1 Ladder Network Example

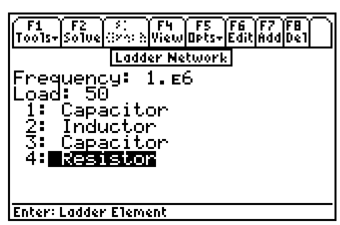


Entering Load and Frequency

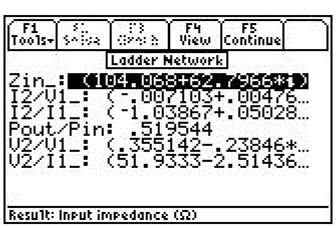
Partial list of Element Choices



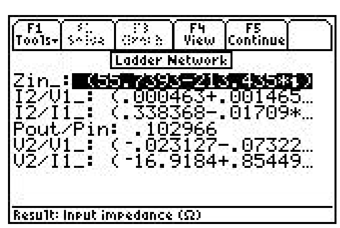
Typical Edit Screen for an Element



List of all the Ladder Components



Output Screen at 1 MHz



Output Screen at 10 MHz

.

1. Enter 1E6 for **Frequency**.
2. Enter 50 for **Load**.
3. Press [F7] to add the first element and move the highlight bar in the pull down menu to **Capacitor** and press [ENTER] to display the input screen for the Capacitor. Select Parallel for **Configuration** of the capacitor and enter the value 50E-12 for **C**. Press [ENTER] to accept the element data and press [F2] to return a listing of the Ladder Network.
4. Move the highlight bar to **1: Capacitor** and press [F7] to enter the second element in this circuit.
5. Move the highlight bar to **Inductor** to display the input screen for the new element. Choose Series for **Config** and enter the value 10E-6 for **L.** Press [ENTER] to accept the value and press [F2] to update the ladder. Enter the remaining two elements: a 100 pF (100E-12) capacitor in parallel and a 50 ohm resistor in series.
6. Press [F2] to calculate the results displayed in the output screen as shown above.
7. To delete an element from the network, highlight it and press [F8], the delete key.

To calculate the ladder network parameters at a second frequency of 10 MHz:
1. Press [ESC] to return to the input screen.
2. In the **Frequency** field, type 10E6.
3. Press [F2] to calculate the results, as displayed in the output screen shown above.

Example 5.2

A transistor amplifier is shown in the figure below. The transistor is characterized by a base resistance of 2500 ohms, a current gain of 100 and is operating at a frequency of 10,000 Hertz. Figure 5.2 and 5.3 show the circuit and its simplified form.

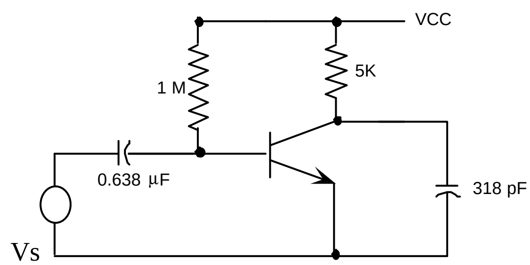


Fig. 5.2 Transistor Amplifier Example

This schematic can be reduced to the ladder network that appears in Fig. 5.3

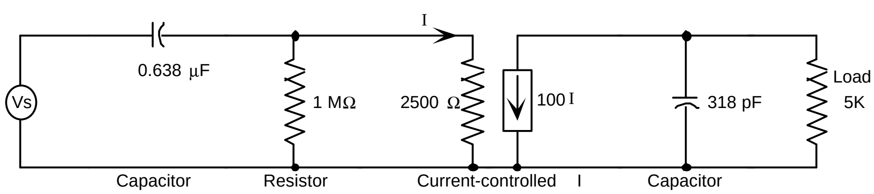
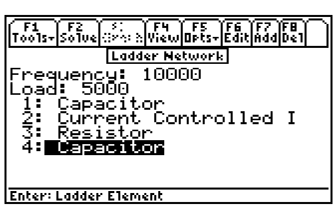
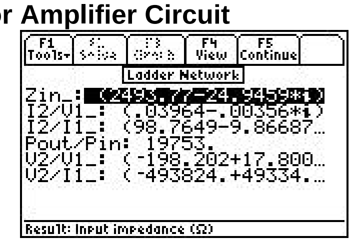


Fig 5.3. Simplified Transistor Amplifier Circuit



Input Screen



Output Screen

1. Enter the frequency and load values:
   Frequency: 10,000 Hz.
   Load: 5000 ohms.
2. Enter the ladder elements in the following order:
   Capacitor: Parallel, 318E-12.
   Current-Controlled I: Enter 2500 ohms for **RB** and 100 for β.
   Resistor: Parallel, 1E6 ohms.
   Capacitor: Series, 0.638E-6 farads.
3. Press [F2] to compute the results, which are displayed in the output screen above**.**

Chapter 6 Filter Design

This chapter covers a description of the software under the heading **Filter Design**. Three filter designs are included in this section. Design computations result in the value of component elements comprising the filter.

- Chebyshev Filter
- Butterworth Filter
- Active Filter

6.1 Chebyshev Filters

This section of the software computes component values for Chebyshev filters between equal terminations. Inputs are termination resistance, pass band characteristics, attenuation at some out-of-band frequency, and allowable passband ripple as shown in Fig. 6.1. The Chebyshev circuit elements are assumed to be ideal, and are illustrated below.

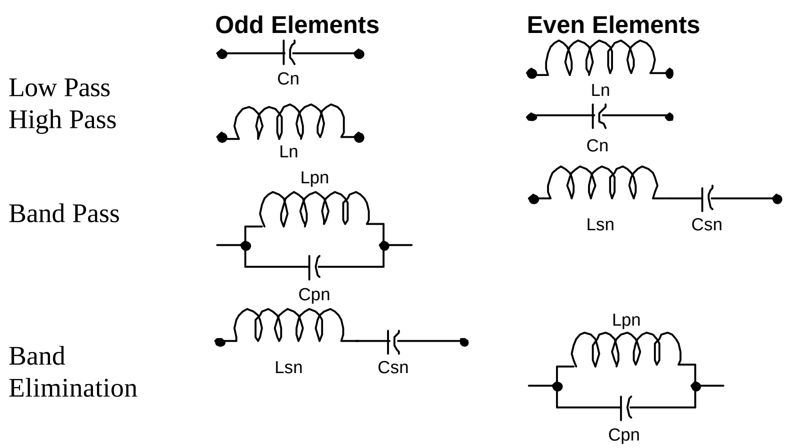


Fig. 6.1 Chebyshev Filter Elements

Field Descriptions - Input Screen

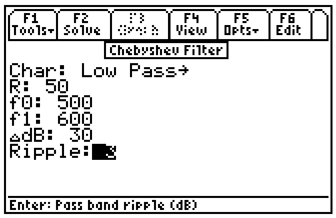
Char:	(*Bandpass Characteristic*)	Press [ENTER] to select Low Pass, High Pass, Band Pass, or Band Elimination.
R:	(*Termination Resistance in ohms*)	Enter a real number, or algebraic expression of defined terms.
f0:	(*Cutoff Frequency in Hz - for Low Pass and High Pass*)	Enter a real number.
	(*Center Frequency in Hz - for Band Pass and Band Elimination*)	Enter a real number.
f1:	(*Attenuation Frequency in Hz*)	Enter a real number.
∆dB:	(*Attenuation in dB*)	Enter a real number.
Bandwidth:	(*Bandwidth in Hz - only appears for Band Pass or Band Elimination*)	Enter a real number.
Ripple:	(*Pass Band Ripple in dB*)	Enter a real number.

Field Descriptions - Output Screen

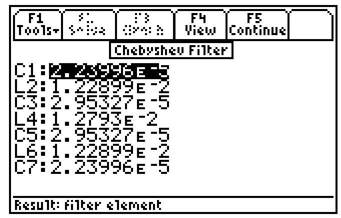
Element1: (*First element in parallel*) Returns a real number.
Element2: (*Second element in series*) Returns a real number.
….
ElementN: (*nth element in series because N is always odd*) Returns a real number.

Example 6.1

Design a low-pass Chebyshev filter with a cutoff at 500 Hz, a termination resistance of 50 ohm, 3 dB pass band ripple, and a 30 dB attenuation at 600 Hz.



Input Screen



Output Screen

1. Enter 50 for **R**, 500 for **f0**, and 600 for **f1**.
2. Enter 30 for **∆dB** and 3 for **Ripple**.
3. Press [F2] to calculate the results displayed in the output screen above.

6.2 Butterworth Filter

This section computes the component values for Butterworth filters between equal terminations. Inputs are termination resistance, pass band characteristics, and attenuation at some out-of-band frequency. The basic form of the filter uses elements shown In Fig. 6.2 below:

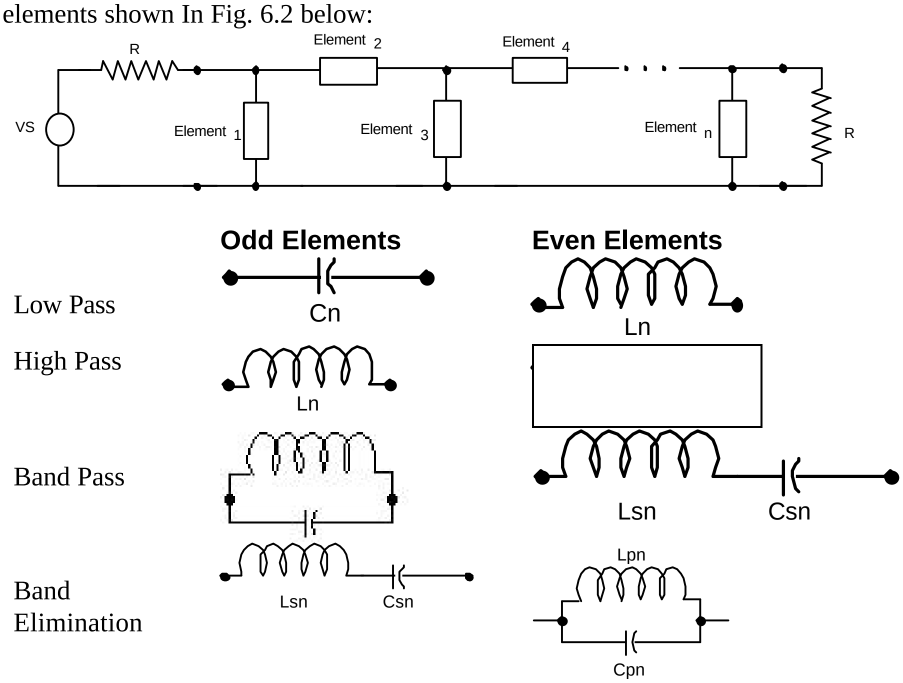


Fig. 6.2 Elements for Butterworth Filter, basic design

Field Descriptions - Input Screen

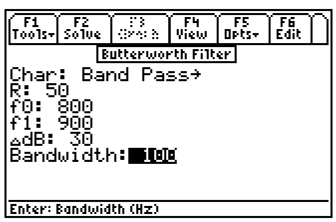
Char:	(*Bandpass Characteristic*)	Press [ENTER] to select Low Pass, High Pass, Band Pass, or Band Elimination.
R:	(*Termination Resistance in Ohms*)	Enter a real number.
f0:	(*Cutoff Frequency in Hz - for Low Pass and High Pass*)	Enter a real number.
	(*Center Frequency in Hz - for Band Pass and Band Elimination*)	Enter a real number.
	(*Center Frequency in Hz - for Band Pass and Band Elimination*)	Enter a real number.
f1:	(*Attenuation Frequency in Hz*)	Enter a real number.
ΔdB:	(*Attenuation in dB*)	Enter a real number.
Bandwidth:	(*Band width in Hz - for Band Pass or Band Elimination*)	Enter a real number.

Field Descriptions - Output Screen

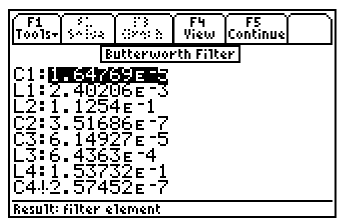
Element1:	(*First element in parallel*)	Returns a real number.
Element2:	(*Second element in series*)	Returns a real number.
Element3:	(*Third element in parallel*)	Returns a real number.
Element4:	(*Fourth element in series*)	Returns a real number.
ElementN:	***n**th element in series (if **n** is odd) or parallel (if **n** is even)*	Returns a real number.

Example 6.2

Design a 100 Hz wide Butterworth band pass filter centered at 800 Hz with a 30 dB attenuation at 900 Hz. The termination and source resistance is 50 ohms.



Input Screen



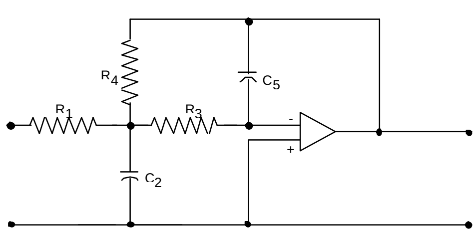
Output Screen

1. Choose Band Pass for **Char**.
2. Enter 50 for **R** and 800 for **f0**, and 900 for **f1**.
3. Enter 30 for **ΔdB** and 100 for **Bandwidth**.
4. Press [F2] to calculate the results, which are displayed in the output screen above.

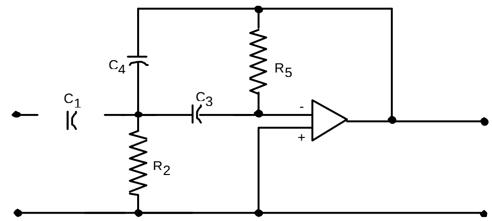
6.3 Active Filter

This topic covers computation of element values for the standard active filter circuits shown below. In each case, five different elements are calculated.

Low Pass Filter



High Pass Filter



Band Pass Filter

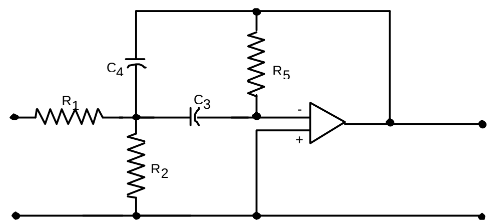


Fig. 6.3 Active Filter Configurations

Field Descriptions - Input Screen

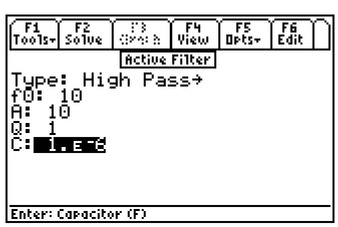
Type:	(*Filter Type*)	Press [ENTER] to select Low Pass, High Pass, or Band Pass.
f0:	(*Band Cutoff in Hz*)	Enter a real number or algebraic expression of defined terms.
A:	(*Midband Gain in dB*)	Enter a real number or algebraic expression of defined terms.
Q:	(*Quality Factor:* $Q = \frac{1}{\alpha} = \frac{1}{2 \cdot \zeta}$ *where* α *is the peaking factor and* ζ *is the damping factor*)	Enter a real number or algebraic expression of defined terms.
C:	(*Capacitor in F*)	Enter a real number or algebraic expression of defined terms.

Field Descriptions - Output Screen

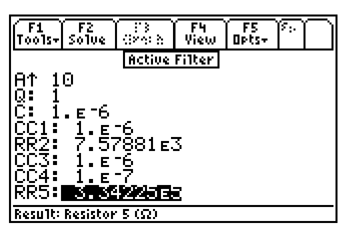
Element1:	(*First element*)	Returns a real number.
Element2:	(*Second element*)	Returns a real number.
Element3:	(*Third element*)	Returns a real number.
Element4:	(*Fourth element*)	Returns a real number.
Element5:	(*Fifth element*)	Returns a real number.

Example 6.3

Design a High Pass active filter with a cutoff at 10 Hz, a midband gain of 10 dB, a quality factor of 1 and a capacitor of 1 μF.



Input Screen



Output Screen

1. Choose High Pass for **Type**.
2. Enter 10 for **f0** and 10 for **A**.
3. Enter 1 for **Q** and 1E-6 for **C**.
4. Press [F2] to calculate the results are displayed on the screen above.

Chapter 7 Gain and Frequency

This chapter covers the basic principles of circuit analysis using a transfer function model and plots the resulting equations using the classical graphical representation often referred to as a Bode diagram for gain or phase:

- Transfer Function
- Bode Diagrams

7.1 Transfer Function

A transfer function is defined as the ratio of an output to its input signal and is generally modified by a network between the two. In the classic sense, the transfer function is dependent upon the output and input definitions and is represented by a ratio of two polynomials of the complex frequency, **s_**. The roots of the numerator and denominator polynomials are referred to as *zeros* and *poles,* respectively. Transfer functions can be defined by the poles and zeros or by the coefficients of the numerator and denominator polynomials. The results computed include symbolic expressions for the transfer function and its partial fraction expansion.

Field Descriptions

Inputs:	(*Type of Input*)	Press [ENTER] to select **Roots** or **Coefficients**. Determines whether the third and fourth fields are **Zeros** and **Poles** or **Numer** and **Denom**.
Constant:	(*Constant Multiplier*)	Enter a real number. Default is 1.
Zeros:	(*Numerator Roots* - *if Roots is chosen for input type*)	Enter an array or list of real numbers. The number of zeros must be less than the number of poles.
Poles:	(*Denominator Roots* - *if Roots is chosen for input type*)	Enter an array or list of real numbers. The number of poles must be greater than the number of zeros.
Numer list:	(*Numerator Coefficients* - *if Coefficients is chosen for input type*)	Enter an array or list of real numbers. The number of numerator coefficients must be less than the number of denominator coefficients.
Denom list:	(*Denominator Coefficients* - *if Coefficients is chosen for input type*)	Enter an array or list of real numbers. The number of denominator coefficients must be greater than the number of numerator coefficients.
H(s)_:	(*Transfer Function*)	Returns a symbolic expression in the following form:

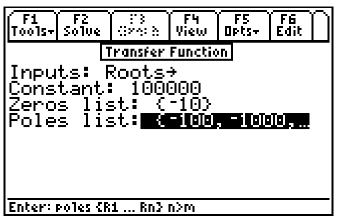
$$K\cdot\frac{\left(1-\frac{s\_}{z1}\right)\left(1-\frac{s\_}{z2}\right)\ldots}{\left(1-\frac{s\_}{p1}\right)\left(1-\frac{s\_}{p2}\right)\ldots} \qquad \textbf{Eq. 7.1.1}$$

PFE_: (*Partial Fraction Expansion*) Returns a symbolic expression of the form:

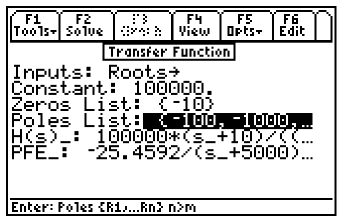
$$\frac{K1}{\left(1-\frac{s\_}{p1}\right)}+\frac{K2}{\left(1-\frac{s\_}{p2}\right)}+\frac{K3}{\left(1-\frac{s\_}{p3}\right)}+\ldots \qquad \textbf{Eq. 7.1.2}$$

Example 7.1

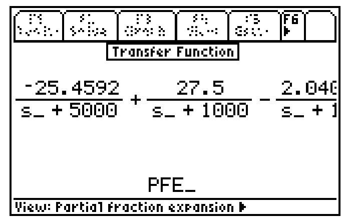
Find the transfer function and its partial fraction expansion for a circuit with a zero located at -10 r/s and three poles located at -100 r/s, -1000 r/s and -5000 r/s. Assume that the multiplier constant is 100000.



Input Screen



Output screen



Partial view of Partial Fraction Expansion form for H(s)

1. Choose Roots for **Inputs**.
2. Enter 100000 for **Constant**, {-10} for **Zeros**, and {-100 -1000 -5000} for **Poles**.
3. Press F2 to calculate **H(s)_** and **PFE_**.
4. To view **H(s)_** in Pretty Print format, press F5 and ENTER. Alternatively, the ▶ key can be pressed to achieve the same result.

Now you are ready to go on to the next example. Press ESC to return to the **Gain and Frequency** screen and select **Bode Diagrams**.

7.2 Bode Diagrams

The behavior of the transfer function, as the frequency of a sinusoidal source varies, is of great interest to engineers. A very effective way to grasp the relationship between transfer function and frequency is to plot the magnitude and the argument of the transfer function on two separate graphs. These plots are often called Bode gain and phase plots. A gain plot shows the magnitude of the transfer function expressed in decibels (dB) as 20*LOG(Magnitude of Transfer Function) as a function of the logarithm of the radian frequency ω on the horizontal scale. The phase plot shows the argument of the transfer function expressed as the phase angle (i.e., ARG (Transfer Function)) plotted as a function of the logarithm of the radian frequency on the horizontal scale.

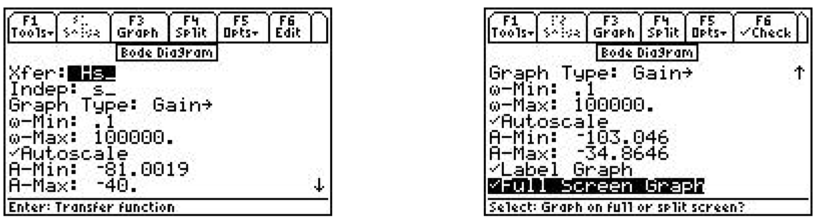
Field Descriptions

Xfer:	(*Transfer Function*)	Enter a symbolic expression.
Indep:	(*Independent Variable*	Enter a global name. Default is '**s_**'.
Graph Type:	(*Bode Gain or Bode Phase*)	Press ENTER and select Gain or Phase. Determines whether the y axis range fields appear as **A-Min** and **A-Max** (for Gain) or **θ-Min** and **θ-Max** (for Phase).

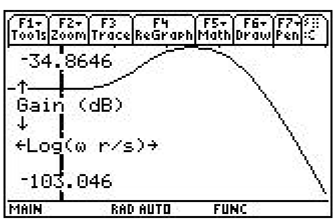
ω-Max: (*Maximum Frequency in r/s - X axis*) Enter a real number.
Autoscale: (*Scales the plot: hides A-min and A-max fields*)
Press [F6] to select.
Label Graph Attaches labels to the graph.
Full Screen Select to graph the results in a full screen display.
A-Min: (*Minimum amplitude in dB (Y axis) - if Gain is chosen for* **Plot Type**)
Enter a real number.
A-Max: (*Maximum amplitude in dB (Y axis) - if Gain is chosen for* **Plot Type**)
Enter a real number.
θ-Min: (*Minimum amplitude in dB (Y axis) - if Phase is chosen for* **Plot Type**)
Enter a real number, which will be interpreted as degrees or radians, depending on the current setting in the Custom Settings screen.

Example 7.2

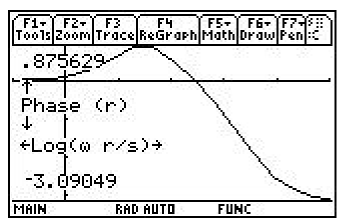
Graph the gain and phase plots for the transfer function just computed in the previous example.



Graph Dialogue (Upper and Lower displays)



Bode Gain Diagram



Bode Phase Diagram

Graph the Bode Gain vs. Radian frequency

1. Complete the entire example for the **Transfer Function** section.
2. In the **Bode Diagram** screen, the **Xfer** field contains the **Transfer Function H(s**)**_** calculated in the previous example. A choice is available to the user for **Graph Type** (Gain or Phase).
3. Choose **s_** for **Indep**. (The default is **s_** and should rarely be changed, because the **Transfer Functions** screen always generates transfer functions as functions of lowercase **s**_).
4. Enter 0.1 for ω**-Min** as the start of the radian frequency plot.
5. Enter 50000 for ω**-Max** as the endpoint of the radian frequency plot.
6. Put a check mark in the **Autoscale** field. Press [F6] if necessary
7. Put a check mark in the **Label Plot** field. Press [F6] if necessary.
8. Put a check mark on **Full Screen** graphing mode. If this field is not checked, the graph will default to the right half of the screen.
9. Press [F3] to graph the transfer function.
10. Press [2nd] followed by [APPS]to toggle between the input screen and the graph window when split-mode is active.

Graph the Bode Phase vs. Radian frequency

1. In order to graph the phase of the transfer function, select Phase for **Graph Type**.

Follow graphing sequence as defined in the section above.

Chapter 8 Fourier Transforms

This section contains software computing discrete "Fast" Fourier transforms and its inverse.

- FFT
- Inverse FFT

8.1 FFT

A physical process can be monitored in two significantly different ways. First, the process can be monitored in time domain in analog or digital form. Second, the data can be collected in the frequency domain in analog or digital form. In a variety of measurement and digital storage devices, data is gathered at regular, discrete time intervals. This data can be converted to its equivalent set in the frequency domain by the use of the so-called FFT algorithm. This algorithm maps a data array of N items to the corresponding array in the frequency domain using the following equation.

$$H_k = \sum_{n=0}^{N-1} h_n \cdot e^{-2\pi\, j \cdot k \cdot n / N} \qquad \textbf{Eq. 8.1.1}$$

The variable $\mathbf{h_n}$ is the nth element in the time domain and $\mathbf{H_k}$ is the kth element in the frequency domain. The FFT algorithm treats the data block provided as though it is one of a periodic sequence. If the underlying data is not periodic, the resulting FFT-created wave is subject to substantial harmonic distortion. This section does not pad the input array with 0's when the number of data points is not a power of 2.

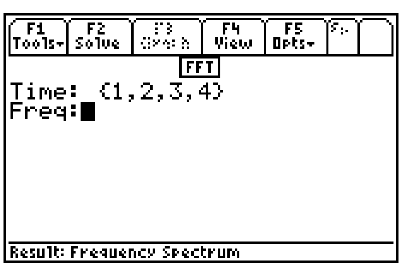
Field Descriptions

Time: (*Time Signal*)	Enter an array or list of real or complex numbers.
Freq: (*Frequency Spectrum*)	Returns spectral coefficients.

Example 8.1

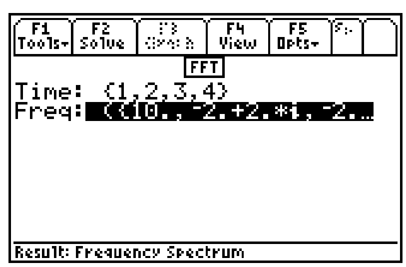
Find spectral coefficients for the periodic time signal [1 2 3 4].

1. Enter [1 2 3 4] for **Time.**
2. Press [F2] to calculate and display results in the frequency domain **Freq.**
3. The screen display of the output and the input are shown below.



←Input Screen

Output of Computation→



8.2 Inverse FFT

This section focuses on transforming data from the frequency domain to the time domain. The inverse transform

$$h_n = \frac{1}{N}\sum_{k=0}^{N-1} H_k \cdot e^{2\pi j \cdot k \cdot n/N} \qquad \textbf{Eq. 8.2.1}$$

algorithm uses the relationship displayed in the above equation, where $\mathbf{H_k}$ is the kth element in the frequency domain and $\mathbf{h_n}$ is the nth element in the time domain.

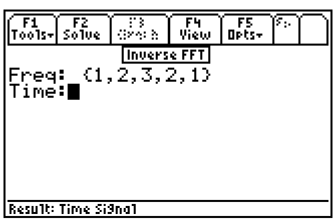
Field Descriptions

Freq: (*Frequency Spectrum*)	Enter an array or list of real or complex numbers.
Time: (*Time Signal*)	Returns time signal.

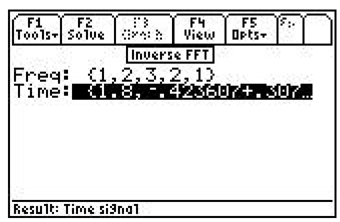
Example 8.2

Find spectral coefficients for the periodic time signal [1 2 3 2 1].

1. Enter [1 2 3 2 1] for **Freq.**
2. Press F2 to calculate and display results in the time domain **Time.**
3. The screen display shows the computed results.



Input Screen



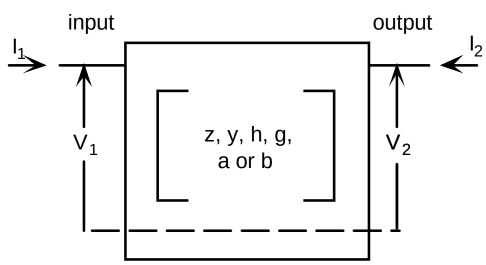
Output Screen

Chapter 9 Two-Port Networks

This chapter covers the basic properties of two-port network analysis under three topical headings.

- ❖ Parameter Conversion
- ❖ Circuit Performance
- ❖ Interconnected Two-Ports

9.1 Parameter Conversion



Many electrical or electronic systems are often modeled as two-port networks with four variables, namely input voltage $\mathbf{V_1}$, input current $\mathbf{I_1}$, output voltage $\mathbf{V_2}$, and output current $\mathbf{I_2}$. The two-port network is a black-box approach to solving simple to sophisticated problems of electrical and electronic circuits. The schematic representation (Fig. 9.1) shows a two-port network where all four variables are identified. For instance, a two-port network characterized by **z** parameters is defined by the following pair of equations:

Fig. 9.1 Two- Port Network Model

$$V1 = I1 \cdot Z11 + I2 \cdot Z12 \qquad \textbf{Eq. 9.1.1}$$
$$V2 = I1 \cdot Z21 + I2 \cdot Z22 \qquad \textbf{Eq. 9.1.2}$$

The four components of **z** parameters are defined as follows:

$Z_{11} = V_1/I_1$ with $I_2 = 0$ $\qquad$ $Z_{21} = V_2/I_1$ with $I_2 = 0$
$Z_{12} = V_1/I_2$ with $I_1 = 0$ $\qquad$ $Z_{22} = V_2/I_2$ with $I_1 = 0$

The table below lists the independent variables for two-port circuits, followed by the dependent variables and two-port parameters associated with each set of independent variables. Conversion of parameters from one type to another is covered in this section.

Independent Variables	Dependent Variables	Two-Port Parameter Type
$\mathbf{I_1, I_2}$	$\mathbf{V_1, V_2}$	**z**
$\mathbf{V_1, V_2}$	$\mathbf{I_1, I_2}$	**y**
$\mathbf{I_1, V_2}$	$\mathbf{V_1, I_2}$	**h**
$\mathbf{I_2, V_1}$	$\mathbf{I_1, V_2}$	**g**
$\mathbf{V_2, I_2}$	$\mathbf{V_1, {}^{-}I_1}$	**b**
$\mathbf{V_1, I_1}$	$\mathbf{V_2, {}^{-}I_2}$	**a**

Field Descriptions - Input Screen

The software is configured for the entry of two-port parameters; an input of one type and an output of another type.

Input Type: Selecting this item (highlighting and pressing [ENTER]) displays a menu of input types available to the user. Selecting **z**, **y**, **h**, **g**, **a**, or **b** automatically updates the names of the remaining parameter to reflect the choice of input type. Thus if **z** were selected, the inputs would have the labels listed below:

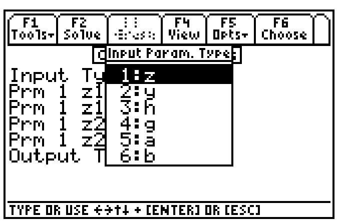
Z11_: Enter a real or complex number, variable name, or algebraic expression of defined terms.
Z12_: Enter a real or complex number, variable name, or algebraic expression of defined terms.
Z21_: Enter a real or complex number, variable name, or algebraic expression of defined terms.
Z22_: Enter a real or complex number, variable name, or algebraic expression of defined terms.

Output Type: Press [ENTER] to display **z**, **y**, **h**, **g**, **a**, or **b,** use ⊝ to move the highlight bar to select the choice and press [ENTER].

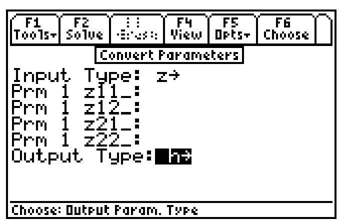
> **Note:** The help text (e.g., "Enter P1 Impedance V1/I1 (I2=0)") shows whether the ratio is an impedance, admittance or dimensionless ratio, which port is being described, and whether it is the current or the voltage that is open.

Field Descriptions - Output Screen

..11_: Returns a real or complex number, variable name, or algebraic expression.
..12_: Returns a real or complex number, variable name, or algebraic expression.
..21_: Returns a real or complex number, variable name, or algebraic expression.
..22_: Returns a real or complex number, variable name, or algebraic expression.



Menu of available Input types

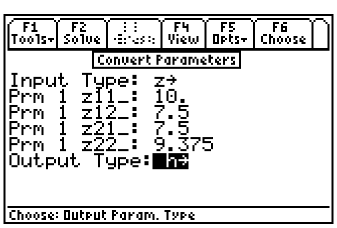


Input screen updates for choice of input type

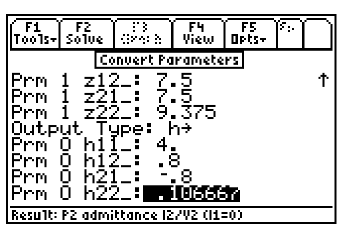
Example 9.1

Convert a resistive two-port network with $z_{11\_}$ = 10, $z_{12\_}$ = 7.5, $z_{21\_}$ = 7.5, $z_{22\_}$ = 9.375 into its equivalent **y** values.

1. Choose **z** for **Input Type**.
2. Enter 10 for **z11_**, 7.5 for **z12_**, 7.5 for **z21_**, and 9.375 for **z22_**.
3. Choose **h** for **Output Type**.
4. Press [F2] to calculate the results which are displayed in the output screen shown below.



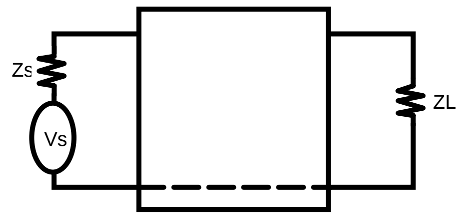
Input Screen



Output Screen

9.2 Circuit Performance

This section computes the circuit performance of a two-port network. Given a voltage source with a finite impedance and a finite load, the software will compute the input and output impedances, the current and voltage gains, the voltage gain with reference to source, the current gain to the source, the power gain, the power available to the load, the maximum power available to the load, and the load impedance for maximum power deliverable to the load.



Field Descriptions - Input Screen

Parameter Type: Press [ENTER] to select **z**, **y**, **h**, **g**, **a**, or **b**.

..11_:	Enter a real or complex number, variable name, or algebraic expression of defined terms.
..12_:	Enter a real or complex number, variable name, or algebraic expression of defined terms.
..21_:	Enter a real or complex number, variable name, or algebraic expression of defined terms.
..22_:	Enter a real or complex number, variable name, or algebraic expression of defined terms.
Vs_: (*Source Voltage in V*)	Enter a real or complex number, variable name, or algebraic expression of defined terms.
Zs_: (*Source Impedance in Ω*)	Enter a real or complex number, variable name, or algebraic expression of defined terms.
ZL_: (*Load Impedance in Ω*)	Enter a real or complex number, variable name, or algebraic expression of defined terms.

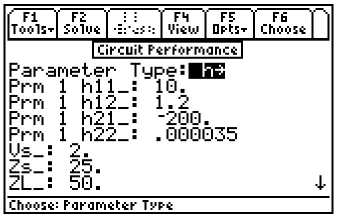
Field Descriptions - Output Screen

Zin_: (*Input Impedance in Ω*)	Returns a real or complex number or algebraic expression.
Iout_: (*Output Current in A*)	Returns a real or complex number or algebraic expression.
Vout_: (*Thevenin Voltage in V*)	Returns a real or complex number or algebraic expression.
Zout_: (*Thevenin Impedance in Ω*)	Returns a real or complex number or algebraic expression.
Igain_: (*Current Gain*)	Returns a real or complex number or algebraic expression.
Vgain_: (*Voltage Gain*)	Returns a real or complex number or algebraic expression.
VgainAbs_: (*Absolute Voltage Gain*)	Returns a real or complex number or algebraic expression.
GP: (*Power Gain*)	Returns a real or complex number or algebraic expression.
Pmax: (*Maximum Power at ZLopt in W*)	Returns a real number or algebraic expression.
ZLopt_: (*Optimum Load Impedance in Ω*)	Returns a real or complex number or algebraic expression.

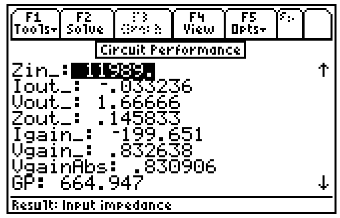
Example 9.2

A transistor has the following **h**-parameters **h11_** = 10 ohms, **h12_** = 1.2, **h21_**= -200, **h22_**= .000035_siemens. The source driving this transistor is a 2 volt source with a source impedance of 25 ohms. The output port is connected to a 50 ohm load. Find the performance characteristics of the circuit.

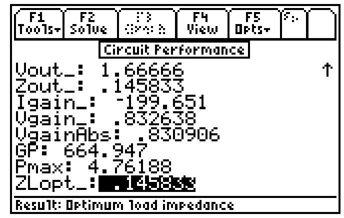
1. Select **h** parameters to prepare the input screen to receive input.
2. Enter **h11_**= 10, **h12_**= 1.2, **h21_**= -200, **h22_**= .000035
3. Enter **Vs_** =2 volts, **Zs_** = 25 ohms, and **ZL_**= 50 ohms.
4. Press [F2] to solve for the characteristics.
5. The result of the calculations is presented below:



Input Screen



Results: Upper Half



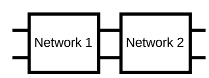
Results: Lower Half

Zin_ (*Input Impedance*)	11989.03667 ohms
Iout_ (*Output Current*)	-.033236 amps
Vout_ (*Thevenin Voltage*)	1.66666 volts
Zout_ (*Thevenin Impedance*)	.145833 ohms
Igain_ (*Current Gain*)	-199.651
Vgain_ (*Voltage Gain*)	.832638
VgainAbs (*Absolute Voltage Gain*)	.830906
GP_ (*Power Gain*)	664.947
Pmax: (*Maximum Power at ZLopt*)	4.76188 watts
ZLopt_ (*Optimum Load Impedance*)	.145833 ohms

9.3 Connected Two-Ports

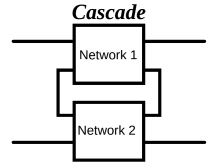
Two-port networks constitute basic building blocks of linear electrical or electronic systems. In the design of large, complex systems, it is easier to synthesize the system by first designing subsections. Large and complex systems can be built using simpler two-port building blocks. Assuming that Brune's criteria is valid for these networks, the two-port subsections can be interconnected in five ways:

1. Cascade: The output of network 1 is connected directly to the input of network 2.



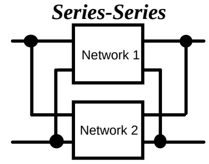
Cascade

2. Series-Series: The inputs and outputs of the two networks are both connected in series.



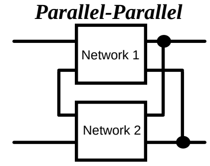
Series-Series

3. Parallel-Parallel: The inputs and outputs of the two networks are both connected in parallel.



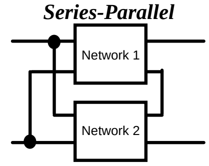
Parallel-Parallel

4. Series-Parallel: The inputs of the two networks are connected in series, while the outputs are connected in parallel.



Series-Parallel

5. Parallel-Series: The inputs of the two networks are connected in parallel, while the outputs are connected in series.



Parallel-Series

This section accepts parameters for either network as **z**, **y**, **h**, **g**, **a**, or **b** and yields the output in any form based on the choice made.

Field Descriptions - Input Screen

Connection: (*Type of Connection*) Press [ENTER] to select Cascade, Series Series, Parallel Parallel, Series Parallel, or Parallel Series.

First Input Type: Press [ENTER] to select parameter type **z**, **y**, **h**, **g**, **a**, or **b** for entry.

- **..111_:** Enter a real or complex number, variable name, or algebraic expression of defined terms.
- **..112_:** Enter a real or complex number, variable name, or algebraic expression of defined terms.
- **..121_:** Enter a real or complex number, variable name, or algebraic expression of defined terms.
- **..122_:** Enter a real or complex number, variable name, or algebraic expression of defined terms.

Second Input Type: Press [ENTER] to select parameter type **z**, **y**, **h**, **g**, **a**, or **b** for entry.

- **..211_:** Enter a real or complex number, variable name, or algebraic expression of defined terms.
- **..212_:** Enter a real or complex number, variable name, or algebraic expression of defined terms.
- **..221_:** Enter a real or complex number, variable name, or algebraic expression of defined terms.
- **..222_:** Enter a real or complex number, variable name, or algebraic expression of defined terms.

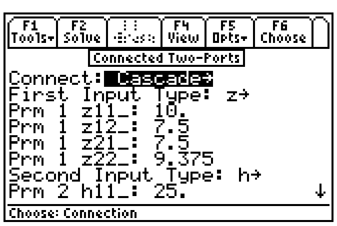
Output Type: Press [ENTER] to select **z**, **y**, **h**, **g**, **a**, or **b.**

- **..11_:** Returns a real or complex number, variable name, or algebraic expression of defined terms.
- **..12_:** Returns a real or complex number, variable name, or algebraic expression of defined terms.
- **..21_:** Returns a real or complex number, variable name, or algebraic expression of defined terms.
- **..22_:** Returns a real or complex number, variable name, or algebraic expression of defined terms.

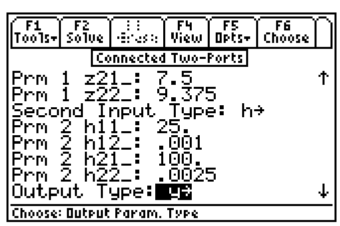
Example 9.3

The 2 two-port networks are defined in terms of their **z** and **h** parameters. The **z** parameters are 10, 7.5, 7.5, 9.375 respectively while the **h** parameters are 25, .001, 100, .0025. If the two-ports are connected in a cascade configuration, compute the **y** parameters for the resulting equivalent two-port. To solve this problem:

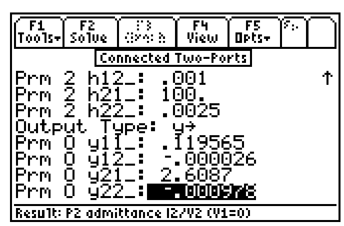
1. Choose Cascade for **Connection**.
2. Choose **z** for **First Input Type**.
3. Enter 10 for **z11_**, 7.5 for **z12_**, 7.5 for **z21_**, and 9.375 for **z22_**.
4. Choose **h** for **Second Input Type**.
5. Enter 25 for **h11_**, .001 for **h12_**, 100 for **h21_**, and .0025 for **h22_**.
6. Choose **y** for **Output Type**.
7. Press [F2] to complete the computation. The resulting data is shown in the screen displays shown.



*Input screen showing **z** parameters for the first two-port.*



*Input screen showing **h** parameters for the Second two-port.*



*Output screen showing **y** parameters of the combined Two-port.*

Chapter 10 Transformer Calculations

This chapter covers the software features used to perform to calculations for electrical transformers. This section is organized under three categories:

- Open Circuit Test
- Short Circuit Test
- Chain parameters

10.1 Open Circuit Test

An open circuit test described here is usually performed at rated conditions of the primary or secondary side of a transformer. It is common practice to apply a voltage to the primary side. The measured parameters which include primary and secondary voltages, current, and power determine the core parameters of the transformer.

Field Descriptions - Input Screen

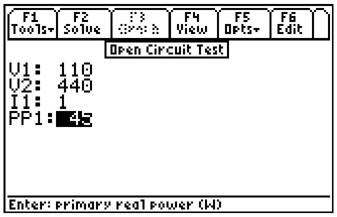
V1:	(*Primary RMS Voltage in V*)	Magnitude only. A real number, variable name, or algebraic expression of defined terms.
V2:	(*Secondary RMS Voltage in V*)	Magnitude only. A real number, variable name, or algebraic expression of defined terms.
I1:	(*Primary RMS Current in A*)	Magnitude only. A real number, variable name, or algebraic expression of defined terms.
PP1:	(*Primary Real Power in W*)	A real number, variable name, or algebraic expression of defined terms.

Field Descriptions - Output Screen

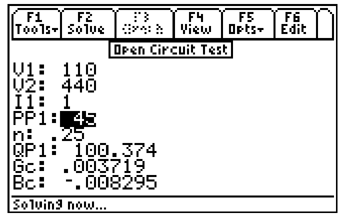
n:	(*Primary to secondary turns ratio*)	Returns a real number or algebraic expression.
Q1:	(*Reactive* power *in W*)	Returns a real number or algebraic expression.
Gc:	*(Primary core conductance in S)*	Returns a real number or algebraic expression.
Bc:	*(Primary core susceptance in S)*	Returns a real number or algebraic expression.

Example 10.1

Perform an open circuit test on the primary side of a transformer using the following data: The input to the primary coils with the secondary side open is 110 volts, and a current of 1 ampere and a power of 45 watts. The secondary open circuit voltage is 440 volts. Find the circuit parameters of the transformer.



Input Screen



Output Screen

1. Enter the values 110 for **V1** and 440 for **V2**.
2. Enter 1 for **I1** and 45 for **PP1**.
3. Press [F2] to calculate and display the results, as shown above.

10.2 Short Circuit Test

Short circuit tests are often a quick method used to determine the winding impedance of a transformer and are usually reported at rated kVA values. This test consists of placing a short circuit across the secondary windings and applying a small primary voltage to measure the secondary current, and power supplied to the transformer. The calculated circuit parameters (i.e., resistance and reactance of primary and secondary coils) are based on the assumption that the heat dissipation in the primary and secondary windings are equal.

Field Descriptions - Input Screen

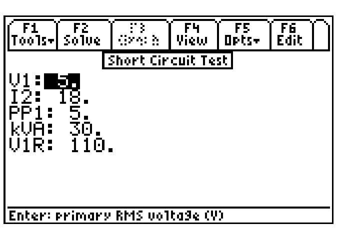
V1:	(*Primary RMS Voltage in V*)	Magnitude only. A real number, variable name, or algebraic expression of defined terms.
I2:	(*Secondary RMS Current in A*)	Magnitude only. A real number, variable name, or algebraic expression of defined terms.
PP1:	(*Primary Real Power in W*)	A real number, variable name, or algebraic expression of defined terms.
kVA:	(*kVA rating in kVA)*	A real number, variable name, or algebraic expression of defined terms.
V1R:	(*Primary Voltage Rating in V*)	A real number, variable name, or algebraic expression of defined terms.

Field Descriptions - Output Screen

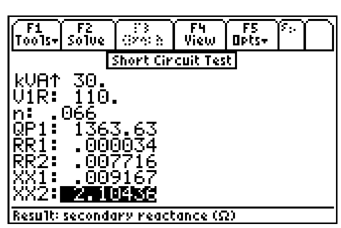
n:	(*Primary to secondary turns ratio*)	Returns a real number or algebraic expression.
QP1:	(*Primary Reactive Power in W*)	Returns a real number or algebraic expression.
RR1:	(*Primary Resistance in Ω*)	Returns a real number or algebraic expression.
RR2:	(*Secondary Resistance in Ω*)	Returns a real number or algebraic expression.
XX1:	(*Primary Reactance in Ω*)	Returns a real number or algebraic expression.
XX2:	(*Secondary Reactance in Ω*)	Returns a real number or algebraic expression.

Example 10.2

Short circuit test data is taken on a transformer. A primary input voltage of 5 volts forces 18 amperes of current into the secondary winding under short circuit conditions. The power supplied for the test is 5 watts. The transformer has a kVA rating of 30 and a primary voltage rating of 110 volts. Find the parameters of the of the transformer.



Input Screen

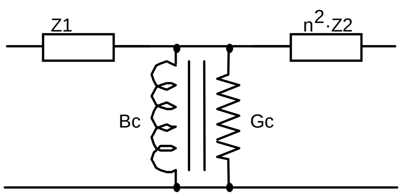


Output Screen

1. Enter the values 5 for **V1** and 18 for **I2**.
2. Enter 5 for **PP1,** 30 **kVA** rating and 110 for **V1R**.
3. Press [F2] to calculate the results, which are displayed in the output screen.

10.3 Chain Parameters

Chain parameters (or the so-called ABCD parameters) are convenient problem-solving tools used in solving transmission and distribution problems. The parameters are expressed essentially as two-port type parameters by the use of the following pair of linear equations:



$$Vin = A \cdot Vout - B \cdot Iout \qquad \textbf{Eq. 10.3.1}$$

$$Iin = C \cdot Vout - D \cdot Iout \qquad \textbf{Eq. 10.3.2}$$

where **Vin** and **Iin** are input voltage and current, and **Vout** and **Iout** are output voltage and current. (All quantities in the diagram refer to the primary winding.) This approach is useful as cascaded transformers follow two-port network rules.

Field Descriptions - Input Screen

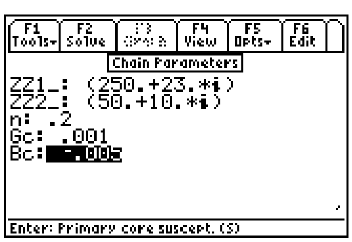
ZZ1_:	(*Primary impedance in Ω*)	A real or complex number, variable name or algebraic expression of defined terms.
ZZ2_:	(*Secondary impedance in Ω*)	A real or complex number, variable name, or algebraic expression of defined terms.
n:	(*Primary to secondary turns ratio*)	Returns a real number, variable name, or algebraic expression.
Gc:	(*Primary core conductance in S*)	A real number, or algebraic expression of defined terms **Gc>0**.
Bc:	(*Primary core susceptance in S*)	A real number, or algebraic expression of defined terms **Bc<0**.

Field Descriptions - Output Screen

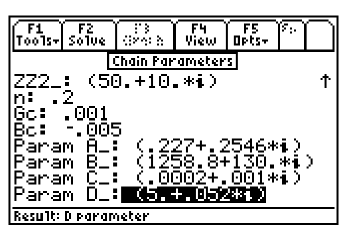
Param A_:	(*A Parameter*)	Returns a real or complex number, or algebraic expression.
Param B_:	(*B Parameter*)	Returns a real or complex number, or algebraic expression.
Param C_:	(*C Parameter*)	Returns a real or complex number, or algebraic expression.
Param D_:	(*D Parameter*)	Returns a real or complex number, or algebraic expression.

Example 10.3

A transformer has a primary and secondary impedance of 250 + 23**i* and 50 + 10**i* and a turns ratio of 0.2. The conductance and susceptance of the primary coil is .001 and -.005 respectively. Find the **A, B, C** and **D** parameters.



Input Screen



Output Screen

1. Enter the values of 250 + 23**i* and 50 + 10**i* for **ZZ1_** and **ZZ2_**.
2. Enter .2 for **n,** .001 and -.005 for **Gc** and **Bc** respectively.
3. Press [F2] to calculate the results, displayed in the output screen above.

Chapter 11 Transmission Lines

This chapter covers the basic principles of transmission line analysis covered under four categories of topics:

- ❖ Line Properties
- ❖ Line Parameters
- ❖ Fault Location Estimate
- ❖ Stub Impedance Matching

11.1 Line Properties

This portion of the software computes the characteristic parameters of a transmission line from fundamental properties of the wires forming the transmission line. A variable name can consist of a single undefined variable (such as 'a' or 'x') or an algebraic expression of defined terms of defined variables which can be simplified into a numerical result (such as 'x+3*y', where x=-3 and y=2). All entered values are assumed to be common SI units (F, A, kg, m, s, Ω) or units arbitrarily chosen by the user (such as such as *length* which can be in m, km, miles or µm).

Field Descriptions - Input Screen

L:	(*Series Inductance in H/unit Length*)	A real number, variable name or algebraic expression of defined terms, L≥0.
R:	(*Series Resistance in Ω/unit Length*)	A real number, variable name or algebraic expression of defined terms ,R≥0.
G:	(*Shunt Conductance in Siemens/unit Length*)	A real number, variable name or algebraic expression of defined terms, G≥0.
C:	(*Shunt Capacitance in F/unit Length*)	A real number, variable name or algebraic expression of defined terms, C≥0.
ZL_:	(*Load Impedance in Ω*)	A real or complex number, variable name or algebraic expression of defined terms, ZL_≥0.
d:	(*Distance to Load - unit length*)	A real number, variable name or algebraic expression of defined terms, d>0.
f:	(*Frequency in Hz*)	A real number, variable name or algebraic expression of defined terms, f>0.

Field Descriptions - Output Screen

ZZ0_:	(*Characteristic Impedance in Ω*)	Returns a real or complex number, variable name, or algebraic expression.
YY0_:	(*Characteristic Admittance in Siemens*)	Returns a real or complex number, variable name, or algebraic expression.
α:	(*Neper Constant in 1/unit length*)	Returns a real number, algebraic expression.

β: (*Phase Constant in degrees or radians/unit length*) Returns a real number, or algebraic expression.

λ: (*Wavelength in unit length*) Returns a real number or algebraic expression.

vp: (*Phase Velocity in unit length/s*) Returns a real number or algebraic expression.

Zoc_: (*Open Circuit Impedance in Ω*) Returns a real or complex number, or algebraic expression.

Zsc_: (*Short Circuit Impedance in Ω*) Returns a real or complex number, or algebraic expression.

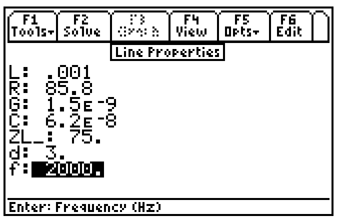
ρ_: (*Reflection Coefficient*) Returns a real or complex number, or algebraic expression.

SWR: (*Standing Wave Ratio*) Returns a real number, or algebraic expression.

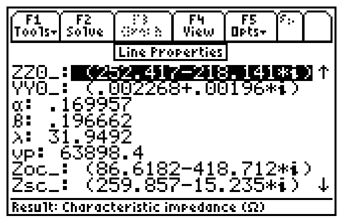
Example 11.1

A transmission line has a series inductance of 1 mH/mile, a line resistance of 85.8 ohm/mile, a conductance of .0015 x 10^{-6} Siemens/mile, and a shunt capacitance of 62 x 10^{-9} F/mile. For a load impedance of 75 ohms and a frequency of 2000 Hz, compute the line characteristics 3 miles away from the load.

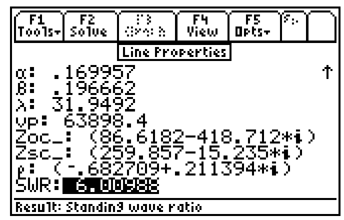
Note: Since the unit length is the mile, all entered and calculated values are with respect to miles.



Input Screen



Output Screen (upper half)



Output Screen (lower half)

1. Enter the values 0.001, 85.8, and .0015E-6 for **L**, **R**, and **G**, respectively.
2. Enter the values 62E-9, 75, and 3 for **C**, **ZL_**, and **d**, respectively.
3. Enter 2000 for **f**.
4. Press [F2] to calculate the results. The input and output screen displays are shown above.

11.2 Line Parameters

This topic computes fundamental parameters of a transmission line from measured data. The algorithm used in this section solves for **γ** in the equation **11.2.1**, where **γ = α + jβ.** In general **γ**, **Zsc_**, and **Zoc_** have complex values. In solving for **γ**, there is a principal value and a set of equivalent values because of the cyclical nature of the equation. Recognizing the fact that physical parameters such as **R**, **L**, **G**, **C**, and **vp** are all real and positive numbers, extreme caution should be exercised when entering input data. In particular, **d** should be less than one wavelength.

$$\tan(\gamma \cdot d) = \sqrt{\frac{Zsc\_}{Zoc\_}} \qquad \textbf{Eq. 11.2.1}$$

Field Descriptions - Input Screen

Zoc_: (*Open Circuit Impedance in Ω*) Enter a real or complex number, variable or algebraic expression of defined terms.

Zsc_: (*Short Circuit Impedance in Ω*) Enter a real or complex number, variable or algebraic expression of defined terms.

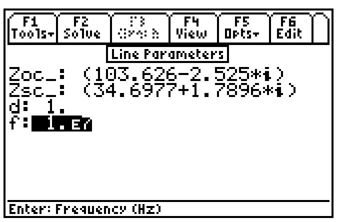
d:	(*Distance to Load Location/ unit length)*	Enter a real number or algebraic expression of defined terms or variable.
f:	(*Frequency in Hertz*)	Enter a real number or variable or algebraic expression of defined terms.

Field Descriptions - Output Screen

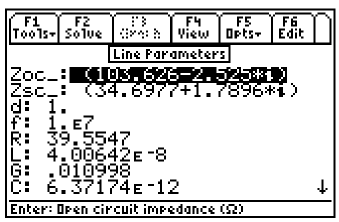
R:	(*Series Resistance in Ω/unit length*)	Returns a real number or algebraic expression.
L:	(*Series Inductance in H/unit length*)	Returns a real number or algebraic expression.
G:	(*Shunt Conductance in Siemens/unit length*)	Returns a real number or algebraic expression.
C:	(*Shunt Capacitance in F/unit length*)	Returns a real number or algebraic expression.
ZZ0:	(*Characteristic Impedance in Ω*)	Returns a real or complex number or algebraic expression.
YY0:	(*Characteristic Admittance in Ω*)	Returns a real or complex number or an algebraic expression. .
α:	(*Neper Constant in 1/unit length*)	Returns a real number or algebraic expression.
β:	(*Phase Constant in degrees or radians/unit length*)	Returns a real number or algebraic expression.
vp:	(*Phase Velocity in unit length/s*)	Returns a real number or algebraic expression.

Example 11.2

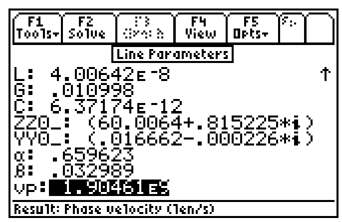
A transmission line is measured to have an open circuit impedance of 103.6255 - 2.525**i*, and an impedance under short circuit conditions of 34.6977 + 1.7896**i*, at a distance 1 unit length from the load location. All measurements are conducted at 10 MHz. Compute all the line parameters.



Input Screen



Output Screen (upper half)



Output Screen (lower half)

1. Enter 103.6255 - 2.525**i* for **Zoc_**.
2. Enter 34.6977 + 1.7896**i* for **Zsc_**.
3. Enter 1 and 10E6 for **d** and **f**, respectively.
4. Press [F2] to calculate the results and display them as shown above.

11.3 Fault Location Estimate

In this section, the equation set estimates the distance to the location of a fault condition in a transmission line. The calculation is made from a few measurements and is based on the underlying assumption that the transmission line is ideal.

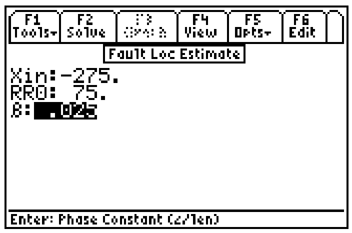
Field Descriptions

Xin:	(*Input Reactance in Ω*)	A real number, variable name, or algebraic expression of defined terms.
RR0:	(*Characteristic Resistance in Ω*)	A real number, variable name, or algebraic expression of defined terms.
β:	(*Phase Constant - degrees or radians /unit length*)	

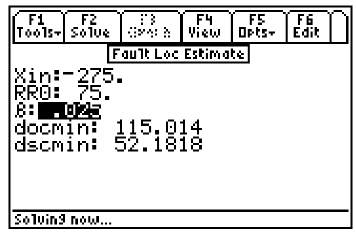
		A real number, variable name, or algebraic expression of defined terms.
docmin:	(*Minimum distance to an open circuit fault in unit lengths*)	Returns a real number, variable name, or algebraic expression.
dscmin:	(*Minimum distance to short circuit fault in unit lengths*)	Returns a real number, variable name, or algebraic expression.

Example 11.3

A transmission line measures a capacitive reactance of -275 ohms. The characteristic line impedance is 75 ohms, and has a phase constant of 0.025 r/length. Estimate the location of the fault.



Input Screen



Output Screen

1. Enter the values -275, 75, and 0.025 for **Xin**, **RR0**, and **β**, respectively.
2. Press [F2] to calculate the results as shown in the screen display above.

11.4 Stub Impedance Matching

This topic calculates the parameters for a single-stub impedance-matching device. The location display and the electrical length of an open and short-circuit stub can be computed from the input data. Because the solution is circular in nature, there are two possible stub-locations **d1** and **d2**.

Field Descriptions - Input Screen

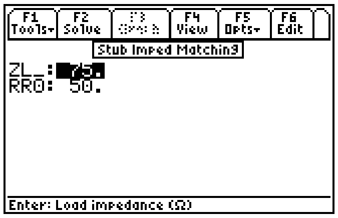
ZL_:	(*Load Impedance in Ω*)	A real or complex number, variable name, or algebraic expression of defined terms.
RR0: defined	(*Characteristic Resistance in Ω*)	A real number , variable name, or algebraic expression of terms.

Field Descriptions - Output Screen

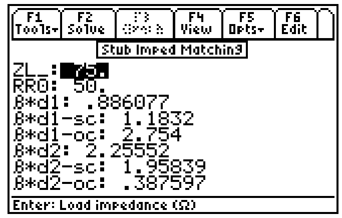
β∗d1:	(*Electrical length from a stub at location d1 to the load in degrees or radians*)	Returns a real or algebraic expression.
β∗d1-sc:	(*Electrical length of a short-circuited shunt stub at distance d1 from load in degrees or radians*)	Returns a real or algebraic expression.
β∗d1-oc:	(*Electrical length of an open-circuited shunt stub at distance d1 from load in degrees or radians*)	Returns a real or algebraic expression of defined terms.
β∗d2:	(*Electrical length from a stub at location d2 to the load in degrees or radians*)	Returns a real or algebraic expression.
β∗d2-sc:	(*Electrical length of a short-circuited shunt stub at distance d2 from load in degrees or radians*)	Returns a real or algebraic expression.
β∗d2-oc:	(*Electrical length of an open-circuited shunt stub at distance d2 from load in degrees or radians*)	Returns a real or algebraic expression.

Example 11.4

A transmission line has a characteristic impedance of 50 ohms and a load of 75 ohms. Estimate the shorting stub location for matching purposes.



Input Screen



Output Screen

1. Enter the values 50 and 75 for **RR0**, and **ZL_** respectively.
2. Press [F2] to calculate the results as shown in the screen displays above.

Chapter 12 Computer Engineering

This chapter covers functions of interest in the design of logic systems and circuits. The modules include binary arithmetic, bit operations, comparisons and a form of logic minimization using the Quine-McCluskey algorithm:

- ❖ Binary Arithmetic
- ❖ Register Operations
- ❖ Bit Operations
- ❖ Binary Conversions
- ❖ Binary Comparisons
- ❖ Karnaugh Map

Read This!

The format of integers in *the Computer Engineering* section of EE•*Pro* is (p)nnnn…, where p is the letter prefix **b**, **o**, **d**, or **h** indicating binary, octal, decimal, and hexadecimal, number systems and n represents the legal digits for the number base. If a number does not begin with a letter prefix in parenthesis, then it is assumed to be in the number base set in the [F4]/**Modes** dialog. With the exception of *Binary Conversion,* no numbers with fraction components are allowed to be entered. The TI-89 built-in binary conversion feature supports 32 bit word lengths. EE•*Pro* has extended this feature to allow the user to modify the word size between 1 and 128 bits.

12.1 Special Mode Settings, the [F4] Key

The screen allows the user to set the parameters for solving binary problems. Press the [F4] key to display a user interface dialog box prompting the user to clarify and specify the foundation for digital arithmetic. Digital arithmetic operations are allowed in binary, octal, decimal and hexadecimal number systems. As shown in the screen display below, user input is needed in the following areas:

Base:	Binary, Octal, Decimal and Hexadecimal.
Word size:	Up to 128 bits.
Sign:	Unsigned, 1’s complement and 2’s complement techniques.

The software allows three conventions for representing numbers.

1. **Unsigned mode -** In the unsigned mode, the most significant bit adds magnitude and not the sign to the number.
2. **1's Complement mode -** One's complement accommodates an equal number of positive and negative numbers, but has two representations for zero; 0 and -0.
3. **2's complement mode -** There is just one representation for zero, but there is always one more negative number than a positive number represented.

Leading 0's are used for internal representation, but are not displayed as such.
Thus a number entered as 000110011 will be displayed as 110011

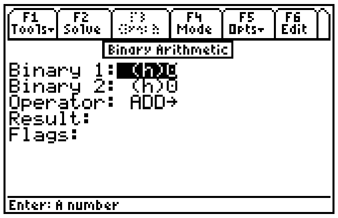
Carry and Range Conditions - The shifting, rotating, arithmetic and bit manipulation operations can result in **Carry** and **Range Flags** being modified. The specific condition for the flags to be set depend upon the operation being performed. Range flag is set if the correct result of the operation cannot be represented in the current word size and the complement mode. When the result is out of range, the lower order bits that fit the word size are displayed.

In Table 12-1 below, we have used an example for a binary word size of 5 bits to convey the conventions and its decimal interpretation.

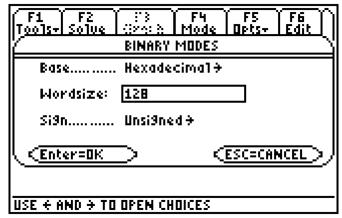
Table 12.1 Decimal Interpretation of a 5 bit Binary

Binary	1's Complement Mode	2's Complement Mode	Unsigned Mode
01111	15	15	15
01110	14	14	14
01101	13	13	13
01100	12	12	12
01011	11	11	11
01010	10	10	10
01001	9	9	9
01000	8	8	8
00111	7	7	7
00110	6	6	6
00101	5	5	5
00100	4	4	4
00011	3	3	3
00010	2	2	2
00001	1	1	1
00000	0	0	0
11111	-0	-1	31
11110	-1	-2	30
11101	-2	-3	29
11100	-3	-4	28
11011	-4	-5	27
11010	-5	-6	26
11001	-6	-7	25
11000	-7	-8	24
10111	-8	-9	23
10110	-9	-10	22
10101	-10	-11	21
10100	-11	-12	20
10011	-12	-13	19
10010	-13	-14	18
10001	-14	-15	17
10000	-15	-16	16

Note: The EE•*Pro* introduces a new convention for entering the binary integers. Binary integers start with **(b),** octal numbers start with **(o),** decimal numbers with **(d)** and hexadecimal numbers by **(h).** This convention is introduced to ensure that the machine convention of using **0d** would be interpreted properly when in hexadecimal mode.



Binary Arithmetic Screen Display



[F4] *activates mode dialog box.*

Once the parameters have been set in the binary mode screen, pressing [ENTER] accepts the entries, while pressing [ESC] cancels the entries made. If an incorrect choice is made in the data entry, a dialog box pops up to alert the user that an error has been detected in the data entered.

12.2 Binary Arithmetic

This section demonstrates how to add, subtract, multiply, and divide binary numbers, as well as negate or find the absolute value of a binary integer.

Field Descriptions

Binary 1: (*Input Field*) Enter an integer in the number base designated in [F4]**/Binary Mode** or an integer preceded by the number base in parenthesis (b, d, o, or h).

Binary 2: (*Input Field*) Enter an integer in the number base designated in [F4]**/Binary Mode** or an integer preceded by the number base in parenthesis (b, d, o, or h).

Operator: (*Binary Operation*) Press [ENTER] to select.

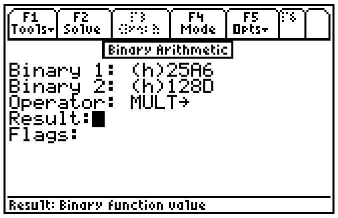
ADD	Adds binary or real integer. Affects the range and carry flags.
SUB	Subtracts the second binary or real integer from the first. Affects both the range And carry flags.
MULT	Multiply the two binary or real numbers. Affects both the range and the carry flags.
DIV	Divide the first binary integer by the second and returns the quotient. Affects carry flag only.
RMD	Divides the first binary integer by the second binary integer and returns the remainder. Does not affect the range or the carry flags.
NEG	Negate a binary integer. Affects the range flag only.
ABS	Find the absolute value of a binary integer. Affects the range flag only.

Result: (*Binary Function Value*) Returns an integer result using the number base set in [F4]**/Binary Mode**.

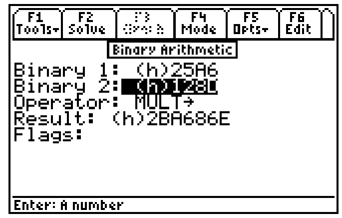
Flags: (*State of Carry and Range Flags*) Returns Carry if the carry flag is set.
Returns Range if the range flag is set.

Example 12.2

Multiply two real hexadecimal numbers 25a6 and 128d.



Input Screen



Output Screen

1. Press [F4] to select hexadecimal for **Base:** for data, 128 bits for **Wordsize**, **Unsigned** number system and press [ENTER] to accept the choice.
2. Enter 25a6 for the first **Binary 1** number.
3. Enter 128d for the second **Binary 2** number.
4. Choose **MULT** for **Operator;** press [F2] to compute the result. The screen displays above show the input screen and the resulting output.

Note: When a binary operation results in a quantity which exceeds the word size selected by the user, the range and carry flags are automatically set, and the right-most digits of the result (i.e., the least significant portion of the answer) will be displayed in the word size allocated. For example, if the word size is set to 32 bits (corresponding to an 8 digit hexadecimal number), and two hexadecimal numbers, 87654321 and FEDCBA98 are added, the result is a 9 digit hexadecimal number 18641FDB9 which exceeds the 32 bit (8 digit) word size allocated for the result.

```
  87654321
+ FEDCBA98
 18641FDB9
```

The carry flag is set and the least significant eight digits of the actual result are displayed (i.e., 8641FDB9). Retention of the least significant digits mimics the usual operation of microprocessors.

12.3 Register Operations

This section allows the user to perform operations on any bit of a binary integer. Such operations include shifting bits to the left or right, rotating bits to the left or right, and shifting or rotating bits through the carry flag.

The input screen is updated to reflect the choice of operator. For instance, if we choose **SL**, **SR**, **RR**, **RL**, **ASR** no additional input lines are displayed. On the other hand, if **SLN**, **SRN**, **RLN**, **RRN** are chosen, a new line appears at the input wanting an entry for the “no. of bits” **N**. When **Carry** is an integral part of the operation in cases such as **RLC**, **RRC**, **RLCN** and **RRCN**, then input screen updates to includes **Carry** and **N** as needed.

Field Descriptions

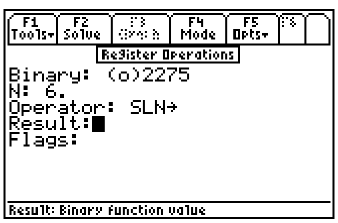
Binary:	(*Input Field*)	Enter an integer in the number base designated in [F4]**/Binary Mode** or an integer preceded by the number base in parenthesis (b, d, o, or h).
N:	(*Number of places for shifting or rotating - appears only when SRN, RLN, RLN, RRN, RLCN, or RRCN are selected*)	Enter a real number.
Operator:	(*Binary Operation*) Press [ENTER] or ► to view options. Use ▼ key to move the highlight bar to the desired operator and press [ENTER] to select.	

Note: Register operations set the carry flag if a 1 is rotated or shifted off the end; otherwise they carry flag is cleared.

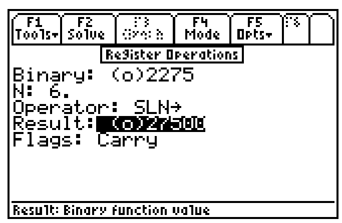
SL	Shifts the input to the left by one bit and shifts a 0 into the right-most position.
SR	Shifts the input to the right by one bit and shifts a 0 into the left-most position.
RL	Rotates the input to the left by one bit. The left-most bit wraps around to the right-most position.
RR	Rotates the input to the right by one bit. The right-most bit wraps around to the left-most position.
RLC	Rotates bits left by one bit through carry. Loads the left-most bit into the carry and moves the carry bit into the right-most position.
RRC	Rotates bits right by one bit through carry. Loads the right-most bit into the carry and moves the carry bit into the left-most position.
ASR	Arithmetic shift right: For 1’s Complement and 2's Complement, it shifts bits to the right, but keeps the left-most bit (and the sign bit) the same. For Unsigned mode, there is no sign bit, a 0 is shifted into the left-most position.
SLN	Shifts left by N bits.
SRN	Shifts right by N bits.
RLN	Rotate left by N bits.
RRN	Rotate right by N bits.
RLCN	Rotate left by N bits through the carry.
RRCN	Rotate right by N bits through the carry.

Result: (*Binary Function Value*) Returns an integer result using the number base set in F4/**Binary Mode**.

Example 12.3 For a binary word 16 bits long, shift left by 6 bits, the octal number 2275.



Input Screen



Output Screen

1. Use the F4 key to access the pop up screen for **Binary Mode** and select octal for **Base:** and 16 bits for **Word size;** press ENTER to accept the settings.
2. Enter 2275 for the **Binary** number.
3. Enter 6 for **N**, and choose **SLN** for the binary operation.
4. Press F2 to compute the result. The screen display above shows the input and the resulting output screens.

12.4 Bit Operations

This section allows you to perform bit-specific operations. You can set a bit, clear a bit, test a bit or find the total number of bits in a set.

Field Descriptions

Binary: (*Input Field*) Enter an integer in the number base designated in F4/**Binary Mode** or an integer preceded by the number base in parenthesis (b, d, o, or h).

Bit #: (*Bit Position - not active if ΣB is selected*) Enter a binary integer.

Operator: (*Binary Operation*) Press [ENTER] or ▶ to select.

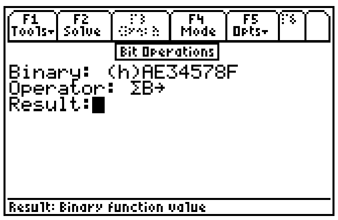
Note: All bit operations affect the carry flag only.

SB Sets the bit in the specified position.
CB Clears the bit in the specified position.
B? Tests the bit in the specified position.
ΣB Returns the number of bits set.

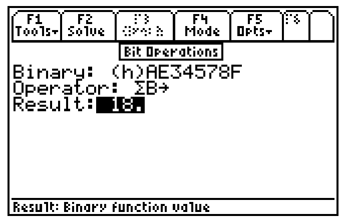
Result: (*Binary Function Value*) Returns an integer result using the number base set in [F4]/**Binary Mode**.

Example 12.4

Find the bit sum of the a hexadecimal number AE34578F which is 32 bits wide.



Input Screen



Output Screen

1. Use [F4] key to select hexadecimal for **Base:** for data type and 32 bits for **Word size**; press [ENTER] to accept the choices made.
2. Enter AE34578F for the Binary number.
3. Choose ΣB for the **Operator.** Press [F2] to compute the result. The screen displays above show the input and the resulting output.

12.5 Binary Conversions

This topic demonstrates the process of converting real numbers to binary numbers and vice versa. The software allows for the conversion of real numbers to the IEEE format. In 1985, the Institute of Electrical and Electronic Engineers (IEEE), a professional association, developed standards for Binary Floating Point Arithmetic. This Standard (referred to Standard 754), specifies two basic forms of floating-point formats: single and double precision. The single precision format has 23 bits (23-bit significands), and 32 bits overall. In EE•*Pro* the computed output is in the single floating-point format. Binary entries in IEEE format are justified to the right with the last binary entry appearing in the 0 bit.

31	30 29 28 27 26 25 24 23	22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
sign (1 bit [31])	base 2 exponent (8 bit [23-30])	mantissa (23 bit floating point [0-22])

Field Descriptions

Binary: (*Input Field for B→R16C and IEEE→*) Enter an integer in the number base designated in [F4]/**Binary Mode** or an integer preceded by the number base in parenthesis (b, d, o, or h).

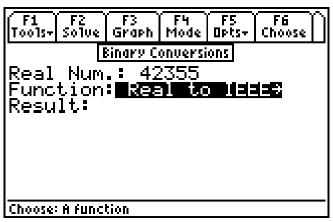
Real: (*Input Field for R→B16C and →IEEE*) Enter a real number.
Function: (*Binary Function*) Press [ENTER] to display choices available.

Real to Binary	Converts a real number to a binary number (binary, octal, decimal or hexadecimal). If a number with a fractional part is entered, the value is rounded to the nearest integer. Affects the range flag only.
Binary to Real	Converts a binary number (decimal, binary, hexadecimal or octal) to a real number.
Real to IEEE	Converts a real number to the IEEE 32 bit format. The word size is automatically set to 32 bits. Affects the range flag only.
IEEE to Real	Converts a IEEE number to a real number. The word size is automatically set to 32 bits. Affects the carry and range flags.

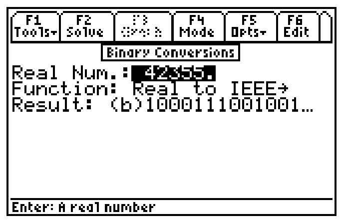
Result: (*Binary Function Value*) Returns an integer result using the number base set in [F4]**/Binary Mode**.

Example 12.5

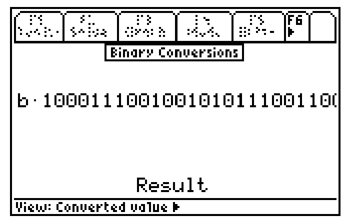
Convert a real decimal number 42355 to its IEEE standard. View the number in binary (base two) mode.



Input Screen



Output Screen



*Result in **Pretty Print** ▶.*

1. Use [F4] key to select Binary for **Base:** and 32 bits for **Wordsize**. Press [ENTER] to accept the choices made
2. Enter 42355 for the **Real Num.**
3. Choose *Real to IEEE* for the **Function:** press [F2] to compute the result. The screen display above shows the input screen and the resulting output.

12.6 Binary Comparisons

This feature conducts a comparison of two binary numbers to determine if they are the same value, unequal, greater than, less than, etc. These functions are commonly needed for software developers.

Field Descriptions

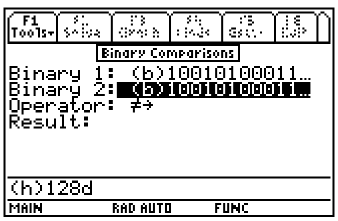
Binary 1:	(*Input Field*)	Enter an integer in the number base designated in [F4]**/Binary Mode** or an integer preceded by the number base in parenthesis (b, d, o, or h).
Binary 2:	(*Input Field*)	Enter an integer in the number base designated in [F4]**/Binary Mode** or an integer preceded by the number base in parenthesis (b, d, o, or h).
Operator:	(*Binary Operation*)	Press [ENTER] to select.

Note: All binary comparison commands affect the carry flag only.

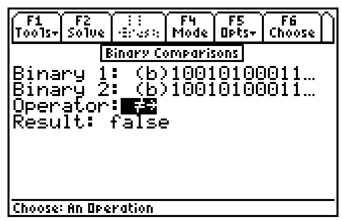
= =	Compares two binary or real numbers. The result field shows a 1 if they are equal, otherwise 0.	
≠	Compares two binary or real numbers. The result field shows a 1 if they are NOT equal, otherwise 0.	
<	Compares two binary or real numbers. If the number in the first field is less than the number in the second field, then the result field displays a 1, otherwise 0.	
>	Compares two binary or real numbers. If the number in the first field is greater than the number in the second field, then the result field displays a 1, otherwise 0.	
≤	Compares two binary or real numbers. If the number in the first field is less than or equal to the number in the second field, then the result field displays a 1, otherwise 0.	
≥	Compares two binary or real numbers. If the number in the first field is greater than or equal to the number in the second field, then the result field displays a 1, otherwise 0.	
Result:	(*Binary Function Value*)	Returns 1 (True) or 0 (False).

Example 12.6

Determine whether the octal value 11215 and the hexadecimal value 128D are unequal.



Input Screen



Output Screen

1. This test can be performed, regardless of the setting for **Base: in** the [F4]/**Binary mode** input screen, by directly entering the number base prefix (b, o, d, or h) in parenthesis before the entered value. The software will immediately convert the number to the base setting (binary, in this case).
2. Enter (o)11215 and (h)128D for **Binary 1** and **Binary 2**, respectively.
3. Choose the ≠ **Operator**, and press [F2] to compute the result. The screen display above shows the input and the resulting output.

12.7 Karnaugh Map

The program provides a symbolic representation of a minimization method in a "sum of products form." The variable name is restricted to one character per variable and is case-sensitive. The output is an algebraic expression for the prime implicants. In this representation, a logic variable (e.g., **A**) represents its true value, while **A'** is used to represent its logical negation.The algorithm uses a form of minimization developed by W.V. Quine and E.J. McCluskey. An exact minimum is usually not possible to obtain because of the amount of computation involved (the problem is not np complete; Ref. Logic Design principles by E. J. McCluskey, Prentice Hall, 1986, p. 246).

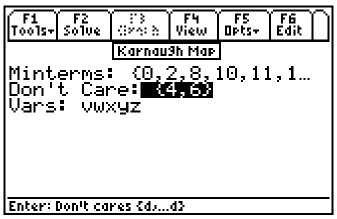
Field Descriptions

Minterms:	(*List if Minterms*)	A list of real positive integers representing the decimal number of the inputs for a true output. Thus if we have 4 inputs, the minterms would be a list such as {2,3,4,6,7,8,15} for which the output is a logical 1.
Don't Care:	(*List of Don't Care Terms*)	A list of real positive integers representing the decimal number of the inputs for which the logical system does not care if the output is true or false. Thus if we have 4 inputs, the Don't Care terms would be a list such as {0,9,10} for which the output can be a 0 or 1.

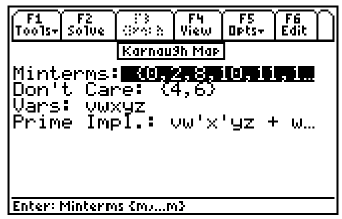
Vars:	(*List of Variables*)	A character string consisting of one letter variable names such as ABCD with no spaces between variable names.
Prime Impl:	(*Prime Implicant Expression*)	Returns a logical algebraic expression in Sum of Products form.

Example 12.7

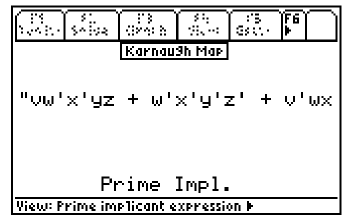
Minimize a five input function with minterms at 0, 2, 4, 6, 8, 10, 11, 12, 13, 14, 16, 19, 29, 30 where minterms 4 and 6 are Don't Cares. The input variables are V, W, X, Y and Z. Find the prime implicant expression.



Input Screen



Output Screen



Partial view of the Prime Implicant Expression

1. Enter {0, 2, 8, 10, 11, 12, 13, 14, 16, 19, 29, 30} for **Minterms** and {4, 6} for **Don't Care**.
2. Enter variable names VWXYZ.
3. Press [F2] to compute the result. The screen displays above show the input screen and the resulting output. A *Pretty Print* form of the resulting *Sum of Products* expression is shown. Variables that are associated with a prime (') indicates a logical inversion.

Chapter 13 Error Functions

This topic demonstrates the procedure for computing numeric solutions for the Error Function and the Complementary Error Function.

- ❖ Error Functions

13.1 Using Error Functions

The definitions of the Error Function and Complementary Error Function are:

$$erf\,(x) = \frac{2}{\sqrt{\pi}} \int_{0}^{x} e^{-t^2}\,dt \qquad \textbf{Eq. 13.1.1}$$

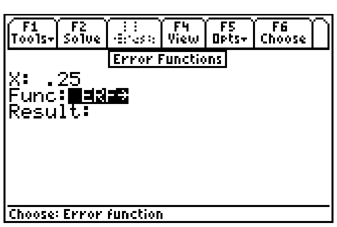
$$erfc(x) = 1 - erf\,(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} e^{-t^2}\,dt \qquad \textbf{Eq. 13.1.2}$$

Field Descriptions

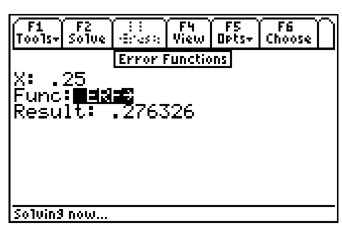
X:	(*Value*)	Enter a real number, global name, or algebraic expression.
Func:	(*Error Function type*)	Press [ENTER] to select **erf** or **erfc.**
Result:	(*Error Function value*)	Returns a real number or algebraic expression

Example 13.1

What is the value of erf(.25)?



Input Screen



Output Screen

1. Enter .25 for **X**.
2. Choose ERF in **Func**.
3. Press [F2] to calculate **Result**.

Chapter 14 Capital Budgeting

This chapter covers the four basic measures of capital budgeting:

- ❖ Payback Period
- ❖ Net Present Value
- ❖ Internal Rate of Return
- ❖ Profitability Index

14.1 Using Capital Budgeting

This section performs analysis of capital expenditure for a project and compares projects against one another. Four measures of capital budgeting are included in this section: Payback period (**Payback**), Net Present Value (**NPV**), Internal Rate of Return (**IRR**), and Profitability Index (**PI**). This module provides the capability of entering, storing and editing capital expenditures for nine different projects. The following equations are used in calculations:

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+k)^t} - CF_{t=0}$$

Eq. 14.1.1

$$\sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} - CF_{t=0} = 0$$

Eq. 14.1.2

$$PI = \frac{\sum_{t=1}^{n} \frac{CF_t}{(1+k)^t}}{CF_{t=0}}$$

Eq. 14.1.3

CF_t: Cash Flow at time t (usually years).

Payback: The number of time periods (usually years) it takes a firm to recover its original investment.
NPV: The present values of all future cash flows, discounted at the selected rate, minus the cost of the investment.
IRR: The discount rate that equates the present value of expected cash flows to the initial cost of the project.
PI: The present value of the future cash flows, discounted at the selected rate, over the initial cash outlay.

Field Descriptions - Input Screen

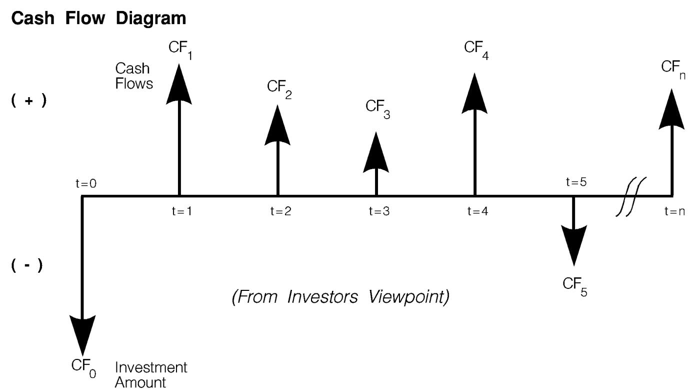
Project:	(*Project*)	Press [ENTER] to select one of nine unique projects or edit the current name of the project by pressing [F4] for Cash option.
k:	(*Discount Rate per Period in %*)	Enter a real number.
Payback:	(*Payback Period*)	Returns a real number.
NPV:	(*Net Present Value*)	Returns a real number.
IRR:	(*Internal Rate of Return*)	Returns a real number (%).
PI:	(*Profitability Index*)	Returns a real number.

Multiple Graphs — Activation of this feature enables the overlay of each successive graph (projects) on the same axis. Press [ENTER] to activate.

Full Screen Graph — Press [ENTER] to activate.

Field Descriptions - Project Edit Screen

Name:	(*Project Name*)	Enter the name of the project.
t0:	(*Investment at t=0*)	Enter a real number.
t1:	(*Cash flow at t=1*)	Enter a positive or negative real number.
....		
tn:	(*Cash flow at t=n*)	Enter a positive or negative real number.

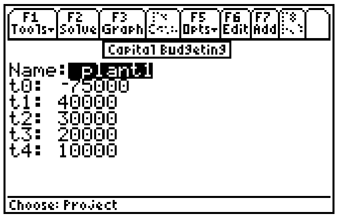


Example 14.1

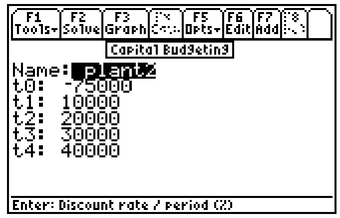
The following projects have been proposed by ACME Consolidated Inc. What is the Payback period, Net Present Value, Internal Rate of Return, and Profitability Index of each project? Which is the more viable project?

Table 14-1 Cash Flow for two projects

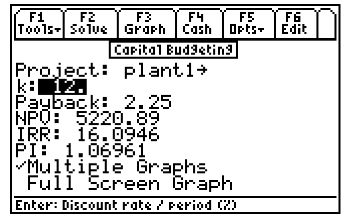
Name of Project: **Investment Outlay:** **Cost of Capital:**	**Plant 1** **$75,000** *(at t=0)* **12%**	**Plant 2** **$75,000** *(at t=0)* **12%**
Year	Net Cash Flow ($)	Net Cash Flow ($)
0	-75,000	-75,000
1	40,000	10,000
2	30,000	20,000
3	20,000	30,000
4	10,000	40,000



Cash Flow Input: plant1



Cash Flow Input: plant2



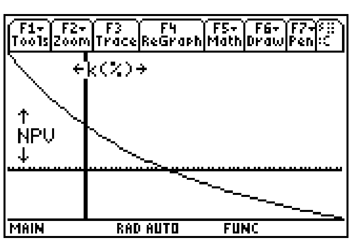
Output Screen

1. With the highlight bar on the **Project** field, press [ENTER] to select a project to edit. Select a project that has not been used (this example uses projects 1 and 2). Press [ENTER] to return to the **Capital Budgeting** screen.
2. Press [F4] to select **Cash** option enter the project edit screen and edit the cash flows.
3. Enter "plant1" in the **Name** field (**Note:** Cash flow data for this project will be stored in a variable of this name, therefore the entered name must begin with a letter, be no more than 8 characters in length, and contain no embedded spaces).
4. Press [F7] 5 times to add 5 time points and enter the cash flows at each time point from the table on the previous page. When finished, your screen should look like the project edit screen above. Be sure to enter 75,000 as a negative number for **t0**. Press [ESC] to save your changes and return to the **Capital Budgeting** screen.
5. Enter 12 for **k**.
6. Press [F2] to calculate **Payback**, **NPV**, **IRR**, and **PI**.
7. Move the highlight bar to **Multiple Graphs** and press [ENTER] to enable overlaying of successive graphs of each project.
8. Press [F3] to graph the curvilinear relationship between the **Net Present Value** and the **Discount Rate**.
9. Press [2nd] followed by [APPS] to enable the graph editing toolbar.

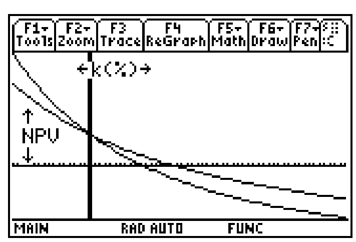
The curve indicates where k=0, the **Net Present Value** is simply cash inflows minus cash outflows. The IRR % is shown at the point where NPV=0. Using the built-in graphing capabilities of the TI 89, you can trace the graph to find the values of these two points. The TI 89 will give you the exact coordinates of any point along the graph. Press [ESC]to return to the **Capital Budgeting** screen.

Repeating steps 1 through 9 for the second project, under the **Project** field, "plant2" and input the values in Table 14-1. Activating the **Multiple Graph** feature enables a simultaneous plot of the two projects. This will overlay a second graph on top of a previously plotted function. First plot *plant1*. After graphing, plot *plant2*. The first curve to appear is *plant1*, the second is *plant2*. The most viable project in terms of discounted cash flows, in this example, is the one with the highest curve.

Pressing [MODE] [F2] [▶] [1] [ENTER] resets the display to full screen.



Plot of Project 1



Overlay of Project 2

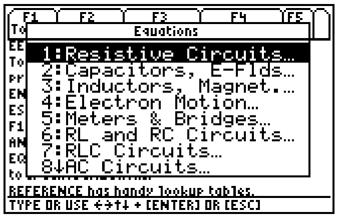
Chapter 15 Introduction to Equations

The *Equations* section of EE•*Pro* contains over 700 equations organized into 16 topic and 105 sub-topic menus.

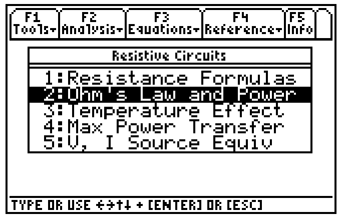
- The user can select several equation sets from a particular sub-topic, display all the variables used in the set of equations, enter the values for the known variables and solve for the unknown variables.
- The equations in each sub-topic can be solved individually, collectively or as a sub-set.
- A unit management feature allows easy entry and display of results.
- Variables in selected equation sets can be graphed to examine the relationship between each other.
- Multiple and partial solutions are possible using techniques developed for EE•*Pro.*
- More information on a particular input can be displayed by highlighting the variable, press [F5] and [2]**/Type:** to show a brief description of a variable and its entry parameters.

15.1 Solving a Set of Equations

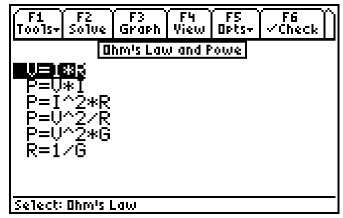
- *Equations* are accessed from the main level of the EE•*Pro* by pressing function key [F3] labeled "**Equations.**" This displays a pull-down menu listing all the topics as shown in the screen display below.
- An arrow to the left of the bottom topic '↓'indicates more items are listed. Pressing [2nd] ⊝ jumps to the bottom of the menu.
- Scroll the highlight bar to an item using the arrow key ⊝ and press [ENTER], or type the subject number appearing next to subject heading (*Resistive Circuits* is selected for this example).
- A second menu will appear listing more subjects (sub-topics) under the topic heading.
- Selecting a sub-topic displays a list of equations under the subject heading (*Ohm's Law and Power* is selected below).
- Use the arrow key ⊝ to move the highlighter and press [ENTER] to select an equation or series of equations which are applicable to a specific problem (pressing [F2] selects all of the equations).
- Press [F2] to display all of the variables in the selected equations. As the cursor bar is moved, a brief description of each variable will appear in the status line at the bottom of the screen.
- Enter values for the known parameters, selecting appropriate units for each value using the toolbar menu which appear at the top of the screen.
- Press [F2] to compute values for the unknown parameters.
- Entered and calculated values are distinguished in the display; '▪' for entered values and '◆' for computed results.



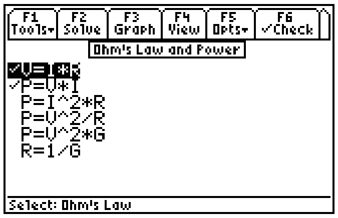
1. Pressing [F3] displays the 'Equations' menu.



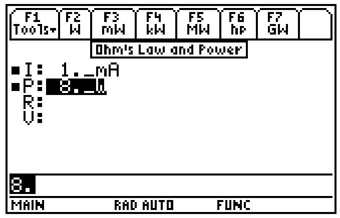
2. Press [1] to display the menu in 'Resistive Circuits'



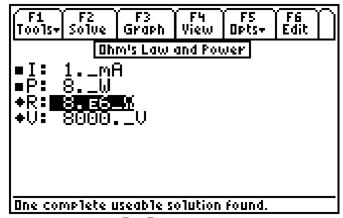
3. Press [2] to display the equations for 'Ohm's Law'.



4. Select equations by highlighting and pressing [ENTER].



5. Press [F2] to display the variables in the selected equations. Enter the known variable values. Use the unit toolbar to select units.

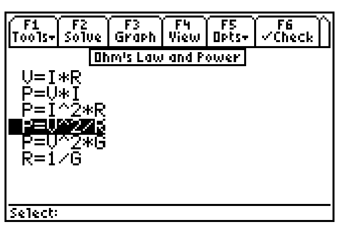


6. Press [F6] to compute the unknown variables. Note: Computed results '♦' are distinguished from entered values '▪'.

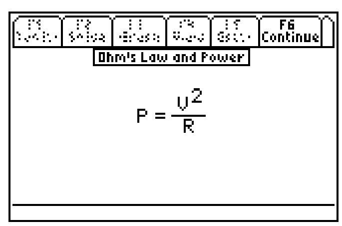
Note: Only values designated as *known* '▪' will be used in a computation. A result displayed from an earlier calculation will not be used unless the user specifically designates the value by selecting the variable and pressing [ENTER]. Press [F2] to compute a new result for any input that is changed.

15.2 Viewing an Equation or Result in *Pretty Print*

Sometimes equations and calculated results exceed the display room of the calculator. The TI-89 and TI 92 plus include a built-in equation display feature called *Pretty* Print which is available in many areas of EE•*Pro* and can be activated by highlighting a variable or equation and pressing the right arrow key ▶ or pressing the [F4] function key when it is designated as *View*. The object can be scrolled using the arrow keys ◀▶. Pressing [ESC] or [F6] reverts to the previous screen.



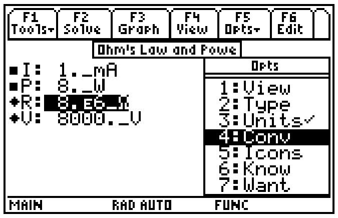
1. To view an equation in, ***Pretty Print***, highlight and press [F4] or ▶.



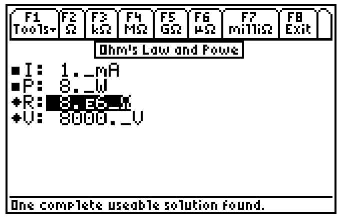
2. Scroll features, using the arrow keys ◀▶, enable a complete view of a large object.

15.3 Viewing a Result in different units

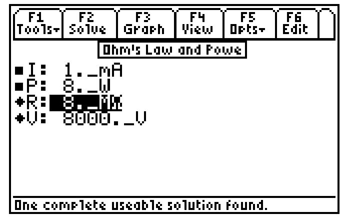
To view a calculated result in units which are different from what is displayed. Highlight the variable, press [F5]**/Options** and [4]**/Conv** to display the unit tool bar at the top of the screen. Press the function key to convert the result to the desired units.



1. Highlight the result to be converted (R). Press F5 to display the Options menu, press 4/Conv.



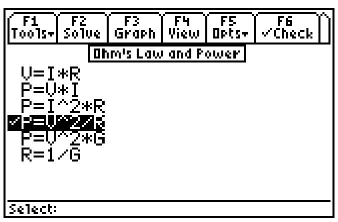
2. The unit menu tool bar is now displayed at the top of the screen.



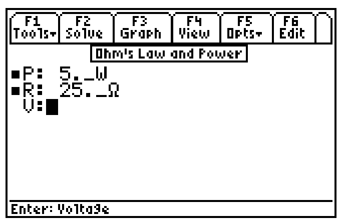
3. Press F4 to convert the. result of 'R' from Ω to MΩ.

15.4 Viewing Multiple Solutions

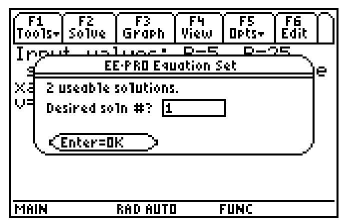
The math engine used by EE•*Pro* is able to manage complex values for variables (where they are permitted) and calculate more than one solution in cases where multiple answers exist for an entered problem. When a multiple solution exists, the user is prompted to select the number of a series of computed answers to be displayed. To view additional solutions, press F2 to repeat the calculation and enter another solution number. The user will need to determine which result is most useful to the application.



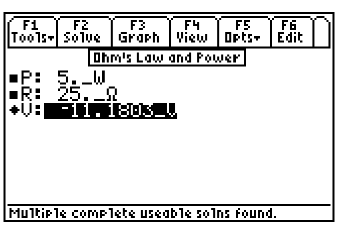
1. Select an equation by highlighting and pressing ENTER. Press F2 to display variables.



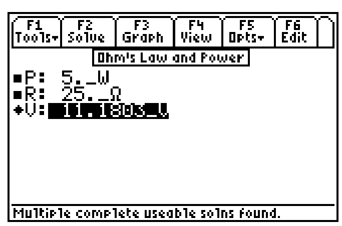
2. Enter known values for each variable using the tool bar to designate units. Press F2 to compute the results.



3. If multiple solution exists, a dialogue box will appear requesting the user to enter the number of a solution to view.



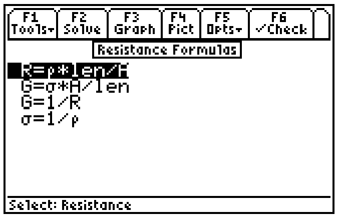
Solution 1: To view another solution, press F2 to re calculation and enter the number. of another solution to be viewed.



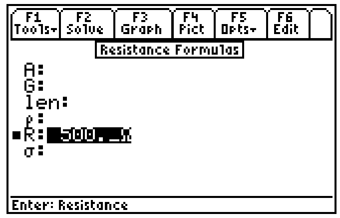
Solution 2: Enter a new number for each solve to display a series of. multiple solutions.

15.5 Partial Solutions

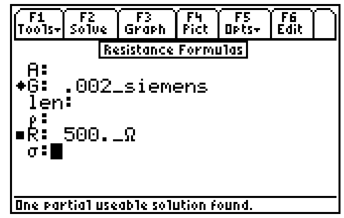
"*One partial useable solution found." or "Multiple partial solutions found."* will be displayed in the status line if values for one or more variables in the selected equation set cannot be computed. This situation can occur if there are more unknowns than equations in the selected set, the entered values do not form consistent relationships with the selected equations, or if the selected equations do not establish a closed form relationship between all of the entered values and the unknowns. In such a case, only the calculated variables will be displayed.



Press [F2] to select all of the *equations in **Resistive Formulas**.*



If there are more unknowns than selected equations or relationships between variables are not established from the selected equations...



...a partial solution will be displayed if one or more of the unknown variables are able to be computed from the entered inputs.

15.6 Copy/Paste

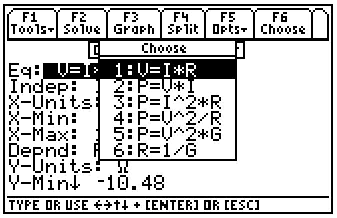
A computed result and it's expressed units can be copied and pasted to the HOME screen or any other location of EE•*Pro* using [F1]**:Tools-5:Copy** key sequence to copy a value and [F1]**:Tools-6:Paste** to paste the item in any appropriate context of the TI system.

15.7 Graphing a Function

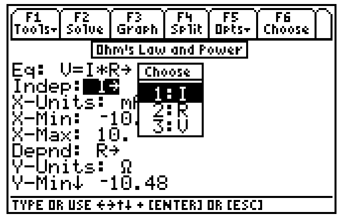
The relationship between two variables in an equation can be graphed on a real number scale if the other variables in the equation are defined.

- After solving an equation, or entering values for the <u>*non* x,y</u> variables in the equation to be plotted, press [F3] **/Graph** to display the graph settings.
- Highlight **Eq:** and press [ENTER] to select the equation from the list to graph.
- Use the same steps as above to select the independent and dependent variables (**Indep:** and **Depnd:**) from the equation. **Note: all pre-existing values stored in the variables used for Indep: and Depnd: will be cleared when the graphing function is executed.**
- The graphing unit scale for each variable reflect the settings in the *Equations* section of EE•*Pro*.
- Scrolling down the list, specify the graphing ranges for the x and y variables, whether to graph in full or split screen modes, automatically scale the graph to fit the viewing area, and label the graph.
- Press [F3] to graph the function.
- Once the graph command has been executed, EE•*Pro* will open a second window to display the plot. All of the TI graphing features are available and are displayed in the toolbar, including *Zoom* [F2], *Trace* [F3], *Math* [F5], etc. The *Math* feature is extremely useful for determining critical function values such as intercepts, inflections, derivatives, integrals, etc. Peak performance, damped resonance and decay functions are able to be evaluated using this tool.
- If the split-screen graphing mode is activated, the user can toggle between the EE•*Pro* graph dialogue display and the TI graph by pressing [2nd] [APPS]. If the full-screen graphing mode is activated, the user can switch between EE•*Pro* and the graph by pressing [APPS] 4:Graph or A:EE•*Pro.*

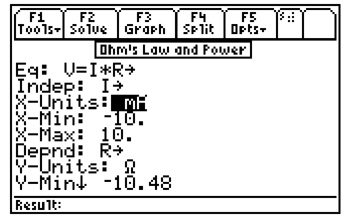
  ***Before graphing an equation, be sure to specify values for variables in an equation which are not going to be used as x and y variables.**



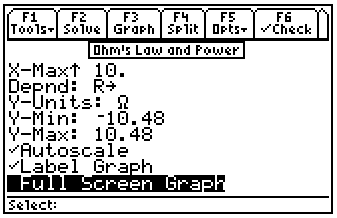
1*. Graph an equation by pressing [F3]. Press [ENTER] to choose an equation.



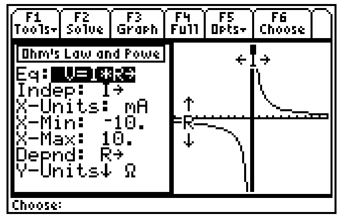
2. Select variables for **Independent** (x) and **Dependent** (y) variables.



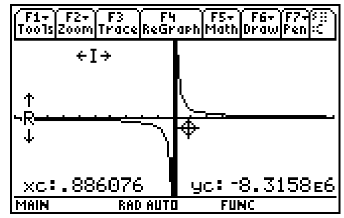
Variable units reflect settings in **EE•Pro**.



4. Select graphing options by pressing [ENTER]



5. Split Screen Mode: Toggle between graph and settings by pressing [2nd] and [APPS].



6: Full Screen Mode: Press [APPS], [alpha] and [A] to return to EE•Pro.

Note: If an error is generated when attempting to graph, be sure that all of the variables in the graphed equation which are not specified as the independent and dependent variables have entered values. In the EE•*Pro* window, press [ESC] to view the equations in the sub-topic, select the equation to be graphed by highlighting and pressing [ENTER], press [F2] to display the list of variables in the equation and enter values. Only the dependent (y) and independent (x) variables do not have to contain specified values. Press [F3] to display the graph dialogue and repeat the above steps to graph the function.

15.8 Storing and recalling variable values in EE•*Pro*-creation of session folders

EE•*Pro* automatically stores its variables in the current folder specified by the user in [MODE] or the HOME screens. The current folder name is displayed in the lower left corner of the screen (default is "Main"). To create a new folder to store values for a particular session of EE•*Pro*, press [F1]**:/TOOLS,** [3]**:/NEW** and type the name of the new folder (see Chapter 5 of the TI-89 Guidebook for the complete details of creating and managing folders). There are several ways to display or recall a value:

- The contents of variables in any folder can be displayed using the [VAR-LINK], moving the cursor to the variable name and pressing [F6] to display the contents of a particular variable.
- Variables in a current folder can be recalled in the HOME screen by typing the variable name.
- Finally, values and units can be copied and recalled using the [F1]**/Tools 5:COPY** and **6:PASTE** feature.

All inputs and calculated results from *Analysis* and *Equations* section are saved as variable names. Previously calculated, or entered values for variables in a folder are replaced when equations are solved using new values for inputs.

Overwriting of variable values in graphing

When an equation or analysis function is graphed, EE•*Pro* creates a function for the TI grapher which expresses the dependent variable in terms of the independent variable. This function is stored under the variable name *pro(x)*. When the EE•*Pro*'s equation grapher is executed, values are inserted into the independent variable for *pro(x)* and values for the dependent value are calculated. Whatever values which previously existed in either of the dependent and independent variables in the current folder are cleared. To preserve data under variable names which may conflict with EE•*Pro*'s variables, run EE•*Pro* in a separate folder.

15.9 solve, nsolve, and csolve and user-defined functions (UDF)

When a set of equations is solved in EE•*Pro*, three different functions in the TI operating system (solve, numeric solve, and complex solve) are used to find the most appropriate solution. In a majority of cases, the entered values are adequate to find numeric solutions using either the *solve* or *csolve* functions. However, there are a few instances when functions external to the equation set (user-defined functions) are incorporated into the solving process and *nsolve* must be used. User defined functions which appear in some of the equation sets of EE•*Pro* are **erfc(x) erf(x), eeGALV(RR2, ….)** and **ni(TT)**.

In most cases, when all the inputs to a UDF are known, *solve* or *csolve* can just pass a computed result to the equation. On the other hand if one is solving for a variable that is an input to the UDF, *solve* or *csolve* are unable to isolate the variable in an explicit form, and the operating system resorts to using *nsolve*. *nsolve* initiates a series of trial and error iterations for the unknown variable until the solution converges. It should be noted that the solution generated by *nsolve is not* guaranteed to be unique (i.e. this solving process cannot determine if multiple solutions exist.).

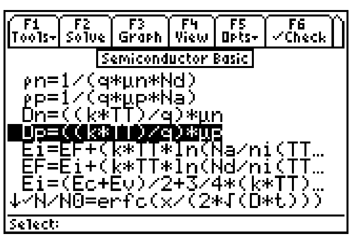
Table 15-1 User Defined Functions

User-defined Function	**Topic**	**Sub-topic**
erf(ts, τp)	Solid State	PN Junction Current
erfc (x,D,t)	Solid State	Semiconductor Basics
eegalv (Rx, RR2, RR3, RR4, Rg, Rs, Vs)	Meters and Bridges	Wheatstone Bridge
ni(TT)	Solid State	Semiconductor Basics, PN Junctions, PN Junction Current, MOS Transistor I

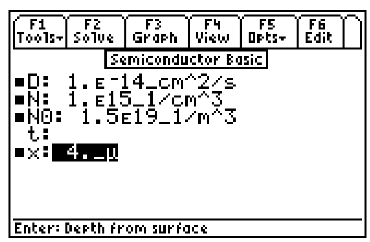
15.10 Entering a guessed value for the unknown using *nsolve*

To accelerate the *nsolve* converging process and, if multiple solutions exist, enhance the possibility that nsolve resolves the correct solution, the user can enter a guessed value for the unknown which nsolve will use as an initial value in the first iteration of its solving process.

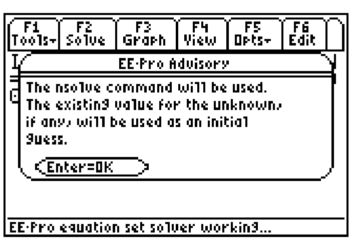
- ❖ Enter guessed a value for the variable in the input dialogue.
- ❖ Press [F5]/Opts, [7]/Want.
- ❖ Press [F2]/ to compute a solution for the variable.



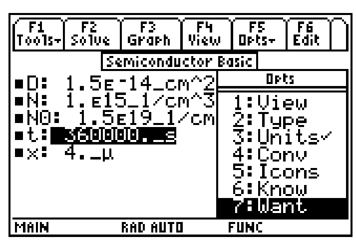
*erfc(x,D,t) is a user defined function that appears in the **Semiconductor Basics** section of **Solid State**.*



Only one input to a user defined function can be specified as an unknown.



EE•*Pro displays a notice if the **nsolve** routine is used.*



*The user can enter a value for for the unknown and designate it as a guessed value to accelerate the **nsolve** convergence process.*

15.11 Why can't I compute a solution?

If a solution is unable to be computed for an entered problem, you might check the following:

1. Are there at least as many equations selected as there are unknown parameters?
2. Are the entered values or units for the known parameters reasonable for a specific case?
3. Are the selected equations consistent in describing a particular case (for example, the choice of certain equations used in the calculation of diode properties depends on whether the donor density of the doping substance **Nd**, exceeds the acceptor density, **Na** in the *Semiconductors* section of **Solid State**)

15.12 Care in choosing a consistent set of equations

The success of the equation solver in generating a useful solution, or a solution at all, is strongly dependent on the user's insight into the problem and care in choosing equations which describe consistent relationships between the parameters.

The following steps are suggested:

- Read the description of each set of equations in a topic to determine which subset of equations in a series are compatible and consistent in describing a particular case.
- Select the equations from a subset which describe the relationships between all of the known and unknown parameters.
- As a rule of thumb, select as many equations from the subset as there are unknowns to avoid redundancy or over-specification. The equations have been researched from a variety of sources and use slightly different approximation techniques. Over-specification (selecting too many equations) may lead to an inability of the equation solver to resolve slight numerical differences in different empirical methods of calculating values for the same variable.

15.13 Notes for the advanced user in troubleshooting calculations

When there are no solutions possible, EE•*Pro* provides important clues via key variables **eeinput, eeprob, eeans,** and **eeanstyp**. These variables are defined during the equation setup process by the built-in multiple equation solver. EE•*Pro* saves a copy of the problem, its inputs, its outputs, and a characterization of the type of solution in the user variables **eeprob**, **eeinput**, **eeans**, and **eeanstyp**. For the developer who is curious to know exactly how the problem was entered into the multiple equation solver, or about what the multiple equation solver returned, and to examine relevant strings. The contents of these variables may be viewed by using VAR-LINK and examining these variables in the current session. Press [VAR-LINK] ([2nd] followed by [-]), scroll to the variable name in the current folder and press [F6] to view the contents of the variable. The string may be recalled to the author line of the home screen, modified and re-executed, if desired.

Table 15.2 Topics and Sub-topics List

1: Resistive Circuits	**2: Capacitors, E-Fields**	**3: Inductors and Magnetism**
1: Resistance Formulas	1: Point Charge	1: Long Line
2: Ohm's Law and Power	2: Long Charged Line	2: Long Strip
3: Temperature Effect	3: Charged Disk	3: Parallel Wires
4: Max. Power Transfer	4: Parallel Plates	4: Loop
5: V, I Source	5: Parallel Wires	5: Coaxial Cable
	6: Coaxial Cable	6: Skin Effect
	7: Sphere	
4: Electron Motion	**5: Meters and Bridge Circuits**	**6: RL and RC Circuits**
1: Beam Deflection	1: A, V, Ω Meters	1: RL Natural Response
2: Thermionic Emission	2: Wheatstone Bridge	2: RC Natural Response
3: Photoemission	3: Wien Bridge	3: RL Step response
	4: Maxwell Bridge	4: RC Step Response
	5: Attenuators - Symmetric R	5: RL Series to Parallel
	6: Attenuators - Unsym R	6: RC Series to Parallel
7: RLC Circuits	**8: AC Circuits**	**9: Polyphase Circuits**
1: Series Impedance	1: RL Series Impedance	1: Balanced Δ Network

2: Parallel Admittance
3: RLC Natural Response
4: Under-damped case
5: Critical Damping
6: Over-damped Case

2: RC Series Impedance
3: Impedance - Admittance
4: 2 Z's in Series
5: 2 Z's in Parallel

2: Balance Wye Network
3: Power Measurements

10: Electrical Resonance
1: Parallel Resonance I
2: Parallel Resonance II
3: Lossy Inductor
4: Series Resonance

11: Op. Amp Circuits
1: Basic Inverter
2: Non-Inverting Amplifier
3: Current Amplifier
4: Transconductance Amplifier
5: Lvl. Detector Invert
6: Lvl. Detector Non-Invert
7: Differentiator
8: Diff. Amplifier

12: Solid State Devices
1: Semiconductor Basics
2: PN Junctions
3: PN Junction Currents
4: Transistor Currents
5: Ebers-Moll Equations
6: Ideal Currents - pnp
7: Switching Transients
8: MOS Transistor I
9: MOS Transistor II
A: MOS Inverter R Load
B: MOS Inverter Sat Load
C: MOS Inverter Depl. Ld
D: CMOS Transistor Pair
E: Junction FET

13: Linear Amplifiers
1: BJT (CB)
2: BJT (CE)
3: BJT (CC)
4: FET (Common Gate)
5: FET (Common Source)
6: FET (Common Drain)
7: Darlington (CC-CC)
8: Darlington (CC-CE)
9: EC Amplifier
A: Differential Amplifier
B: Source Coupled JFET

14: Class A, B, C Amps
1: Class A Amplifier
2: Power Transistor
3: Push-Pull Principle
4: Class B Amplifier
5: Class C Amplifier

15: Transformers
1. Ideal Transformer
2: Linear Equiv. Circuit

16: Motors, Generators
1: Energy Conversion
2: DC Generator
3: Sep. Excited DC Gen.
4: DC Shunt Generator
5: DC Series Generator
6: Sep Excite DC Motor
7: DC Shunt Motor
8: DC Series Motor
9: Perm Magnet Motor
A: Induction Motor I
B: Induction Motor II
C: 1 ϕ Induction Motor
D: Synchronous Machines

Chapter 16 Resistive Circuits

This software section performs routine calculations of resistive circuits. The software is organized in a number of topics listed below.

- Resistance and Conductance
- Ohm's Law and Power
- Temperature Effects
- Maximum Power Theorem
- V and I Source Equivalence

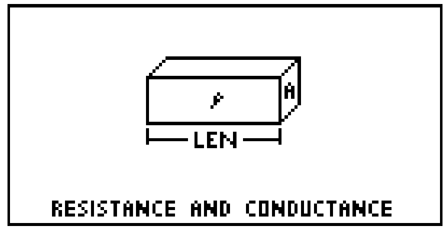
Variables

A complete list of all the variables used, a brief description and applicable base unit is given below.

Variable	**Description**	**Unit**
A	Area	m^2
G	Conductance	S
I	Current	A
Il	Load current	A
Is	Current source	A
len	Length	m
P	Power	W
Pmax	Maximum power in load	W
R	Resistance	Ω
Rl	Load resistance	Ω
Rlm	Match load resistance	Ω
RR1	Resistance, T1	Ω
RR2	Resistance, T2	Ω
Rs	Source resistance	Ω
T1	Temperature 1	K
T2	Temperature 2	K
V	Voltage	V
Vl	Load voltage	V
Vs	Source voltage	V
α	Temperature coefficient	1/°K
ρ	Resistivity	Ω*m
σ	Conductivity	S/m

16.1 Resistance Formulas

Four equations in this topic represent the basic relationship between resistance and conductance. The first equation links the resistance **R** of a bar with a length **len** and a uniform cross-sectional area **A** with a resistivity ρ. The second equation defines the conductance **G** of the same bar in terms of conductivity σ, **len** and **A.** The third and fourth equations show the reciprocity of conductance **G** resistance **R**, resistivity ρ and conductivity σ.



$$R = \frac{\rho \cdot len}{A}$$ **Eq. 16.1.1**

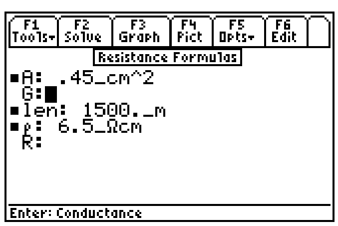
$$G = \frac{\sigma \cdot A}{len}$$ **Eq. 16.1.2**

$$G = \frac{1}{R}$$ **Eq. 16.1.3**

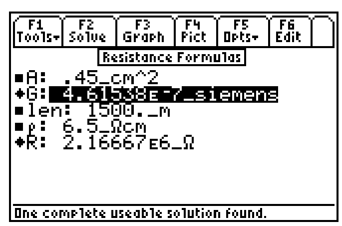
$$\sigma = \frac{1}{\rho}$$ **Eq. 16.1.4**

Example 16.1 - A copper wire 1500_m long has a resistivity of 6.5_ohm*cm and a cross sectional area of .45_cm^2. Compute the its resistance and conductance.

Solution - Upon examining the problem, two choices are noted. Equations **16.1.1, 16.1.2** and **16.1.4** or **16.1.1** and **16.1.3** can be used to solve the problem. The second choice was made here. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation set. The computed results are shown in the screen display shown here.



Entered Values



Computed results

Known Variables: len = 1500_m, **ρ** = 6.5_ohm*cm, **A** = .45_cm^2

Computed Results: R = 2.16667E6_ohm, **G** = .461538E-7_siemens

16.2 Ohm's Law and Power

The fundamental relationships between voltage, current and power are presented in this section. The first equation is the classic Ohm's Law, computes the voltage **V** in terms of the current **I,** and the resistance **R.** The next four equations describe the relationship between power dissipation **P**, voltage **V**, current **I,** resistance **R** and conductance **G** in a variety of alternate forms. The final equation represents the reciprocity between resistance **R** and conductance **G**.

$$V = I \cdot R \qquad \textbf{Eq. 16.2.1}$$

$$P = V \cdot I \qquad \textbf{Eq. 16.2.2}$$

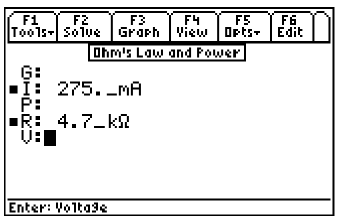
$$P = I^2 \cdot R \qquad \textbf{Eq. 16.2.3}$$

$$P = \frac{V^2}{R} \qquad \textbf{Eq. 16.2.4}$$

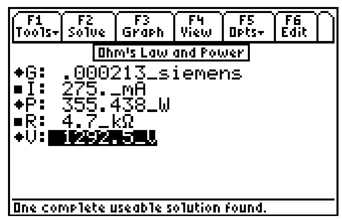
$$P = V^2 \cdot G \qquad \textbf{Eq. 16.2.5}$$

$$R = \frac{1}{G} \qquad \textbf{Eq. 16.2.6}$$

Example 16.2 - A 4.7_kohm load carries a current of 275_ma. Calculate the voltage across the load, power dissipated and load conductance.



Entered Values



Computed results

Solution - Upon examining the problem, several choices are noted. Either Equations **16.2.1, 16.2.2 and 16.2.6,** or **16.2.2, 16.2.3** and **16.2.5** or **16.2.2, 16.2.3** and **16.2.6** or **16.2.1, 16.2.2** and **16.2.5** or **all** the equations. Choose the last option, press [F2] to open the input screen, enter all the known variables and press [F2] to solve.

Known Variables: **I** = 275_ma, **R** = 4.7_kΩ.

Computed Results: **V** = 1292.5_V, **P** = 355.438_W, **G** = .000213_siemens

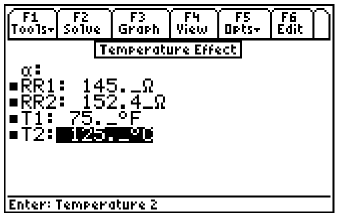
16.3 Temperature Effect

This equation models the effect of temperature on resistance. Electrical resistance changes from **RR1** to **RR2** when the temperature change from **T1** to **T2** is modulated by the temperature coefficient of resistance **α.**

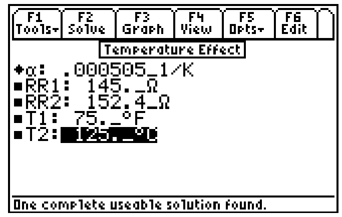
$$RR2 = RR1 \cdot \left(1 + \alpha \cdot \left(T2 - T1\right)\right) \qquad \textbf{Eq. 16.3.1}$$

Example 16.3 - A 145_Ω resistor at 75_°F reads 152.4_Ω at 125_ºC. Find the temperature coefficient of resistance.

Solution - Since there is only one equation in this topic, there is no need to make a choice of equation. Press [F2] to display the input screen. Enter the variable values and press [F2] to solve for the unknown variable.



User entered Variables



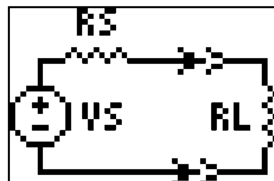
Computed results

Known Variables: **RR2** = 152.4_Ω, **RR1** = 145_Ω, **T1** = 75_°F **T2** = 125_°C

Computed Results: α = .000505_1/°K

16.4 Maximum DC Power Transfer

The equations under this topic are organized to compute load voltage **Vl,** load current **Il,** power dissipation in the load **P**, maximum power available in the load **Pmax**, and load impedance **Rlm** needed for maximum power deliverable to the load. The first equation finds the load voltage **Vl** of circuit with a voltage source **Vs**, source resistance **Rs**, and a load resistance **Rl.** The next equation defines the load current **Il** in terms of **Vs, Rs** and **Rl.** The power dissipation in the load is defined by the equation relating **P** with **Il** and **Vl.** The next equation links **Pmax** to **Vs** and **Rs**. The last equation represents load resistance needed for a maximum power.



DC Voltage source with load

$$Vl = \frac{Vs \cdot Rl}{Rs + Rl}$$ **Eq. 16.4.1**

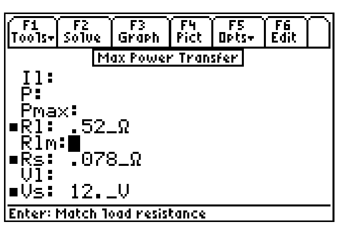
$$Il = \frac{Vs}{Rs + Rl}$$ **Eq. 16.4.2**

$$P = Il \cdot Vl$$ **Eq. 16.4.3**

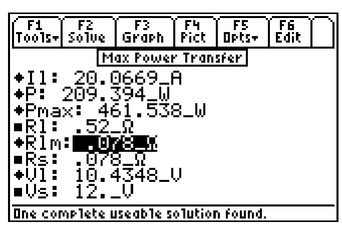
$$P\max = \frac{Vs^2}{4 \cdot Rs}$$ **Eq. 16.4.4**

$$Rlm = Rs$$ **Eq. 16.4.5**

Example 16.4 - A 12_V car battery has a resistive load of .52_ohm. The battery has a source impedance of 0.078_ohm. Find the maximum power deliverable from this battery, and the power delivered to this resistive load.



Entered Values



Computed results

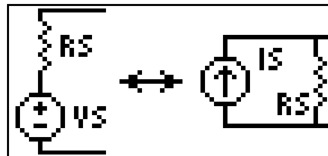
Solution - The second, third and fourth equations are needed to compute the solution for this problem. Select these by highlighting and pressing the [ENTER] key. Press [F2] to display the input screen, enter the known variables and press [F2] to solve the unknowns.

Known Variables: **Vs** = 12_V, **Rs** = .078_ohm **Rl** = .52_ohm

Computed Results: **Pmax** = 461.538_W, **P** = 209.394_W

16.5 V and I Source Equivalence

The two equations in this topic show the equivalence between a voltage source and a current source. A voltage source **Vs** with an internal series resistance of **Rs** is equivalent in all its functionality to a current source **Is** with a source resistance **Rs** connected across it.

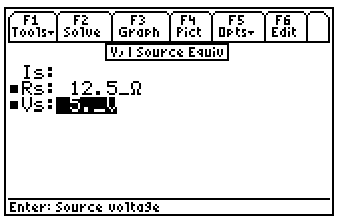


Voltage and current sources and its equivalence

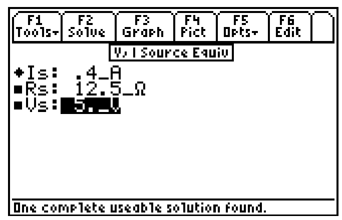
$$Is = \frac{Vs}{Rs}$$ **Eq. 16.5.1**

$$Vs = Is \cdot Rs$$ **Eq. 16.5.2**

Example 16.5 - Find the short circuit current equivalent for a 5_V source with a 12.5_ohm source resistance.



Entered Values



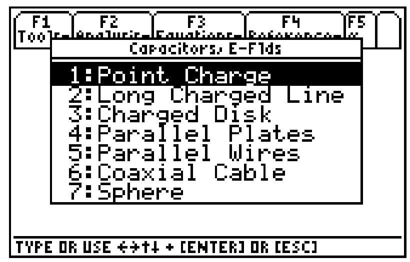
Computed results

Solution - Either form of the equation can be used to solve the equation. Press F2 to display the user interface, enter the values of all known inputs, and press F2 to solve for **Is**.

Known Variables: **Vs** = 5_V, **Rs** = 12.5_Ω

Computed Results: **Is** = .4_A

Chapter 17 Capacitors, Electric Fields



This section covers seven topics to compute electric field properties and capacitance of various types of structures.

When the section is accessed, the software displays the topics in a pop up menu shown above.

- ❖ Point Charge
- ❖ Long Charged Line
- ❖ Charged Disk
- ❖ Parallel Plates
- ❖ Parallel Wires
- ❖ Coaxial Cable
- ❖ Sphere

Variables

A complete list of all the variables used in this section is given below.

Variable	**Description**	**Unit**
A	Area	m^2
C	Capacitance	F
cl	Capacitance per unit length	F/m
d	Separation	m
E	Electric field	V/m
Er	Radial electric field	V/m
Ez	Electric field along z axis	V/m
F	Force on plate	N
Q	Charge	C
r	Radial distance	m
ra	Inner radius, wire radius	m
rb	Outer radius	m
V	Potential	V
Vz	Potential along z axis	V
W	Energy stored	J
z	z axis distance from disk	m
εr	Relative permittivity	unitless
ρl	Line charge	C/m
ρs	Charge density	C/m^2

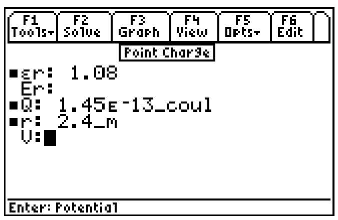
17.1 Point Charge

The two equations in this topic calculate the radial electric field **Er** and the potential **V** at a point located a distance **r** away from a point change **Q**. The first equation shows the inverse square relationship between **Er** and **r**, while the second equation shows the inverse relationship between the potential **V** and distance **r**. The equations have been generalized to include **εr**, the relative permittivity of the medium.

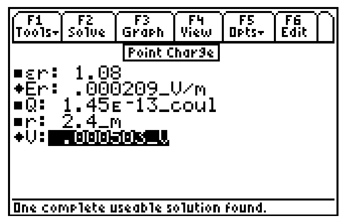
$$Er = \frac{Q}{4 \cdot \pi \cdot \varepsilon 0 \cdot \varepsilon r \cdot r^2} \qquad \textbf{Eq. 17.1.1}$$

$$V = \frac{Q}{4 \cdot \pi \cdot \varepsilon 0 \cdot \varepsilon r \cdot r} \qquad \textbf{Eq. 17.1.2}$$

Example 17.1 - A point charge of 14.5E-14_coulomb is located 2.4_m away from an instrument measuring electric field and absolute potential. The permittivity of air is 1.08. Compute the electric field and potential.



Entered Values



Computed results

Solution - Both equations are needed to solve this problem. Press [F2] to display the input screen, enter all the known variables, and press [F2] to solve for the unknown values. Note that **ε0**, the permittivity of free space does not appear as one of the variables that needs to be entered. It is entered automatically by the software. However, **εr,** the relative permittivity must be entered as a known value.

Known Variables: **Q** = 14.5E-14_coulomb, **r** = 2.4_m, **εr** = 1.08

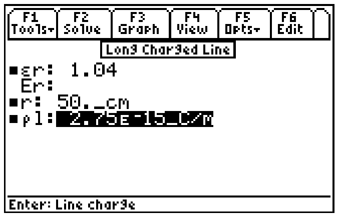
Computed Results: **Er** = .000209_V/m, **V** = .000503_V

17.2 Long Charged Line

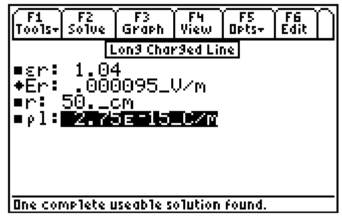
An infinite line with a linear charge density, **ρl,** (coulombs per unit length) exerts a radial electric field, **Er**, a distance **r** away from the line. The equation has been generalized to include **εr**, the relative permittivity of the medium.

$$Er = \frac{\rho l}{2 \cdot \pi \cdot \varepsilon 0 \cdot \varepsilon r \cdot r} \qquad \textbf{Eq. 17.2.1}$$

Example 17.2 - An aluminum wire suspended in air carries a charge density of 2.75E-15_coulombs/m. Find the electric field 50_cm away. Assume the relative permittivity of air to be 1.04.



Entered Values



Computed results

Solution - Press [F2] to display the input screen, enter all the known variables, and press [F2] to solve the selected equation set. The screen display above shows the computed results.

Known Variables: **ρl** = 2.75 E-15_coulombs/m, **r** = 50_cm, **εr** = 1.04

Computed Results: **Er** = .000095_V/m

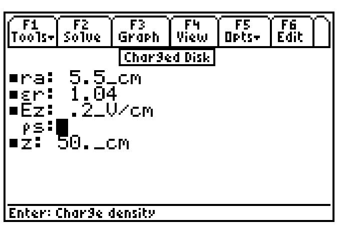
17.3 Charged Disk

These two equations describe the electric field and potential along the vertical axis through the center of a uniformly charged disk. The first equation defines the electric field along the z-axis of the disk with a radius **ra** and charge density of **ρs**, a distance **z** from the plane of the disk. The second equation computes the electrostatic potential **Vz** at an arbitrary point along the z-axis.

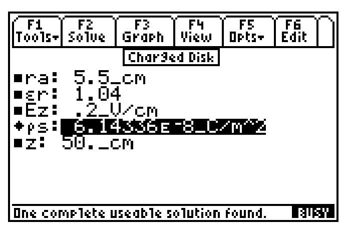
$$Ez = \frac{\rho s}{2 \cdot \varepsilon 0 \cdot \varepsilon r} \cdot \left(1 - \frac{|z|}{\sqrt{ra^2 + z^2}} \right) \qquad \textbf{Eq. 17.3.1}$$

$$Vz = \frac{\rho s}{2 \cdot \varepsilon 0 \cdot \varepsilon r} \cdot \left(\sqrt{ra^2 + z^2} - |z| \right) \qquad \textbf{Eq. 17.3.2}$$

Example 17.3 - A charged disc 5.5_cm in radius produces an electric field of .2_V/cm 50_cm away from the surface of the disc. Assuming that relative permittivity of air is 1.04, what is the charge density on the surface of the disc?



Entered Values



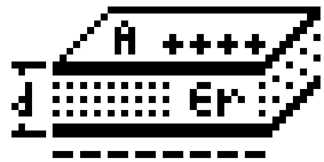
Computed Results

Solution - Select the first equation by pressing [ENTER] key, press [F2] to display the input screen for this equation, enter all the known variables, and press [F2]. The computed results are shown in the screen display above.

Known Variables: **ra** = 5.5_cm, **εr** = 1.04, **Ez** = .2_V/cm, **z** = 50_cm

Computed Results: **ρs** = 6.14336E-8_coulomb/m^2

17.4 Parallel Plates



The five equations listed in this topic describe the electrical and mechanical forces in a parallel plate capacitor. Two plates are separated by a distance **d** which is small compared to the lateral dimensions so fringing field effects can be ignored. The first equation computes the electric field **E** at the plate for a potential difference **V** between the plates separated by a small distance **d**. The second equation calculates capacitance **C** with a dielectric given the relative permittivity **εr** and area **A**. The third equation shows the charge **Q** on each parallel plate. The last two equations compute the mechanical properties associated with this parallel plate capacitor such as the Force **F** on the plates and energy **W** stored in the capacitor.

$$E = \frac{V}{d} \qquad \textbf{Eq. 17.4.1}$$

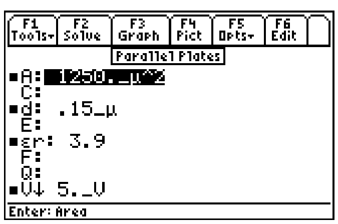
$$C = \frac{\varepsilon 0 \cdot \varepsilon r \cdot A}{d} \qquad \textbf{Eq. 17.4.2}$$

$$Q = C \cdot V \qquad \textbf{Eq. 17.4.3}$$

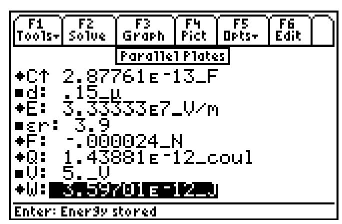
$$F = -\frac{1}{2} \cdot \frac{V^2 \cdot C}{d} \qquad \textbf{Eq. 17.4.4}$$

$$W = \frac{1}{2} \cdot V^2 \cdot C \qquad \textbf{Eq. 17.4.5}$$

Example 17.4 - A silicon dioxide insulator forms the insulator for the gate of a MOS transistor. Calculate the charge, electric field and mechanical force on the plates of a 5_V MOS capacitor with an area of 1250_μ^2 and a thickness of .15_μ. Use a value of 3.9 for permittivity of SiO2.



Entered Values



Computed results

Solution - All of the equations are needed to compute the solution to this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve. The computed results are shown above.

Known Variables: **V** = 5_V, **εr** = 3.9, **d** = .15_μ. **A**=1250_μ^2

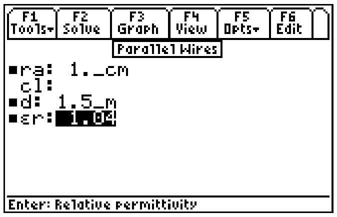
Computed Results: **C** = 2.87761E-13_F, **E** = 3.33333E7_V/m,
F = -.000024_N, **W** = 3.59701E-12_J

17.5 Parallel Wires

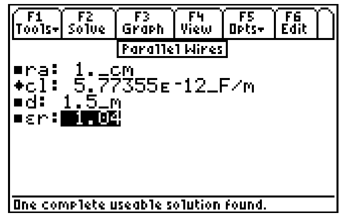
The equation listed under this topic represents the calculation of capacitance per unit length, **cl,** of a pair of transmission lines of radius **ra** and center to center spacing **d** in a dielectric medium with a relative permittivity of **εr**.

$$cl = \frac{\pi \cdot \varepsilon 0 \cdot \varepsilon r}{\cosh^{-1}\left(\frac{d}{2 \cdot ra}\right)}$$ **Eq. 17.5.1**

Example 17.5 - Compute the capacitance per unit length of a set of power lines 1_cm radius, and 1.5_m apart. The dielectric medium separating the wires is air with a relative permittivity of 1.04.



Entered Values



Calculated Output

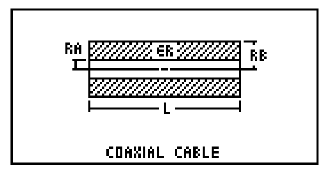
Solution - Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation set.

Known Variables: **εr** = 1.04, **ra** = 1_cm, **d** = 1.5_m

Computed Results: **cl** = 5.77355E-12_F/m

17.6 Coaxial Cable

These three equations describe capacitive and electric field properties of a coaxial cable. The first two equations compute the voltage between the two conductors of the cable carrying a charge of **ρl** per unit length, and an insulator with a relative permittivity **εr.** The inner conductor has a radius **ra** while the outer conductor has a radius **rb.** The last equation computes the cable capacitance **cl** per unit length based on mechanical properties of the cable and insulator.



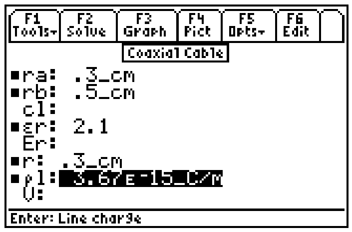
$$V = \frac{\rho l}{2 \cdot \pi \cdot \varepsilon 0 \cdot \varepsilon r} \cdot \ln\left(\frac{rb}{ra}\right)$$ **Eq. 17.6.1**

$$Er = \frac{V}{r \cdot \ln\left(\frac{rb}{ra}\right)}$$ **Eq. 17.6.2**

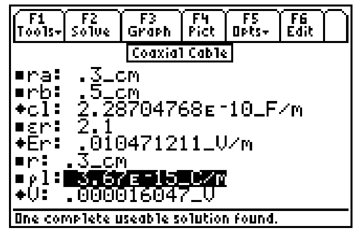
$$cl = \frac{2 \cdot \pi \cdot \varepsilon 0 \cdot \varepsilon r}{\ln\left(\frac{rb}{ra}\right)}$$ **Eq. 17.6.3**

Example 17.6 - A coaxial cable with an inner cable radius of .3_cm, and an outer conductor with an inside radius of .5_cm has a mica filled insulator with a permittivity of 2.1. If the inner conductor carries a linear charge of 3.67E-15_coulombs/m, find the electric field at the outer edge of the inner conductor and potential between the two conductors. Compute the capacitance per m of the cable.

Solution - After examining the problem, all the three equations need to be selected to solve the problem. Press [F2] to display the input variable screen. Enter all the known variables, and press [F2] to solve the selected equation set. The computed results are shown in the screen display below.



Input Values for the example



Computed results

Known Variables: ra = .3_cm, **rb** = .5_cm, **εr** = 2.1, **r** = .3_cm, **ρl** =3.67E-15_coulombs/m.

Computed Results: cl = 2.28705E-10_F/m, **Er** =.010407_V/m and **V**=.000016_V.

17.7 Sphere

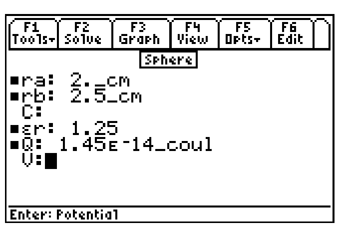
The first equation in this topic computes the potential between two concentric spheres of radius **ra** and **rb**, with a charge **Q**, and separated by a medium with a relative permittivity of **εr**. The second equation computes the electric field outside a sphere at a distance **r** from the center of the sphere. The last equation computes the capacitance between the spheres.

$$V = \frac{Q}{4 \cdot \pi \cdot \varepsilon 0 \cdot \varepsilon r} \cdot \left(\frac{1}{ra} - \frac{1}{rb} \right) \qquad \textbf{Eq. 17.7.1}$$

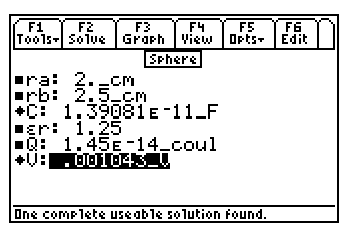
$$Er = \frac{Q}{4 \cdot \pi \cdot \varepsilon 0 \cdot \varepsilon r \cdot r^2} \qquad \textbf{Eq. 17.7.2}$$

$$C = \frac{4 \cdot \pi \cdot \varepsilon 0 \cdot \varepsilon r \cdot ra \cdot rb}{rb - ra} \qquad \textbf{Eq. 17.7.3}$$

Example 17.7 - Two concentric spheres 2_cm and 2.5_cm radius, are separated with a dielectric with a relative permittivity of 1.25. The inner sphere has a charge of 1.45E-14_coulombs. Find the potential difference between the two spherical plates of the capacitor as well as the capacitance.



Entered Values



Computed results

Solution - Upon examining the problem, equations 17.7.1 and 17.7.3 are needed to compute a solution. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen. Enter all the known variables, and press [F2] to solve the selected equation set. The computed results are shown in the screen display shown here.

Known Variables: **ra** = 2_cm , **rb** =2.5_cm, **εr** = 1.25, and **Q** = 1.45E-14_coulombs

Computed Results: **V**= .001043_V, **C** =1.39081E-11_F

Chapter 18 Inductors and Magnetism

Topics in this section focus on electrical and magnetic properties of physical elements.

- ❖ Long Line
- ❖ Long Strip
- ❖ Parallel Wires
- ❖ Loop
- ❖ Coaxial Cable
- ❖ Skin Effect

Variables

A complete list of all the variables used in the various topics of this section are listed below along with the default units used for those variables.

Variable	Description	Unit
θ	Angle	radian
μr	Relative permeability	unitless
a	Loop radius or side of a rectangular loop	m
B	Magnetic field	T
bl	Width of rectangular loop	m
Bx	Magnetic field, x axis	T
By	Magnetic field, y axis	T
D	Center-center wire spacing	m
d	Strip width	m
f	Frequency	Hz
Fw	Force between wires/unit length	N/m
I	Current	A
I1	Current in line 1	A
I2	Current in line 2	A
Is	Current in strip	A/m
L	Inductance per unit length	H/m
L12	Mutual inductance	H
Ls	Loop self-inductance	H
r	Radial distance	m
ra	Radius of inner conductor	m
rb	Radius of outer conductor	m
Reff	Effective resistance	Ω
rr0	Wire radius	m
T12	Torque	N*m
x	x axis distance	m
y	y axis distance	m
z	Distance to loop z axis	m

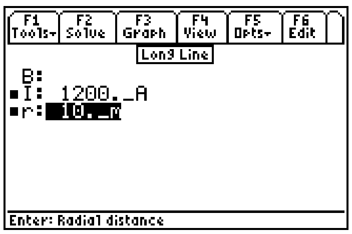
δ	Skin depth	m
ρ	Resistivity	Ω*m

18.1 Long Line

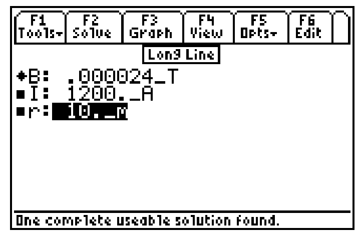
The magnetic field **B** from a current **I** in an infinite wire in an infinitely long line is computed at a distance **r** from the line.

$$B = \frac{\mu 0 \cdot I}{2 \cdot \pi \cdot r} \qquad \textbf{Eq. 18.1.1}$$

Example 18.1 - An overhead transmission line carries a current of 1200_A, 10_m away from the surface of the earth. Find the magnetic field at the surface of the earth.



Input Screen



Calculated Results

Solution - Since there is only equation, press [F2] to display the input screen. Enter all the known variables, and press [F2] to solve the equation. The computed results are shown in the screen display above.

Known Variables: **I** = 1200_A, **r** = 10_m

Computed Results: **B** = 0.000024_T

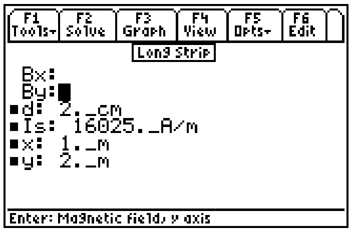
18.2 Long Strip

A thin conducting ribbon strip of width **d** is infinitely long and carrying a current **Is** amperes per meter. The **x** and **y** component of the magnetic field **Bx** and **By** are dependent upon the location described by (x, y) coordinates.

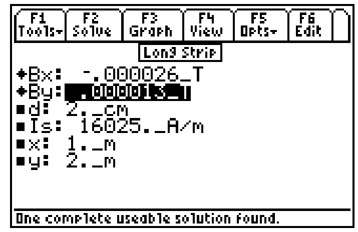
$$Bx = \frac{-\mu 0 \cdot Is}{2 \cdot \pi} \cdot \left(\tan^{-1}\left(\frac{x + \frac{d}{2}}{y} \right) - \tan^{-1}\left(\frac{x - \frac{d}{2}}{y} \right) \right) \qquad \textbf{Eq. 18.2.1}$$

$$By = \frac{\mu 0 \cdot Is}{4 \cdot \pi} \cdot \ln\left(\frac{y^2 + \left(x + \frac{d}{2}\right)^2}{y^2 + \left(x - \frac{d}{2}\right)^2} \right) \qquad \textbf{Eq. 18.2.2}$$

Example 18.2 - A strip transmission line 2_cm wide carries a current of 16025_A/m. Find the magnetic field values 1_m away and 2_m from the surface of the strip.



Input Screen



Calculated Results

Solution - Both equations need to be used to compute the solution. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen display above.

Known Variables: **Is** = 16025_A/m, **d** = 2_cm, **x** = 1_m, **y** = 2_m

Computed Results: **Bx** = -.000026_T, **By** = .000013_T

18.3 Parallel Wires

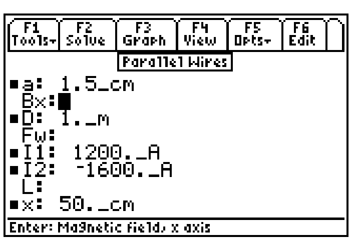
Two thin parallel wires of infinite length carrying currents **I1** and **I2** separated by a distance **D** exert a force **F** newtons/meter between them. The second equation computes the magnetic field **Bx** between the two parallel wires at a distance **x** from the line carrying current **I1.** The final equation in this set computes the inductance **L** from the two wires of diameter **a,** with a spacing of **D**.

$$Fw = \frac{\mu 0 \cdot I1 \cdot I2}{2 \cdot \pi \cdot D}$$ **Eq. 18.3.1**

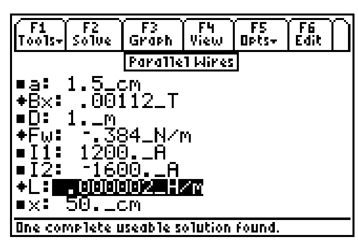
$$Bx = \frac{\mu 0}{2 \cdot \pi} \cdot \left(\frac{I1}{x} - \frac{I2}{D - x} \right)$$ **Eq. 18.3.2**

$$L = \frac{\mu 0}{4 \cdot \pi} + \frac{\mu 0}{\pi} \cdot \cosh^{-1}\left(\frac{D}{2 \cdot a} \right)$$ **Eq. 18.3.3**

Example 18.3 - A pair of aluminum wires 1.5_cm in diameter are separated by 1_m and carry currents of 1200_A and 1600_A in opposite directions. Find the force of attraction, the magnetic field generated midway between the wires and the inductance per unit length resulting from their proximity.



Input Screen



Calculated Results

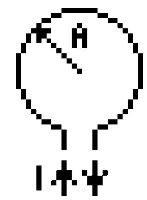
Solution - Upon examining the problem, all the three equations are needed. Press [F2] to display the input screen. Enter all the known variables, and press [F2] to solve the equation set. The computed results are shown in the screen display above.

Known Variables: **I1** = 1200_A, **I2** = -1600_A, **x** = 50_cm, **D** = 1_m, **a** = 1.5_cm

Computed Results: **F** = -.384_N/m, **L** = .000002_H/m, **Bx** = .00112_T

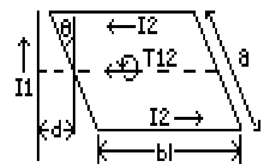
18.4 Loop

The first two equations consider the magnetic properties of wire with a radius **rr0**, bent into a circular loop of radius **a**, carrying a current, **I**. The equation for the magnetic field **B** is computed at any point along the z-axis through the center of the loop at a distance **z** from the plane of the loop. The second equation computes the self-inductance, **Ls**, of the loop.



Circular Loop

The final two equations calculate the torque, **T12** and the inductance, **L12**, of a rectangular loop carrying a current, **I2**, in the proximity of an infinitely long wire carrying a current, **I1**. The rectangular loop has a width, **bl**, *parallel* to its axis of rotation, and a length, **a**, *perpendicular* to the axis of rotation. The loop axis of rotation and the infinitely long wire intersect at a 90 degree angle. The loop's angle of tilt, θ, is relative to the plane containing the loop plane and the infinite wire. In the side of the loop closest to the infinite wire, the current flows in the opposite direction when θ = 0. The distance **d** between wire and the closest edge of the of the loop is measured along the loop axis.



Rectangular Loop

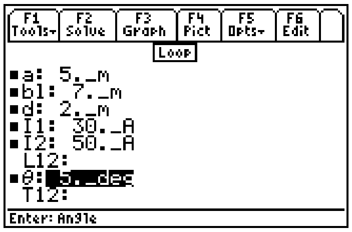
$$B = \frac{\mu 0 \cdot I \cdot a^2}{2 \cdot \left(\sqrt{a^2 + z^2}\right)^3} \qquad \textbf{Eq. 18.4.1}$$

$$Ls = \mu 0 \cdot a \cdot \left(\ln\left(\frac{8 \cdot a}{rr0} \right) - 2 \right) \qquad \textbf{Eq. 18.4.2}$$

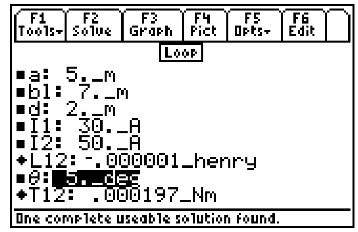
$$L12 = \frac{\mu 0 \cdot a \cdot \cos(\theta)}{2 \cdot \pi} \cdot \ln\left(\frac{bl + d}{d} \right) \qquad \textbf{Eq. 18.4.3}$$

$$T12 = \frac{\mu 0 \cdot a \cdot \sin(\theta)}{2 \cdot \pi} \cdot I1 \cdot I2 \cdot \ln\left(\frac{bl + d}{d} \right) \qquad \textbf{Eq. 18.4.4}$$

Example 18.4 - Calculate the torque and inductance for a rectangular loop of width 7 m and length 5 m, carrying a current of 50 A, separated by a distance of 2 m from a wire of infinite length carrying a current of 30 A. The loop angle of incidence is 5 degrees relative to the parallel plane intersecting the infinite wire.



Input Screen



Calculated Results

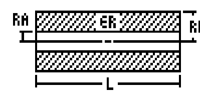
Solution - Upon examining the problem, the last two equations are needed. Select these using the [ENTER]| key and press [F2]to display the input screen. Enter the known variables and press [F2] to solve the selected equation set. The screen display of the input and calculated results are shown below.

Known Variables: **a** = 5._m, **bl** = 7._m, **d** = 2._m, **I1** = 30._A, **I2** = 50._A, **θ** = 5_deg

Computed Results: **L12** = -.000001_henry, **T12** = .000197_N*m

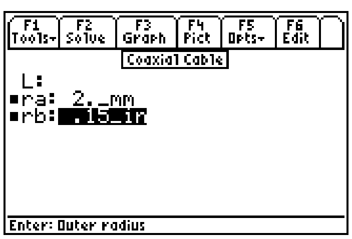
18.5 Coaxial Cable

A coaxial transmission line with an outer radius of inn the inner conductor of **ra** and inner radius of the outer conductor of **rb** is characterized by the inductance L per unit length.

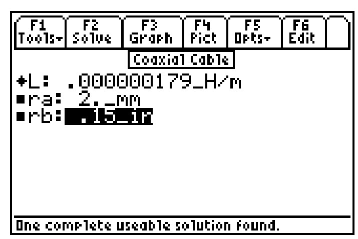


$$L = \frac{\mu 0}{8 \cdot \pi} + \frac{\mu 0}{2 \cdot \pi} \cdot \ln\left(\frac{rb}{ra}\right) \qquad \textbf{Eq. 18.5.1}$$

Example 18.5 - A coaxial cable has an inner conductor radius of 2_mm and the outer conductor radius of .15_in. Find its inductance per meter.



Input Screen



Calculated Results

Solution - Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation. The computed results are shown in the screen display shown here.

Known Variables: **ra** = 2_mm, **rb** = .15_in

Computed Results: **L** = .000000179_H/m

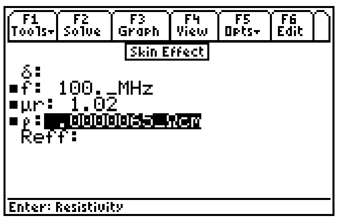
18.6 Skin Effect

These two equations represent the effect of high frequency on the properties of a conductor. The first equation relates the skin depth, **δ,** with the frequency **f** and the resistivity ρ, while the second equation computes the effect of higher frequencies on resistance, **Reff**, in ohms. Since the skin effect is a direct consequence of internal magnetic fields in the conductor, the relative permeability, **μr,** influences these properties.

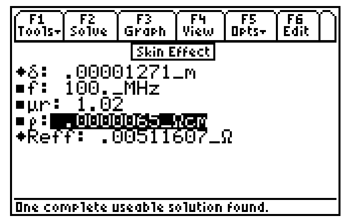
$$\delta = \frac{1}{\sqrt{\frac{\pi \cdot f \cdot \mu 0 \cdot \mu r}{\rho}}} \qquad \textbf{Eq. 18.6.1}$$

$$\mathrm{Re}\,ff = \sqrt{\pi \cdot f \cdot \mu 0 \cdot \mu r \cdot \rho} \qquad \textbf{Eq. 18.6.2}$$

Example 18.6 - Find the effect on depth of signal penetration for a 100 MHz signal in copper with a resistivity of 6.5E-6 _ohm*cm. The relative permeability of copper is 1.02.



Input Screen



Calculated Results

Solution - Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation set. The computed results are shown in the screen display shown here.

Known Variables: **ρ** = 6.5E-6_ohm*cm, **f** = 100_MHz, **μr** = 1.02

Computed Results: **Reff** = .00511637_ohms/square, δ = 12.7050601_μ

Chapter 19 Electron Motion

This section covers equations describing the trajectories of electrons under the influence of electric and magnetic fields. These equations are divided into three topics.

- Electron Beam Deflection
- Thermionic Emission
- Photoemission

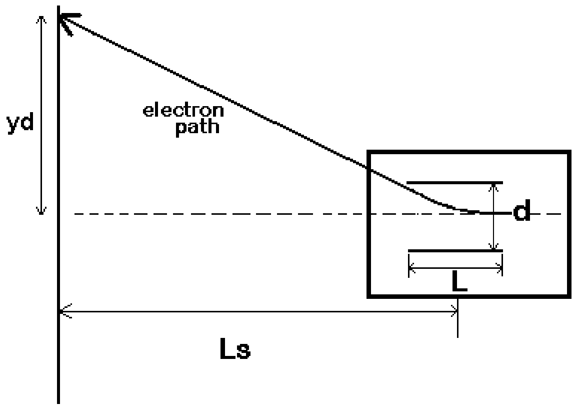
Variables

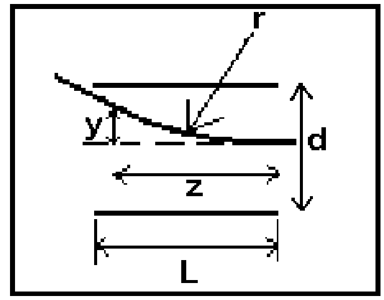
The table below lists all the variables used in this chapter.

Variable	Description	Unit
A0	Richardson's constant	$A/(m^2*K^2)$
B	Magnetic field	T
d	Deflection tube diameter, plate spacing	m
f	Frequency	Hz
f0	Critical frequency	Hz
I	Thermionic current	A
L	Deflecting plate length	m
Ls	Beam length to destination	m
r	Radius of circular path	m
S	Surface area	m^2
T	Temperature	K
v	Vertical velocity	m/s
Va	Accelerating voltage	V
Vd	Deflecting voltage	V
y	Vertical deflection	m
yd	Beam deflection on screen	m
z	Distance along beam axis	m
ϕ	Work function	V

19.1 Electron Beam Deflection

An electron beam that is subjected to an accelerating voltage **Va** achieves a velocity **v** as defined by the first equation. The second equation calculates the radius of curvature **r** as these electrons in the beam move with a velocity **v** passing through a magnetic field **B**. The third equation calculates the y-deflection **yd** at distance **Ls** from the center of deflection plates separated by a distance **d** and length **L** making the approximation that the **Ls**>>**L**. The final equation calculates the vertical displacement **y** *inside* the deflection region with distance **z** from entry into the plate region and subject to a deflecting voltage **Vd.**





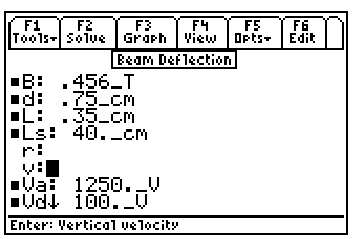
$$v = \sqrt{2 \cdot \frac{q}{me} \cdot Va}$$ **Eq. 19.1.1**

$$r = \frac{me \cdot v}{q \cdot B}$$ **Eq. 19.1.2**

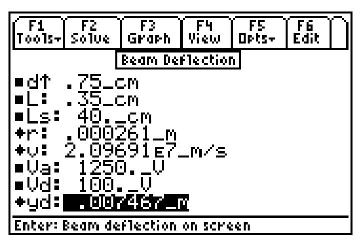
$$yd = \frac{L \cdot Ls}{2 \cdot d \cdot Va} \cdot Vd$$ **Eq. 19.1.3**

$$y = \frac{q \cdot Vd}{2 \cdot me \cdot d \cdot v^2} \cdot z^2$$ **Eq. 19.1.4**

Example 19.1- An electron beam in a CRT is subjected an accelerating voltage of 1250_V. The screen target is 40_cm away from the center of the deflection section. The plate separation is 0.75_cm and the horizontal path length through the deflection region is .35 cm. The deflection region is controlled by a 100_V voltage. A magnetic field of 0.456_T puts the electrons in the beam in a circular orbit. What is the vertical deflection distance of the beam when it reaches the CRT screen?



Display of Input Values



Calculated Results

Solution - The first three equations are needed to solve this problem. Select these by highlighting and pressing [ENTER]. Press [F2] to display the input screen, enter values of all known variables and press [F2] to solve the equation. The computed results are shown in the screen display above.

Known Variables: **Va** = 1250_V, **B** = .456_T, **Vd** = 100_V, **Ls** = 40_cm , **L** = .35_cm, **d** = .75_cm

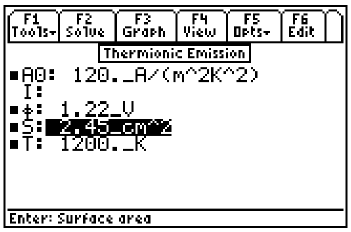
Computed Results: **v** = 2.09691 E7_m/s, **yd** = 0.07467_m, **r** = .000261_m

19.2 Thermionic Emission

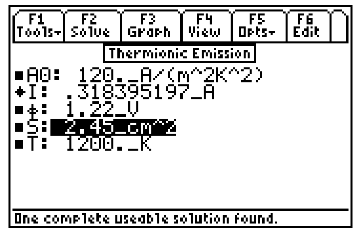
When certain electronic materials are heated to a high temperature **T,** the free electrons gain enough thermal energy, forcing a finite fraction to escape the work function barrier **ϕ** and contribute to the external current **I**. The current also depends directly on the surface area **S** and the so-called Richardson's constant **A0**.

$$I = A0 \cdot S \cdot T^2 \cdot e^{-\frac{q \cdot \phi}{k \cdot T}} \qquad \textbf{Eq. 19.2.1}$$

Example 19.2 - A cathode consists of a cesium coated tungsten with a surface area of 2.45_cm^2. It is heated to 1200_°K in a power vacuum tube. If the Richardson's constant is 120_A/(m^2*K^2), and the work function is 1.22_V, find the current available from such the cathode.



Display of Input Values



Calculated Results

Solution - Since there is only equation, press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen display shown here.

Known Variables: A0 = 120_A/(m^2*K^2), **S** = 2.45_cm^2, **T** = 1200_°K, ϕ = 1.22_V

Computed Results: I = 0.3184_A

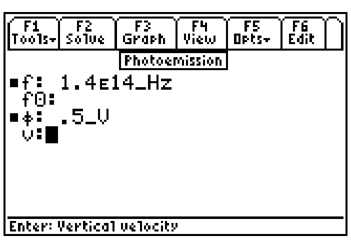
19.3 Photoemission

The two equations in this topic represent the behavior of electrons when excited by photon energy. A light beam with a frequency **f** generates an RMS velocity **v** for electrons that have to overcome a work function ϕ. The second equation shows the threshold frequency for the light beam to extract electrons from the surface of a solid.

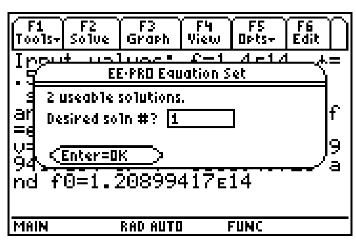
$$h \cdot f = q \cdot \phi + \frac{1}{2} \cdot me \cdot v^2 \qquad \textbf{Eq. 19.3.1}$$

$$f0 = \frac{q \cdot \phi}{h} \qquad \textbf{Eq. 19.3.2}$$

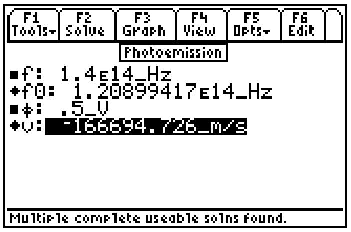
Example 19.3 - A red light beam with a frequency of 1.4E14_Hz, is influencing an electron beam to overcome a barrier of 0.5_V. What is the electron velocity, and find the threshold frequency of the light.



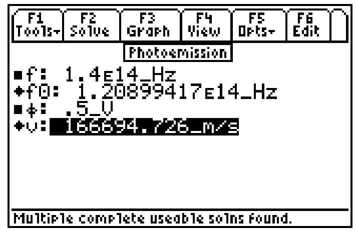
Display of Input Values



EE•Pro display of Multiple Solution Sets



Display of Solution 1



Display of Solution 2

Solution - Both equations are needed to solve the problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. EE•Pro displays a notice that multiple solution sets exist for the entered data, in which case the user needs to select a solution which is meaningful to the application. When viewing one of a multiple solution set, the number of a solution should be entered (1, 2, 3...etc.) followed by pressing [ENTER] twice. The process of solving and choosing a solution set should be repeated each time the user wishes to view a different solution. In this case, a positive electron velocity has physical significance.

Known Variables: ϕ = 0.5_V, **f** = 1.4E14_Hz

Computed Results: **f0** = 1.20899417E14_Hz, **v** = 166694.726_m/s

Chapter 20 Meters and Bridge Circuits

This section covers a variety of topics on meters, commonly used bridge and attenuator circuits. These equations are organized under seven titles.

- Amp, Volt, and Ohmmeter
- Wheatstone Bridge
- Wien Bridge
- Maxwell Bridge
- Owen Bridge
- Symmetrical Resistive Attenuator
- Unsymmetrical Resistive Attenuator

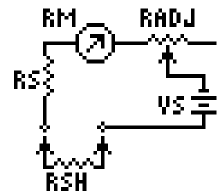
Variables

The following is a list of all the variables used in this section.

Variable	Description	Unit
a	Resistance multiplier	unitless
b	Resistance Multiplier	unitless
c	Resistance Multiplier	unitless
CC3	Capacitance, arm 3	F
CC4	Capacitance, arm 4	F
Cs	Series capacitor	F
Cx	Unknown capacitor	F
DB	Attenuator loss	unitless
f	Frequency	Hz
Ig	Galvanometer current	A
Imax	Maximum current	A
Isen	Current sensitivity	A
Lx	Unknown inductance	unitless
Q	Quality Factor	unitless
Radj	Adjustable resistor	Ω
Rg	Galvanometer resistance	Ω
Rj	Resistance in L pad	Ω
Rk	Resistance in L pad	Ω
Rl	Resistance from left	Ω
Rm	Meter resistance	Ω
Rr	Resistance from right	Ω
RR1	Resistance, arm 1	Ω
RR2	Resistance, arm 2	Ω
RR3	Resistance, arm 3	Ω
RR4	Resistance, arm 4	Ω
Rs	Series resistance	Ω
Rse	Series resistance	Ω

Rsh	Shunt resistance	A
Rx	Unknown resistance	Ω
Vm	Voltage across meter	V
Vmax	Maximum voltage	V
Vs	Source voltage	V
Vsen	Voltage sensitivity	V
ω	Radian frequency	r/s

20.1 Amp, Volt, and Ohmmeter



The three equations in this section describe the use of resistors in extending the range of ammeters, voltmeters and ohmmeters. A shunt resistor **Rsh** increases the range of an ammeter with a current sensitivity **Isen** and a maximum range **Imax.** A series resistance **Rse** can extend the range of a voltmeter. The third equation extends the range of a series ohmmeter with an internal resistance **Rm** and internal voltage **Vs,** with an adjustable resistor **Radj.** In a practical setup, **Radj** is usually set at its midpoint to compensate for variations in the component values, resulting in a systematic error in the measured result.

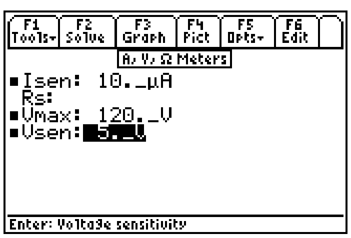
$$Rsh = \frac{Rm \cdot Isen}{\mathrm{Im}ax - Isen} \qquad \textbf{Eq. 20.1.1}$$

$$Rs = \frac{V\max - Vsen}{Isen} \qquad \textbf{Eq. 20.1.2}$$

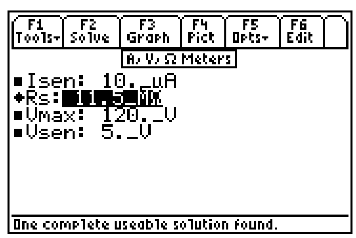
$$Isen = \frac{Vs}{Rs + Rm + \frac{Radj}{2}} \qquad \textbf{Eq. 20.1.3}$$

Example - 20.1

What resistance can be added to a voltmeter with a current sensitivity of 10 μA, and a voltage sensitivity of 5 V to read 120 V?



Input Variables



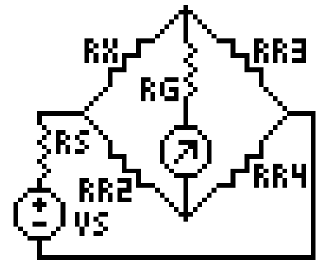
Computed Results

Solution - The second equation needs to be selected to solve this problem. Enter the known values for **Isen, Vmax,** and **Vsen** and press [F2] to solve the equation.

Known Variables: **Isen** = 10._μA, **Vmax** = 120._V, **Vsen** = 5._V

Computed Results: **Rs** = 11.5 MΩ

20.2 Wheatstone Bridge



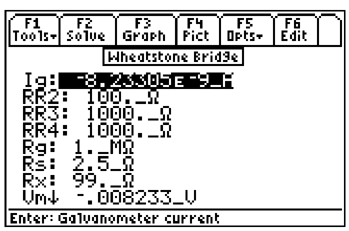
A Wheatstone bridge with four resistor elements **Rx, RR2, RR3** and **RR4** is the foundation of modern measuring systems. When the bridge is balanced, there is no current in the galvanometer circuit. The first equation defines the requirement for a balanced bridge. The voltage across the bridge **Vm** and the galvanometer current **Ig** are calculated in as follows**.** A special function **GALV** calculates the voltage across the bridge, and is a complex function of **Vs, Rx, RR2, RR3, RR4, Rg** and **Rs.**

$$\frac{Rx}{R2} = \frac{R3}{R4}$$ **Eq. 20.2.1**

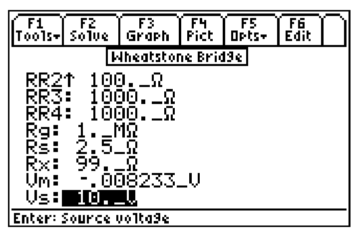
$$Vm = eegalv\left(Rx, RR2, RR3, RR4, Rg, Rs, Vs\right)$$ **Eq. 20.2.2**

$$Ig = \frac{Vm}{Rg}$$ **Eq. 20.2.3**

Example 20.2- A Wheatstone bridge circuit has a resistor **RR2** of 100Ω on the unknown side of the bridge and two 1000 Ω resistors connected on the known side of the bridge. A resistor of 99 Ω was connected to the bridge in the location where the unknown resistor would normally be present. The bridge is supplied by a 10 V source with a resistance of 2.5 Ω. The galvonemetric resistance is 1 MΩ. Find the voltage across the meter and the galvanometric current.



Entered Values
(Lower portion of display)



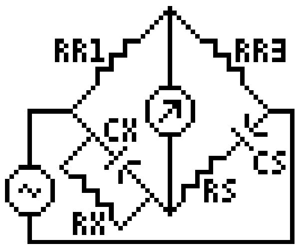
Calculated Results
(Upper portion of display)

Solution - The second and third equations are needed to solve the problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen display above.

Known Variables: **RR2 =** 100._Ω, **RR3**= 1000._Ω, **RR4**=1000._Ω, **Rs**=2.5_Ω, **Rg**=1._MΩ
Vs = 10._V, **Rx** = 99._ Ω

Computed Results: **Vm** = -.008233_V, **Ig** = -8.23305-9_A

20.3 Wien Bridge



A Wien bridge circuit is designed to measure an unknown capacitance **Cx** using a bridge arrangement shown here**.** The circuit has two methods of varying parameters of the bridge to achieve null. In the first approach, **Cx** can be computed in terms of **RR3, RR1**, **Rs** and **Rx** while in the second equation, the source frequency can be used as a key controlling parameter. The bridge can also be used to measure the frequency **f** with the third equation after setting **Cx=Cs**, **Rx=Rs**, and **RR3=2*RR1**. The final equation relates **f** to radian frequency **ω.**

$$\frac{Cx}{Cs} = \left(\frac{RR3}{RR1} - \frac{Rs}{Rx}\right) \qquad \textbf{Eq. 20.3.1}$$

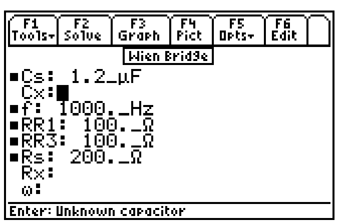
$$Cs \cdot Cx = \frac{1}{\omega^2 \cdot Rs \cdot Rx} \qquad \textbf{Eq. 20.3.2}$$

$$f = \frac{1}{\frac{2}{\pi} \cdot Cs \cdot Rs} \qquad \textbf{Eq. 20.3.3}$$

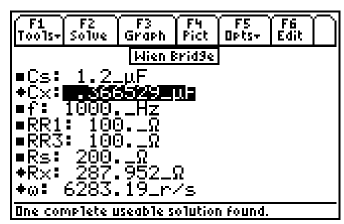
$$\omega = 2 \cdot \pi \cdot f \qquad \textbf{Eq. 20.3.4}$$

Example -20.3

A set of measurements obtained using a Wien bridge is based on the following input. All measurements are carried out at 1000_Hz. The known resistors **RR1** and **RR3** are 100 **Ω** each, the series resistance is 200 **Ω**, and **Cs** is 1.2_µF. Find the values of the unknown RC circuit components and the radian frequency.



Entered Values



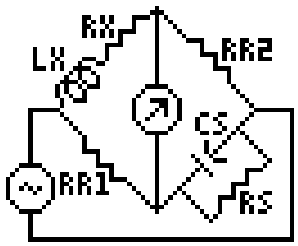
Calculated Results

Solution - Use the first, second and fourth equations to solve the problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve for the unknowns. The computed results are shown in the screen display above.

Known Variables: **Cs** = 1.2_µF, **f** = 1000._Hz, **RR1** = 100._Ω, **RR3** = 100._Ω, **Rs** = 200._ Ω

Computed Results: **Cx** = .366529_µF, **Rx** = 287.952_Ω, **ω** = 6283.19_r/s

20.4 Maxwell Bridge



A Maxwell bridge is designed to measure the inductance **Lx** and its series resistance **Rx** in a bridge circuit. The input stimulus to the bridge circuit is an AC source with a variable frequency and an AC meter detecting a null. The first two equations measure the unknown inductance **Lx** and its resistance **Rx** by varying the capacitance **Cs,** and its parallel resistance **Rs** and bridge arm resistances **RR1** and **RR2.** The third and fourth equations measure the quality factor **Q** by using either measured values of **Lx** and **Rx** or **Cs** and **Rs.** The final equation links the radian frequency **ω** to the frequency **f.**

$$Lx = RR2 \cdot RR3 \cdot Cs \qquad \textbf{Eq. 20.4.1}$$

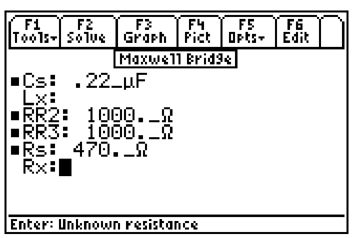
$$Rx = \frac{RR2 \cdot RR3}{Rs} \qquad \textbf{Eq. 20.4.2}$$

$$Q = \omega \cdot \left(\frac{Lx}{Rx}\right) \qquad \textbf{Eq. 20.4.3}$$

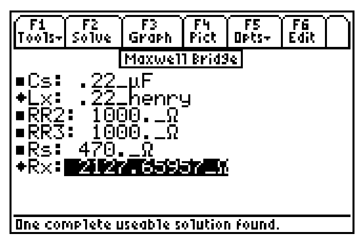
$$Q = \omega \cdot Cs \cdot Rs \qquad \textbf{Eq. 20.4.4}$$

$$\omega = 2 \cdot \pi \cdot f \qquad \textbf{Eq. 20.4.5}$$

Example 20.4- Find the inductance and resistance of an inductive element using the Maxwell bridge. The bridge are resistors are 1000_Ω each with a .22 µF capacitor and 470 Ω parallel resistance. Compute **Lx** and **Rx**.



Entered Values



Calculated Results

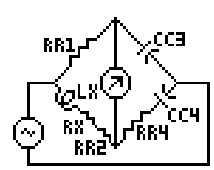
Solution - The first two equations are needed to solve the problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to compute the solution. The calculated results are shown in the screen display above.

Known Variables: **Cs** = .22_µ, **RR2** = 470._Ω, **RR3** = 470._Ω

Computed Results: **Lx** = .22_henry, **Rx** = 2127.65957_Ω

20.5 Owen Bridge

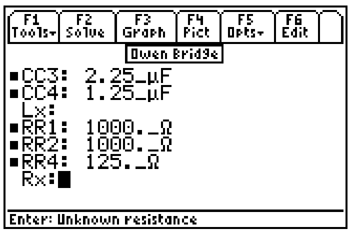
The Owen bridge circuit is an alternative AC bridge circuit used to measure an inductance and its series resistance. The input stimulus to the bridge circuit is typically an AC source with variable frequency and an AC meter detecting a null. The inductance **Lx** is measured in terms of the capacitor **CC3,** and the branch resistance **RR1** and **RR4**. The series resistance **Rx** is measured by a ratio of the capacitors **CC3** and **CC4** and tempered by **RR2**, the variable resistance in the **Lx** arm of the bridge.



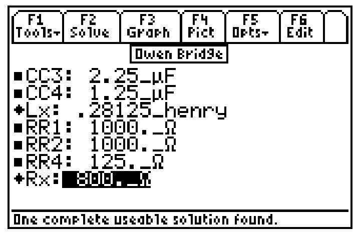
$$Lx = CC3 \cdot RR1 \cdot RR4 \qquad \textbf{Eq. 20.5.1}$$

$$Rx = \frac{CC3 \cdot RR1}{CC4} - RR2 \qquad \textbf{Eq. 20.5.2}$$

Example 20.5- A lossy inductor is plugged into an Owen bridge to measure its properties. The resistance branch has 1000_Ω resistors and a capacitor of 2.25µF on the non-resistor leg and 1.25_µF capacitor on the resistor leg of the bridge. A series resistance of 125_Ω connects the CC4 leg to balance the inductive element.



Entered Values



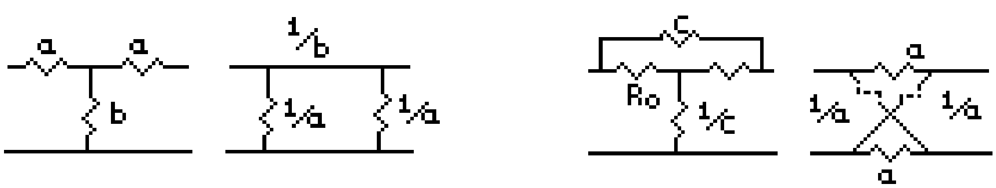
Calculated Results

Solution - Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen display shown here.

Known Variables: **CC3** = 2.25_µF, **CC4** = 1.25_µF, **RR1** = 1000._Ω, **RR2** = 1000. _Ω

Computed Results: **Lx** = .28125_henry, **Rx** = 800_Ω

20.6 Symmetrical Resistive Attenuator



Tee Pad *Pi Pad* *Bridged Pad* *Balanced Pad*

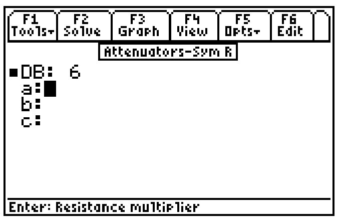
Balanced resistive networks are commonly used as attenuators in transmission line circuits. The three equations below form the basis of the design for resistive attenuators in a Tee pad, a Pi pad, a bridged Tee pad or a balanced pad configuration. These design equations compute the value of the multiplier in the circuit for a given an attenuation loss **dB**, in decibels**.** The values of **a, b** or **c** define the attenuator network. The figure above show the four key various configurations for the attenuator pads. For example, if the terminating resistance is 100 ohms, and a 20 db attenuation is desired, computing a and b will be adequate to design a Tee pad or a Pi pad. The resistance of each leg is computed by the terminating resistance by the multiplier factor.

$$a = \frac{\left(10^{\frac{DB}{20}} - 1\right)}{10^{\frac{DB}{20}} + 1}$$ **Eq. 20.6.1**

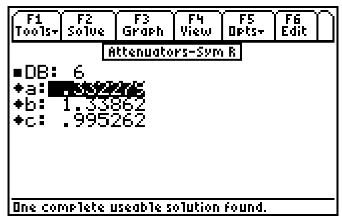
$$b = \frac{2 \cdot 10^{\frac{DB}{20}}}{10^{\frac{DB}{10}} - 1}$$ **Eq. 20.6.2**

$$c = \left(10^{\frac{DB}{20}} - 1\right)$$ **Eq. 20.6.3**

Example 20.6- Design a symmetrical and Bridges Tee attenuator for a 50 Ω load and a 6 DB loss.



Entered Values



Calculated Results

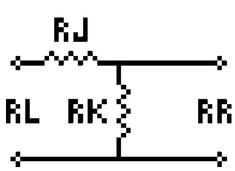
Solution - All three equations are needed. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown above.

Known Variables: **DB** = 6

Computed Results: **a** = .33279 , **b** = 1.33862 , **c** =.995262

Having computed the values of the multipliers a and b, a Tee pad can be constructed using the values **Ro*a** (or 16.6395_ohms) for the two sides of the Tee, and a calue **Ro*b** (or 66.931_ohms) for the vertical leg of the network.

20.7 Unsymmetrical Resistive Attenuator



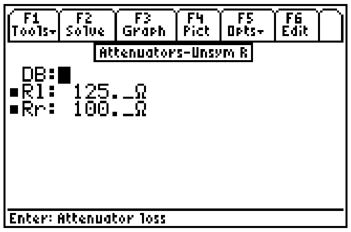
This section contains equations for unsymmetrical resistive attenuator design. These equations compute the resistance values for a minimum loss L pad of an unsymmetrical network with an impedance **Rl** to the left of the L-network and an impedance **Rr** to the right of the network. The first two equations calculate **Rj** and **Rk**, the resistor values of the L network. The third equation determines the minimum loss of signal strength **DB**.

$$Rj = Rl - \frac{Rk \cdot Rr}{Rk + Rr}$$ **Eq. 20.7.1**

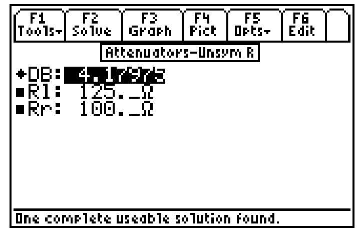
$$Rk = \sqrt{\frac{Rl \cdot Rr^2}{Rl - Rr}}$$ **Eq. 20.7.2**

$$DB = 20 \cdot \log_{10} \cdot \left(\sqrt{\frac{Rl - Rr}{Rr}} + \sqrt{\frac{Rl}{Rr}} \right) \quad \textbf{Eq. 20.7.3}$$

Example 20.7- A network needs to be patched by an unsymmetrical attenuator. The network to the right of the attenuator presents a resistive load of 125 Ω, while the network to the left of the attenuator possesses an impedance of 100 Ω. What is the expected loss in dB?



Entered Values



Calculated Results

Solution - The last equation is needed to compute the signal attenuation. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen display above.

Known Variables: **Rl** = 125_Ω, **Rr** = 100_Ω

Computed Result: **DB** = 4.17975

Rj and **Rk** can be computed from the first two equations above.

Chapter 21 RL and RC Circuits

This chapter covers the natural and transient properties of simple RL and RC circuits. The section is organized under six topics.

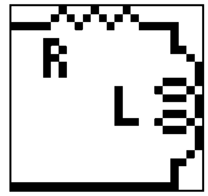
- RL Natural Response
- RC Natural Response
- RL Step Response
- RC Step Response
- RL Series to Parallel
- RC Series to Parallel

Variables

The table below lists all the variables used in this chapter, along with a brief description and appropriate units.

Variable	Description	Unit
C	Capacitor	F
Cs	Series capacitance	F
Cp	Parallel capacitance	F
f	Frequency	Hz
iC	Capacitor current	A
iL	Inductor current	A
I0	Initial inductor current	A
L	Inductance	H
Lp	Parallel inductance	H
Ls	Series inductance	H
Qp	Q, parallel circuit	unitless
Qs	Q, series circuit	unitless
R	Resistance	Ω
Rp	Parallel resistance	Ω
Rs	Series resistance	Ω
τ	Time constant	s
t	Time	s
vC	Capacitor voltage	V
vL	Inductor voltage	V
V0	Initial capacitor voltage	V
Vs	Voltage stimulus	V
ω	Radian frequency	r/s
W	Energy dissipated	J

21.1 RL Natural Response



These four equations define all the key properties for the natural response of an RL circuit with no energy sources. The first equation shows the characteristic time constant **τ** in terms of the resistance **R** and the inductance **L**. The second equation computes the decay of the voltage **vL** across the inductor with an initial current **I0**. The third equation displays the decay of the inductor current **iL**. The final equation expresses the energy dissipation characteristic **W** of the circuit for the specified conditions.

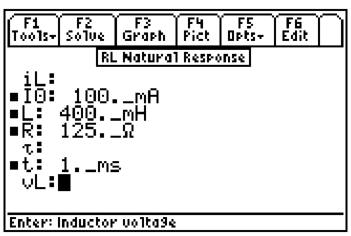
$$\tau = \frac{L}{R} \qquad \textbf{Eq. 21.1.1}$$

$$vL = I0 \cdot R \cdot e^{-\frac{t}{\tau}} \qquad \textbf{Eq. 21.1.2}$$

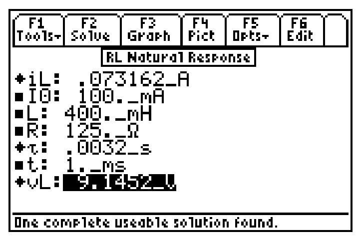
$$iL = I0 \cdot e^{-\frac{t}{\tau}} \qquad \textbf{Eq. 21.1.3}$$

$$W = \frac{1}{2} \cdot L \cdot I0^2 \cdot \left(1 - e^{-\frac{2 \cdot t}{\tau}}\right) \qquad \textbf{Eq. 21.1.4}$$

Example 21.1 An RL circuit consists of a 400_mH inductor and a 125_Ω resistor. With an initial current of 100_mA, find the inductor current and voltage across the inductor 1_ms and 10_ms after the switch has been closed.



Entered Values



Calculated Results (1 ms)

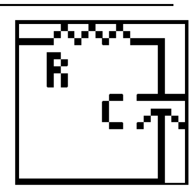
Solution - Upon examining the problem, the first three equations are needed to solve the problem. Select these equations using the highlight bar and pressing [ENTER], press [F2] to display the input screen, enter all the known variables and press [F2] to solve. Perform the computations for a time of 1_ms, write down all the results, enter 10 ms for t and press [F2] to recalculate the results for the new time entry.

Known Variables: **I0** = 100_mA, **L** = 400_mH, **R** = 125_Ω, **t** = 1_ms, 10_ms.

Computed Results: **iL** = .073162_A , **vL** = 9.1452_V after 1_ms
iL = 4.39369_mA , **vL** = 0.549212_V after 10_ms

21.2 RC Natural Response

These four equations define the natural response of an RC circuit with no energy sources. The first equation specifies the characteristic time constant **τ** in terms of the resistance **R** and the



capacitance **C**. The second equation computes the decay of the voltage **vC** across the capacitor with an initial voltage of **V0**. The third equation shows the decay of the capacitor current **iC**. The final equation computes the energy dissipation **W**.

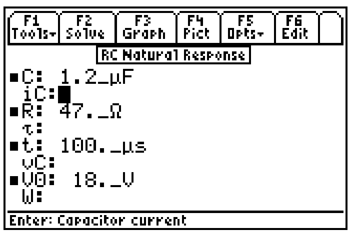
$$\tau = R \cdot C \qquad \textbf{Eq. 21.2.1}$$

$$vC = V0 \cdot e^{-\frac{t}{\tau}} \qquad \textbf{Eq. 21.2.2}$$

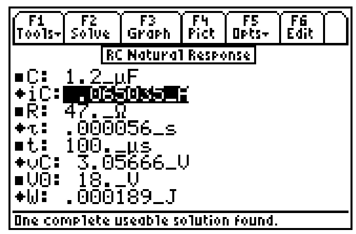
$$iC = \frac{V0}{R} \cdot e^{-\frac{t}{\tau}} \qquad \textbf{Eq. 21.2.3}$$

$$W = \frac{1}{2} \cdot C \cdot V0^2 \cdot \left(1 - e^{-\frac{2 \cdot t}{\tau}}\right) \qquad \textbf{Eq. 21.2.4}$$

Example 21.2- An RC circuit consists of a 1.2_µfarad capacitor and a 47_Ω resistor. The capacitor has been charged to 18_V. A switch disconnects the energy source. Find the voltage across the capacitor 100_µs later. How much energy is left in the capacitor?



Entered Values



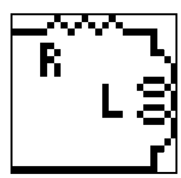
Calculated Results

Solution - Upon examining the problem, all of the equations are needed to solve the problem. Press [F2] to display the input screen. Enter all the known variables and press [F2] to solve the set of equations.

Known Variables: **C** = 1.2_µF, **R** = 47_Ω, **V0** = 18_V, **t** = 100_µs

Computed Results: **vC** = 3.05666_V, **iC** = .065035_A, **W** = .000189_ J, **τ** = .000056_s

21.3 RL Step Response



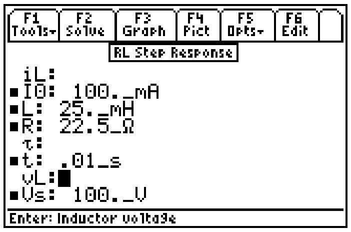
These equations describe the response of an inductive circuit to a voltage step stimulus. The first equation calculates the time constant **τ** in terms of the inductance **L** and the resistance **R**. The last two equations compute the inductor voltage **vL** and current **iL** in terms of the step stimulus **Vs**, initial condition **I0**, time **t**, and time constant **τ.**

$$\tau = \frac{L}{R} \qquad \textbf{Eq. 21.3.1}$$

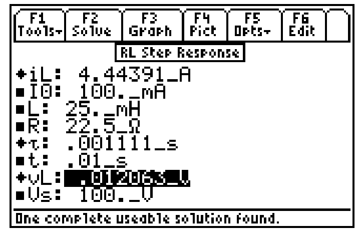
$$vL = \cdot(Vs - I0 \cdot R) \cdot e^{-\frac{t}{\tau}} \qquad \textbf{Eq. 21.3.2}$$

$$iL = \frac{Vs}{R} + \left(I0 - \frac{Vs}{R}\right) \cdot e^{-\frac{t}{\tau}} \qquad \textbf{Eq. 21.3.3}$$

Example 21.3 - An inductor circuit consisting of 25_mH inductance and 22.5_Ω resistance. Prior to applying a 100_V stimulus, the inductor carries a current of 100_mA. Find the current in and the voltage across the inductor after .01_s.



Entered Values



Calculated Results

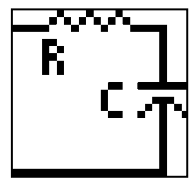
Solution - Upon examining the problem, all three equations are need to be solve the problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to compute the solution.

Known Variables: **L** = 25_mH, **R** = 22.5_Ω, **I0** = 100_mA, **t** = .01_s, **Vs** = 100_V.

Computed Results: **iL** = 4.44391_A, **vL** =.012063_V

21.4 RC Step Response

These three equations describe the step response properties of an RC circuit. The first equation defines the characteristic time constant, **τ**, in terms of the resistance **R** and the capacitance **C**. The last two equations compute the capacitor voltage **vC** and current **iC** in terms of the step stimulus voltage **Vs**, the initial capacitor voltage **V0**, time **t**, and time constant **τ**.

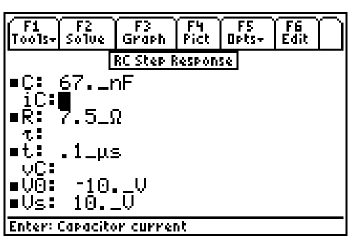


$$\tau = R \cdot C \qquad \textbf{Eq. 21.4.1}$$

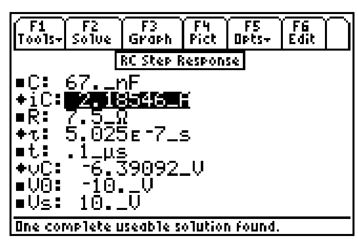
$$vC = Vs + (V0 - Vs) \cdot e^{-\frac{t}{\tau}} \qquad \textbf{Eq. 21.4.2}$$

$$iC = \frac{(Vs - V0)}{R} \cdot e^{-\frac{t}{\tau}} \qquad \textbf{Eq. 21.4.3}$$

Example 21.4- A 10_V step function is applied to an RC circuit with a 7.5_Ω resistor and a 67_nfarad capacitor. The capacitor was charged to an initial potential of –10_V. What is the voltage across the.1_µs after the step function has been applied?



Entered Values



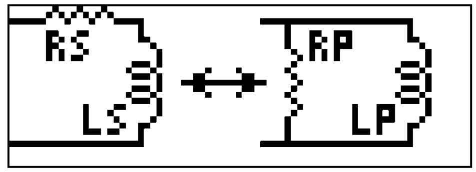
Calculated Results

Solution - All three equations are needed to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve.

Known Variables: **V0** = -10_V, **C** = 67_nfarad, **R** = 7.5_Ω, **t** = .1_µs, **Vs** = 10_V

Computed Results: **vC** = -6.3909_V, **iC** = 2.185455_A

21.5 RL Series to Parallel



The equations in this topic show the equivalence relationship between a series RL circuit (**Rs** and **Ls)** and its parallel equivalent circuit, **Rp**, **Lp**. The first equation translates the frequency, **f,** to its radian frequency, ω. The second equation specifies the quality factor **Qs** for **Rs** and **Ls**. The third and fourth equations define the values of **Rp** and **Lp** in terms of **Rs, Ls** and ω**.** The fifth equation computes Qp in terms of **Rp, Lp** and ω. The sixth and seventh equations calculate **Rs** and **Ls** in terms of **Rp**, **Lp** and ω. The eighth and ninth equations compute **Rp** and **Lp** in terms of **Rs, Ls** and **Qs**. The last two of equations calculate **Rs** and **Ls** in terms of **Rp, Lp** and **Qp.**

$$\omega = 2 \cdot \pi \cdot f \qquad \textbf{Eq. 21.5.1}$$

$$Qs = \frac{\omega \cdot Ls}{Rs} \qquad \textbf{Eq. 21.5.2}$$

$$Rp = \frac{Rs^2 + \omega^2 \cdot Ls^2}{Rs} \qquad \textbf{Eq. 21.5.3}$$

$$Lp = \frac{Rs^2 + \omega^2 \cdot Ls^2}{\omega^2 \cdot Ls} \qquad \textbf{Eq. 21.5.4}$$

$$Qp = \frac{Rp}{\omega \cdot Lp} \qquad \textbf{Eq. 21.5.5}$$

$$Rs = \frac{\omega^2 \cdot Lp^2 \cdot Rp}{Rp^2 + \omega^2 \cdot Lp^2} \qquad \textbf{Eq. 21.5.6}$$

$$Ls = \frac{Rp^2 \cdot Lp}{Rp^2 + \omega^2 \cdot Lp^2} \qquad \textbf{Eq. 21.5.7}$$

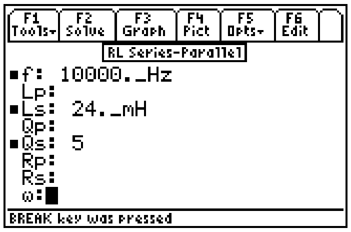
$$Rp = Rs \cdot \left(1 + Qs^2\right) \qquad \textbf{Eq. 21.5.8}$$

$$Lp = Ls \cdot \left(1 + \frac{1}{Qs^2}\right) \qquad \textbf{Eq. 21.5.9}$$

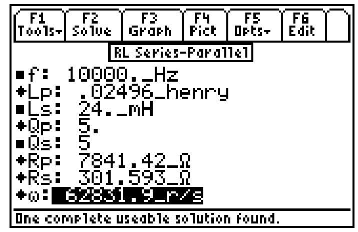
$$Rs = \frac{Rp}{1 + Qp^2} \qquad \textbf{Eq. 21.5.10}$$

$$Ls = \frac{Qp^2 \cdot Lp}{1 + Qp^2} \qquad \textbf{Eq. 21.5.11}$$

Example 21.5 - A 24_mH inductor has a quality factor of 5 at 10000_Hz. Find its series resistance and the parallel equivalent circuit parameters.



Entered Values



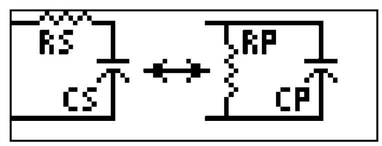
Calculated Results

Solution - Upon examining the problem, the first six equations need to be solved as a set. Select these equations, and press [F2] to display the input screen enter all the known variables and press [F2] to solve. The computed results are shown in the screen display shown here.

Known Variables: **Ls** = 24_mH, **Qs** = 5, **f** = 10000_Hz

Computed Results: **Lp** = .02496_H, **Rs** = 301.593_Ω, **Rp** = 7841.42_Ω, **ω** = 62831.9 r/s

21.6 RC Series to Parallel



The equations in this topic show the equivalence between a series RC circuit (**Rs** and **Cs)** and its parallel equivalent circuit with values **Rp**, and **Cp**. The first equation converts frequency, **f**, to its radian equivalent radian frequency, **ω**. The second equation computes the quality factor **Qs** in terms of **ω, Rs** and **Cs**. The next two equations compute the parallel equivalent values as a function of **Rs, Cs** and **ω**. The fifth equation defines Qp in terms of **Rp, Cp** and **ω.** The sixth and seventh equations compute **Rs** and **Cs** in terms of **Rp, Cp** and **ω**. The last four equations describe the relationships between **Rs, Cs, Rp, Cp, Qs** and **Qp** in a symmetrical and complementary form.

$$\omega = 2 \cdot \pi \cdot f$$ **Eq. 21.6.1**

$$Qs = \frac{1}{\omega \cdot Rs \cdot Cs}$$ **Eq. 21.6.2**

$$Rp = Rs \cdot \left(1 + \frac{1}{\omega^2 \cdot Rs^2 \cdot Cs^2}\right)$$ **Eq. 21.6.3**

$$Cp = \frac{Cs}{1 + \omega^2 \cdot Cs^2 \cdot Rs^2}$$ **Eq. 21.6.4**

$$Qp = \omega \cdot Rp \cdot Cp$$ **Eq. 21.6.5**

$$Rs = \frac{Rp}{1 + \omega^2 \cdot Rp^2 \cdot Cp^2}$$ **Eq. 21.6.6**

$$Cs = \frac{1 + \omega^2 \cdot Rp^2 \cdot Cp^2}{\omega^2 \cdot Rp^2 \cdot Cp}$$ **Eq. 21.6.7**

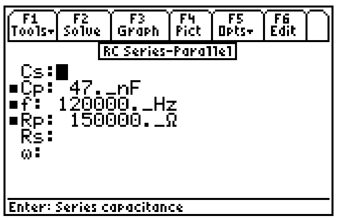
$$Rp = Rs \cdot \left(1 + Qs^2\right)$$ **Eq. 21.6.8**

$$Cp = \frac{Cs}{1 + \frac{1}{Qs^2}}$$ **Eq. 21.6.9**

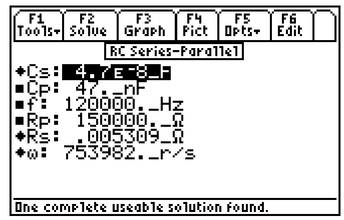
$$Rs = \frac{Rp}{1 + Qp^2}$$ **Eq. 21.6.10**

$$Cs = \frac{Cp \cdot \left(1 + Qp^2\right)}{Qp^2}$$ **Eq. 21.6.11**

Example 21.6 - A parallel RC Circuit consists of a 47_µfarad and 150000_Ω at 120000_Hz. Find its series equivalent.



Entered Values



Calculated Results

Solution - Upon examining the problem, use equations 21.6.1, 21.6.3, 21.6.4, 21.6.6, 21.6.7 are needed to solve the problem. Select these by highlighting each equation and pressing the ENTER key. Press F2 to display the input screen, enter all the known variables and press F2 to solve.

Known Variables: **Cp** = 47_nF, **Rp** = 150000_Ω, **f** = 120000_Hz

Computed Results: **Rs** = 5.30873E-3_Ω, **Cs** = 4.700E-8_F

Chapter 22 RLC Circuits

The essential equations for computing impedance and admittance, natural response, and transient behavior of RLC circuits are organized into six topics.

- ❖ Series Impedance
- ❖ Parallel Admittance
- ❖ RLC Natural Response
- ❖ Underdamped Transient
- ❖ Critically-Damped Transient
- ❖ Overdamped Transient

Variables

All the variables used here are listed along with a brief description and units.

Variable	**Description**		**Unit**
α	Neper's frequency		rad/s
A1	Constant		V
A2	Constant		V
B	Susceptance		S
B1	Constant		V
B2	Constant		V
BC	Capacitive susceptance		S
BL	Inductive susceptance		S
C	Capacitance		F
D1	Constant		V/s
D2	Constant		V
f	Frequency		Hz
G	Conductance		S
I0	Initial inductor current		A
L	Inductance		H
θ	Phase angle		rad
R	Resistance		Ω
s1	Characteristic frequency		rad/s
s2	Characteristic frequency		rad/s
s1i	Characteristic frequency	(imaginary)	rad/s
s1r	Characteristic frequency	(real)	rad/s
s2i	Characteristic frequency	(imaginary)	rad/s
s2i	Characteristic frequency	(real)	rad/s
t	Time		s
v	Capacitor voltage		V
V0	Initial capacitor voltage		V
ω	Radian Frequency		rad/s
ωd	Damped radian frequency		rad/s

ω0	Classical radian frequency	rad/s
X	Reactance	Ω
XXC	Capacitive reactance	Ω
XL	Inductive reactance	Ω
Ym	Admittance – magnitude	S
Zm	Impedance – magnitude	S

22.1 Series Impedance

The series impedance of an RLC circuit is calculated using the first two equations. The magnitude |Zm| and phase angle **θ** of the impedance is calculated from the resistance the **R** and reactance **X** in the first two equations. The reactance **X** in the third equation is calculated in terms of the inductive reactance **XL.** In the fifth equation, the capacitive reactance **XXC** is calculated from the frequency **ω** and capacitance **C**. In the final equation, **ω** is expressed in terms of the oscillation frequency, **f**.

$$\left(\left|Zm\right|\right)^2 = R^2 + X^2 \qquad \textbf{Eq. 22.1.1}$$

$$\theta = \tan^{-1}\left(\frac{X}{R}\right) \qquad \textbf{Eq. 22.1.2}$$

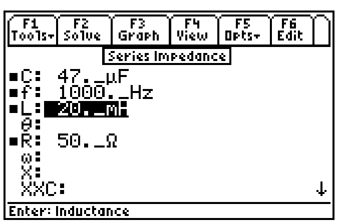
$$X = XL + XXC \qquad \textbf{Eq. 22.1.3}$$

$$XL = \omega \cdot L \qquad \textbf{Eq. 22.1.4}$$

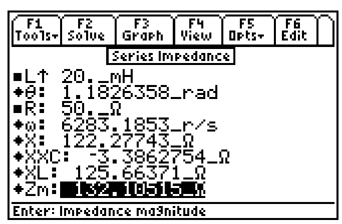
$$XXC = \frac{-1}{\omega \cdot C} \qquad \textbf{Eq. 22.1.5}$$

$$\omega = 2 \cdot \pi \cdot f \qquad \textbf{Eq. 22.1.6}$$

Example 22.1 - A circuit consists of a 50 ohm resistor in series with a 20_mhenry inductor and 47_μfarad capacitor. At a frequency of 1000_Hz, calculate the impedance, phase angle of impedance, .



Entered Values



Calculated Results

Solution - All of the equations are needed to compute the solution for this problem. Press [F2] to display the input screen ,enter all of the known variables and press [F2] to solve for the unknowns.

Known Variables: **L** = 20_mhenry, **R**=50_ohm **C**=47_μfarad, **f**=1000_Hz

Computed Results: **ω** = 6283.19_rad/s, **XL**=125.664_Ω, **XXC**=-3.38628_Ω, **X**=122.277_Ω, **Zm** = 132.105_Ω, **θ**=1.1826_rad.

22.2 Parallel Admittance

The admittance of a parallel RLC circuit consists of a magnitude, **Ym**, and phase angle **θ.** Both can be calculated in terms of the conductance **G** and susceptance **B**. The conductance **G** is expressed in terms of resistance **R**, while the susceptance **B** is expressed in terms of the inductive and capacitive components **BL** and **BC.**

$$(|Ym|)^2 = G^2 + B^2 \qquad \textbf{Eq. 22.2.1}$$

$$\theta = \tan^{-1}\left(\frac{G}{B}\right) \qquad \textbf{Eq. 22.2.2}$$

$$G = \frac{1}{R} \qquad \textbf{Eq. 22.2.3}$$

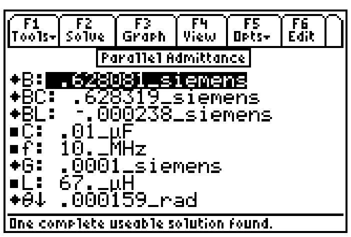
$$B = BL + BC \qquad \textbf{Eq. 22.2.4}$$

$$BL = \frac{-1}{\omega \cdot L} \qquad \textbf{Eq. 22.2.5}$$

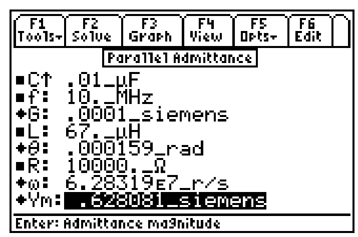
$$BC = \omega \cdot C \qquad \textbf{Eq. 22.2.6}$$

$$\omega = 2 \cdot \pi \cdot f \qquad \textbf{Eq. 22.2.7}$$

Example 22.2 - A parallel RLC Circuit consists of a 10,000 ohm resistor, 67 µhenry and .01 µfarads. Find the circuit admittance parameters at a frequency of 10 MHz.



Input and calculated results (upper half)



Input and calculated results (lower half)

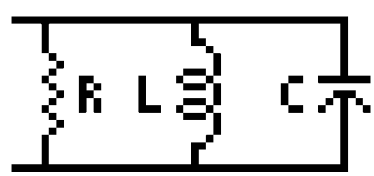
Solution - All of the equations need to be used to solve this problem. Press F2 to display the input screen and enter the values of all known variables. Press F2 to compute the unknown parameters.

Known Variables: **f** = 10_MHz, **R** = 10000_ohm, **L** = 67_µhenry, **C** = .01_µfarad.

Computed Results: **Ym** = .6281_ siemens, **G** = .0001_ siemens, **BL** = -.0002_siemens, **BC** = .6283_ siemens, **θ** = .000159_rad, **ω** = 62831853.0718_rad/s

22.3 RLC Natural Response

These equations compute the complex frequencies of an RLC circuit. In general, every RLC circuit has two complex frequencies **s1** and **s2** with real and imaginary parts **s1r**, **s1i**, **s2r**, and **s2i.** These frequencies are complex conjugates of each other which are computed from the resonant frequency **ω0**, and Neper's frequency **α**, defined by the final two equations.



$$s1r = real\left(-\alpha + \sqrt{\alpha^2 - \omega 0^2}\right) \qquad \textbf{Eq. 22.3.1}$$

$$s1i = imag\left(-\alpha + \sqrt{\alpha^2 - \omega 0^2}\right) \qquad \textbf{Eq. 22.3.2}$$

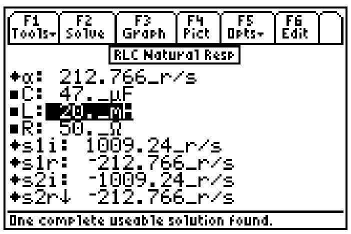
$$s2r = real\left(-\alpha - \sqrt{\alpha^2 - \omega 0^2}\right) \qquad \textbf{Eq. 22.3.3}$$

$$s2i = imag\left(-\alpha - \sqrt{\alpha^2 - \omega 0^2}\right) \qquad \textbf{Eq. 22.3.4}$$

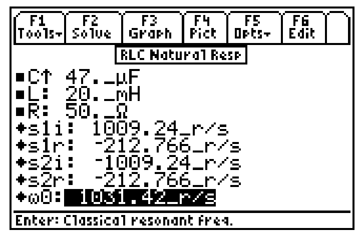
$$\omega 0 = \sqrt{\frac{1}{L \cdot C}} \qquad \textbf{Eq. 22.3.5}$$

$$\alpha = \frac{1}{2 \cdot R \cdot C} \qquad \textbf{Eq. 22.3.6}$$

Example 22.3 – A series RLC circuit of Example 22.1 is used to compute the circuit parameters.



Input and calculated results (upper half)



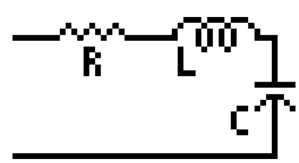
Input and calculated results (lower half)

Solution - All of the equations are needed to solve the parameters from these given set of variables. Press [F2] to access the input screen and enter all known variables, press [F2] to solve for the unknowns.

Known Variables: **L** = 20_mhenry, **R** = 50_ohm, **C** = 47_μfarad.

Computed Results: **s1r** = -212.7660_rad/s, **s1i** = 1009.2376_rad/s, **ω0** = 1031.4212_rad/s, **s2r** = -212.7660_rad/s, **s2i** = -1009.2376_rad/s

22.4 Underdamped Case



The equations in this section represent the transient response of an underdamped RLC circuit. The classical radian frequency **ω0** is calculated from the inductance, **L** and the capacitance, **C** in Equation 22.4.1. The Neper's frequency α is shown by the second equation. ***The condition for an underdamped system is that* ω0 >**α. The damped resonant frequency **ωd** is expressed in equation 22.4.3 in terms of **ω0** and α**.** The voltage across the capacitor **v**, is defined in terms of two constants **B1** and **B2.** **B1** is equivalent to the initial capacitor voltage **V0,** and **B2** is related to the initial inductor current **I0, C, ωd** and α resistance **R**. The voltage **v** has an oscillation frequency of **ωd**.

$$\omega 0 = \sqrt{\frac{1}{L \cdot C}} \qquad \textbf{Eq. 22.4.1}$$

$$\alpha = \frac{1}{2 \cdot R \cdot C} \qquad \textbf{Eq. 22.4.2}$$

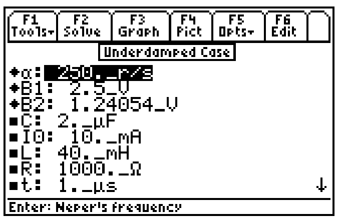
$$\omega d = \sqrt{\omega 0^2 - \alpha^2} \qquad \textbf{Eq. 22.4.3}$$

$$v = B1 \cdot e^{-\alpha \cdot t} \cdot \cos(\omega d \cdot t) + B2 \cdot e^{-\alpha \cdot t} \cdot \sin(\omega d \cdot t) \qquad \textbf{Eq. 22.4.4}$$

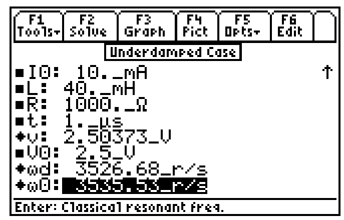
$$B1 = V0 \qquad \textbf{Eq. 22.4.5}$$

$$B2 = -\frac{\alpha}{\omega d} \cdot (V0 - 2 \cdot I0 \cdot R) \qquad \textbf{Eq. 22.4.6}$$

Example 22.4 - A parallel RLC circuit is designed with a 1000 Ω resistor, a 40 mH inductor and a 2 μF capacitor. The initial current in the inductor is 10 mA and the initial charge in the capacitor is 2.5 V. Calculate the resonant frequency and the voltage across the capacitor 1 μs after the input stimulus has been applied.



Calculated Results (Upper display)



Calculated Results (Lower display)

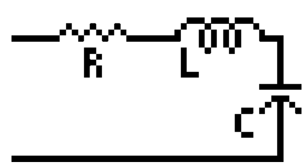
Solution - All of the equations need to be selected to solve this problem. Press [F2] and enter the known variables followed by a second press of [F2] to solve for the unknowns.

Known Variables: **C** = 2._μF, **I0** = 10._mA, **L** = 40._mH, **R** = 1000._Ω, **t** = 1._μs

Computed Results: **α** = 250._r/s, **B1** = 2.5._V, **B2** = 1.24054_V, **v** = 2.50373_V, **ωd** = 3526.68_r/s, **ω0** = 3535.53_r/s

22.5 Critical-Damping

The equations in this section represent the RLC transient response of a critically-damped circuit. *The condition for a critically-damped system is* **ω0 = α**. The first two equations define the Neper's frequency **α** and the classical resonant frequency **ω0**. The transient response to a step function stimulus of a voltage across the capacitor **v**, is expressed in terms of constants **D1** and **D2**, **α**, and time **t**. The constants **D1** and **D2** are defined in terms of the capacitor voltage **V0** and the initial inductor current **I0**.



$$\alpha = \frac{1}{2 \cdot R \cdot C} \qquad \textbf{Eq. 22.5.1}$$

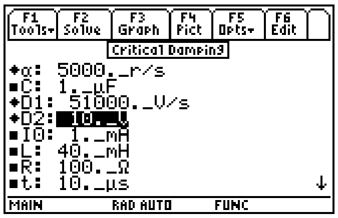
$$\omega 0 = \sqrt{\frac{1}{L \cdot C}} \qquad \textbf{Eq. 22.5.2}$$

$$v = D1 \cdot e^{-\alpha \cdot t} \cdot t + D2 \cdot e^{-\alpha \cdot t} \qquad \textbf{Eq. 22.5.3}$$

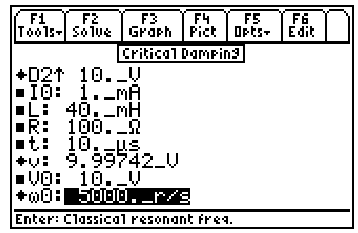
$$D1 = \frac{I0}{C} + \alpha * V0$$ **Eq. 22.5.4**

$$D2 = V0$$ **Eq. 22.5.5**

Example 22.5 - A critically damped RLC circuit consists of a 100 Ω resistor in series with a 40 mH inductor and a 1 μF capacitor. The initial inductor current is 1 mA and the initial capacitor charge is 10 V. Find the voltage across the capacitor after 10 μs.



Calculated Results (Upper display)



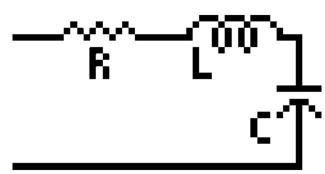
Calculated Results (Lower display)

Solution - All of the equations need to be selected to solve this problem. Press [F2] and enter the known variables followed by a second press of [F2] to solve for the unknowns.

Known Variables: **C** = 1._μF, **I0** = 1_mA, **L** = 40._mH, **R** = 100._Ω, **t** = 10._μs, **V0** = 10._V,

Computed Results: **D1** = 51000._V/s, **D2** = 10._V, **v** = 9.99742_V, **ω0** = 5000._r/s, **α** = 5000._r/s

22.6 Overdamped Case



These equations show the transient performance of an overdamped RLC circuit. ***The condition for an overdamped system is that α > ω0***. The first two equations define the characteristic frequencies **s1** and **s2** in terms of the Neper's frequency α and the classical resonant frequency **ω0**. The transient response to a step function stimulus of the voltage is found by the constants **A1, A2, s1** and **s2**, and time **t**. The constants **A1** and **A2** relate to the initial capacitor voltage **V0**, the initial inductor current **I0**, **s1** and **s2:**

$$s1 = -\alpha + \sqrt{\alpha^2 - \omega^2}$$ **Eq. 22.6.1**

$$s2 = -\alpha - \sqrt{\alpha^2 - \omega 0^2}$$ **Eq. 22.6.2**

$$\omega 0 = \sqrt{\frac{1}{L \cdot C}}$$ **Eq. 22.6.3**

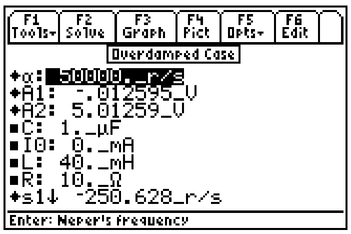
$$\alpha = \frac{1}{2 \cdot R \cdot C}$$ **Eq. 22.6.4**

$$v = A1 \cdot e^{s1 \cdot t} + A2 \cdot e^{s2 \cdot t}$$ **Eq. 22.6.5**

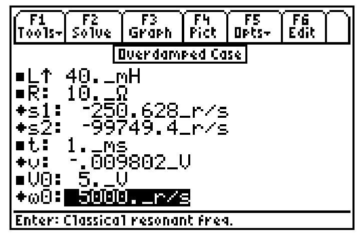
$$A1 = \frac{V0 \cdot s2 + \frac{1}{C} \cdot \left(\frac{V0}{R} + I0 \right)}{s2 - s1} \qquad \textbf{Eq. 22.6.6}$$

$$A2 = \frac{-\left(V0 \cdot s1 + \frac{1}{C} \cdot \left(\frac{V0}{R} + I0 \right) \right)}{s2 - s1} \qquad \textbf{Eq. 22.6.7}$$

Example 22.6 - An overdamped RLC circuit consists of a 10 Ω resistor in series with a 40 mH inductor and a 1 μF capacitor. If the initial inductor current is 0 mA and the capacitor is charged to a potential of 5 V, find the voltage across the capacitor after 1 ms.



Calculated Results (Upper display)



Calculated Results (Lower display)

Solution - All of the equations need to be selected to solve this problem. Press [F2] and enter the known variables followed by a second press of [F2] to solve for the unknowns. The solver takes about five minutes to solve this problem.

Known Variables: **C** = 1._μF, **I0** = 0._mA, **L** = 40._mH, **R** = 10._Ω, **t** = 1._ms, **V0** = 5._V

Computed Results: **s1** = -250.628._r/s, **s2** = -99749.4_r/s, **v** = -0.009802_V, **ω0** = 5000._r/s

Chapter 23 AC Circuits

This chapter covers equations describing the properties of AC circuits.

- ♦ RL Series Impedance
- ♦ RC Series Impedance
- ♦ Impedance ↔ Admittance
- ♦ Two Impedances in Series
- ♦ Two Impedances in Parallel

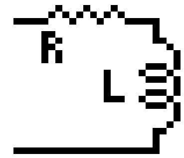
Variables

All the variables here are listed with a brief description and appropriate units.

Variable	Description	Unit
C	Capacitance	F
f	Frequency	Hz
I	Instantaneous current	A
Im	Current amplitude	A
L	Inductance	H
θ	Impedance phase angle	rad
θ1	Phase angle 1	rad
θ2	Phase angle 2	r
R	Resistance	Ω
RR1	Resistance 1	Ω
RR2	Resistance 2	Ω
t	Time	s
V	Total voltage	V
VC	Voltage across capacitor	V
VL	Voltage across inductor	V
Vm	Maximum voltage	V
VR	Voltage across resistor	V
ω	Radian frequency	r/s
X	Reactance	Ω
XX1	Reactance 1	Ω
XX2	Reactance 2	Ω
Y_	Admittance	S
Z1m	Impedance 1 magnitude	Ω
Z2m	Impedance 2 magnitude	Ω
Z_	Complex impedance	Ω
Zm	Impedance magnitude	Ω

23.1 RL Series Impedance

The equations in this section describe the relationships of an RL series circuit. The first equation shows the sinusoidal behavior of current, **I,** defined by the amplitude, **Im**, radian frequency **ω**, and time **t**. The second equation defines the magnitude of impedance **Zm** in terms of the resistance **R**, the inductance **L** and **ω**. The voltages **VR** and **VL** across the resistor and inductor are defined by the next two equations. The fifth equation calculates the total voltage drop **V** of the circuit as the sum of the individual voltage drops of the resistor and inductor. The next two equations compute the amplitude **Vm** and phase **θ** of the voltage across the circuit. The final equation relates the radian frequency and frequency **f**. Note: **I, VR,** and **VL** are functions of time.



$$I = \mathrm{Im} \cdot \sin(\omega \cdot t) \qquad \textbf{Eq. 23.1.1}$$

$$abs(Zm)^2 = R^2 + \omega^2 \cdot L^2 \qquad \textbf{Eq. 23.1.2}$$

$$VR = Zm \cdot \mathrm{Im} \cdot \sin(\omega \cdot t) \cdot \cos(\theta) \qquad \textbf{Eq. 23.1.3}$$

$$VL = Zm \cdot \mathrm{Im} \cdot \cos(\omega \cdot t) \cdot \sin(\theta) \qquad \textbf{Eq. 23.1.4}$$

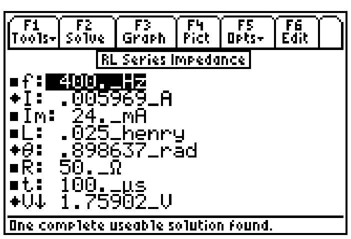
$$V = VR + VL \qquad \textbf{Eq. 23.1.5}$$

$$Vm = Zm \cdot \mathrm{Im} \qquad \textbf{Eq. 23.1.6}$$

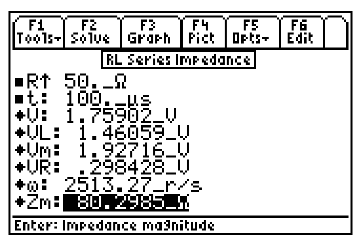
$$\theta = \tan^{-1}\left(\frac{\omega \cdot L}{R}\right) \qquad \textbf{Eq. 23.1.7}$$

$$\omega = 2 \cdot \pi \cdot f \qquad \textbf{Eq. 23.1.8}$$

Example 23.1 - An RL circuit consists of a 50 Ω resistor and a 0.025 henry inductor. At a frequency of 400 Hz, the current amplitude is 24 mA. Find the impedance of the circuit and the voltage drops across the resistor and inductor after 100 µs.



Upper Display



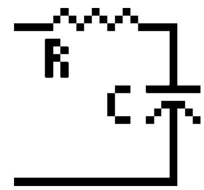
Lower Display

Solution - All of the equations are needed to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: **f** = 400._Hz, **Im** = 24._mA, **L** = .025_henry, **R** = 50._Ω, **t** = 100._µs

Computed Results: **I** = .005969_A, **θ** = .898637_rad, **V** = 1.75902_V, **VL** = 1.46059_V, **Vm** = 1.92716_V, **VR** = .298428_V, **ω** = 2513.27_r/s, **Zm** = 80.2985_Ω

23.2 RC Series Impedance



The equations in this section describe the key relationships involved in an RC series circuit. The first equation shows the sinusoidal behavior of current, **I,** defined by the amplitude **Im**, the radian frequency **ω**, and time **t**. The magnitude **Zm** of the impedance of the circuit is calculated in terms of the resistance **R**, capacitance **C**, and **ω** in the second equation. The voltage **VR** across **R** and the voltage **VC** across **C** are given in the next two equations. The total RC voltage drop **V** is expressed in the fifth equation. The amplitude **Vm** and phase **θ** of the voltage across the circuit is expressed in equations 6 & 7. The last equation is relationship between the radian frequency **ω** and actual frequency **f**. Note: **I**, **VR**, and **VC** are functions of time.

$$I = \mathrm{Im} \cdot \sin(\omega \cdot t) \qquad \textbf{Eq. 23.2.1}$$

$$abs(Zm)^2 = R^2 + \frac{1}{\omega^2 \cdot C^2} \qquad \textbf{Eq. 23.2.2}$$

$$VR = Zm \cdot \mathrm{Im} \cdot \sin(\omega \cdot t) \cdot \cos(\theta) \qquad \textbf{Eq. 23.2.3}$$

$$VC = Zm \cdot \mathrm{Im} \cdot \cos(\omega \cdot t) \cdot \sin(\theta) \qquad \textbf{Eq. 23.2.4}$$

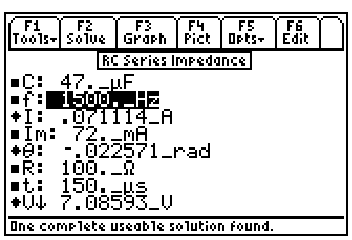
$$V = VR + VC \qquad \textbf{Eq. 23.2.5}$$

$$Vm = Zm \cdot \mathrm{Im} \qquad \textbf{Eq. 23.2.6}$$

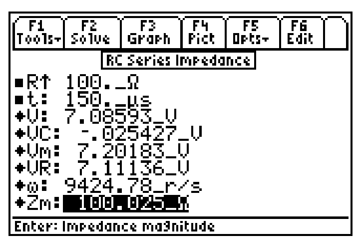
$$\theta = \tan^{-1}\left(\frac{-1}{\omega \cdot C \cdot R}\right) \qquad \textbf{Eq. 23.2.7}$$

$$\omega = 2 \cdot \pi \cdot f \qquad \textbf{Eq. 23.2.8}$$

Example 23.2 - An RC circuit consists of a 100 Ω resistor in series with a 47 μF capacitor. At a frequency of 1500 Hz, the current peaks at an amplitude of 72 mA. Find all the parameters of the RC circuit and the voltage drop after 150μs.



Computed Results
Upper Display



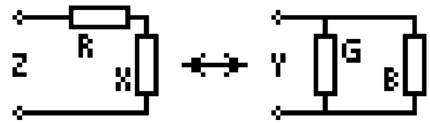
Computed results
Lower Display

Solution - Use all of the equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: **C** = 47._μF, **f** = 1500._Hz**,** **Im** = 72._mA, **R** = 100._Ω, **t** = 150._μs

Computed Results: **I** = .071114_A, **θ =** -.022571_rad, **V** = 7.08593_V, **VC** = -.025427_V, **Vm** = 7.20183_V, **VR** = 7.11136_V, **ω** = 9424.78_r/s, **Zm** = 100.025_Ω

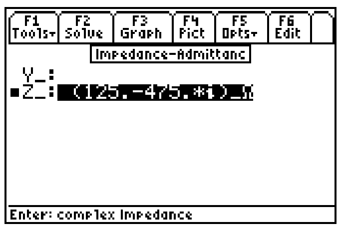
23.3 Impedance ↔ Admittance



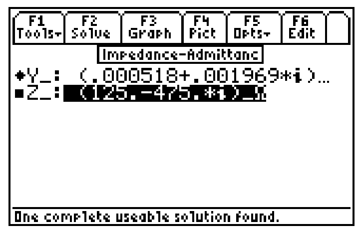
The equation is designed to convert impedances to admittances with unit management built-in. As shown in the figure to the right, an impedance Z consists of a real and reactive components (R and X) to describe it. The admittance Y consists of real and reactive components (G and B) to describe it. The variables Z and Y have an _ attached to them to add emphasize that they are complex in general and have units attached.

$$Y\_ = \frac{1}{Z\_}$$ **Eq. 23.3.1**

Example 23.3 - Find the admittance of an impedance consisting of a resistive part of 125 Ω and a reactance part of 475_ Ω.



Entered Value



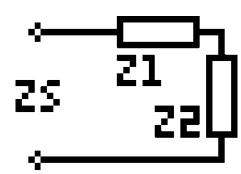
Calculated Result

Solution -Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: $\mathbf{Z} = (125.\text{-}475.*i)\_\Omega$

Computed Results: $\mathbf{Y} = (.000518 + .001969 * i)\_\text{Siemens}$

23.4 Two Impedances in Series



These equations combine two impedances **Z1** and **Z2** in series with real and imaginary parts **RR1** and **XX1**, **RR2** and **XX2**, respectively. The impedances **Z1** and **Z2** are expressed by their magnitudes **Z1m** and **Z2m**, and phase angles **θ1** and **θ2** respectively. The combined result of the two impedances in series is an impedance with a magnitude **Zm** and a phase angle **θ.**

$$abs(Zm)^2 = R^2 + X^2$$ **Eq. 23.4.1**

$$\theta = \tan^{-1}\left(\frac{X}{R}\right)$$ **Eq. 23.4.2**

$$R = RR1 + RR2$$ **Eq. 23.4.3**

$$X = XX1 + XX2$$ **Eq. 23.4.4**

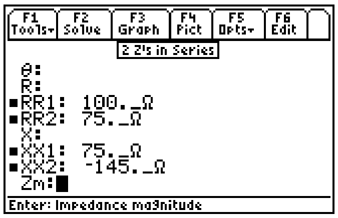
$$abs(Z1m)^2 = RR1^2 + XX1^2$$ **Eq. 23.4.5**

$$abs(Z2m)^2 = RR2^2 + XX2^2$$ **Eq. 23.4.6**

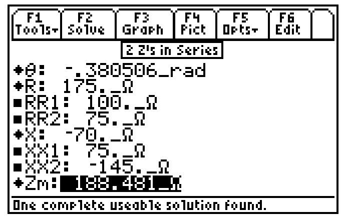
$$\theta 1 = \tan^{-1}\left(\frac{XX1}{RR1}\right)$$ **Eq. 23.4.7**

$$\theta 2 = \tan^{-1}\left(\frac{XX2}{RR2}\right)$$ **Eq. 23.4.8**

Example 23.4 - Two impedances consisting of resistances of 100 Ω and 75 Ω and reactive components 75 and -145, respectively are connected in series. Find the magnitude and phase angle of the combination.



Input Variables



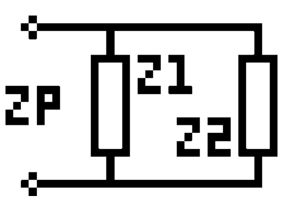
Computed results

Solution - Select the first four equations to solve the problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: RR1 = 100._Ω, **RR2** = 75._Ω, **XX1** = 75._Ω, **XX2** = -145._ Ω

Computed Results: Zm = 188.481_Ω, **θ** = -.380506_rad, **R** = 175._ Ω **X** = -70._ Ω

23.5 Two Impedances in Parallel



Two impedances **Z1** and **Z2** when connected in parallel result in an equivalent parallel impedance Zp, represented by a real part **R** and a reactive part **X**. The impedances **Z1** and **Z2** have real and reactive parts **RR1, XX1** and **RR2**, **XX2** respectively. The first two equations show a numeric expression for magnitude **Zm** and phase θ. Simpler versions of **R** and **X** are shown in the third and fourth equations. The last four equations calculate the magnitude and phase of **Z1** and **Z2** as **Z1m** and **θ1,** and **Z2m** and **θ2**, respectively.

$$abs(Zm)^2 = \frac{(RR1 \cdot RR2 - XX1 \cdot XX2)^2 + (RR1 \cdot XX2 + RR2 \cdot XX1)^2}{(RR1 + RR2)^2 + (XX1 + XX2)^2}$$ **Eq. 23.5.1**

$$\theta = \tan^{-1}\left(\frac{XX1 \cdot RR2 + RR1 \cdot X2}{RR1 \cdot RR2 - XX1 \cdot X2}\right) - \tan^{-1}\left(\frac{XX1 + XX2}{RR1 + RR2}\right)$$ **Eq. 23.5.2**

$$R = Zm \cdot \cos(\theta)$$ **Eq. 23.5.3**

$$X = Zm \cdot \sin(\theta)$$ **Eq. 23.5.4**

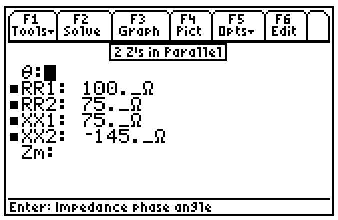
$$abs(Z1m)^2 = RR1^2 + XX1^2$$ **Eq. 23.5.5**

$$abs(Z2m)^2 = RR2^2 + XX2^2$$ **Eq. 23.5.6**

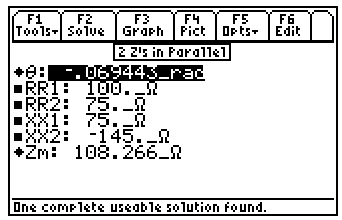
$$\theta 1 = \tan^{-1}\left(\frac{XX1}{RR1}\right) \qquad \textbf{Eq. 23.5.7}$$

$$\theta 2 = \tan^{-1}\left(\frac{XX2}{RR2}\right) \qquad \textbf{Eq. 23.5.8}$$

Example 23.5 - For two impedances in parallel possessing values identical to the previous example, calculate the magnitude and phase of the combination.



Entered Values



Calculated Results

Solution - Use the first and second equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: RR1 = 100._Ω, **RR2** = 75._Ω, **XX1** = 75._Ω, **XX2** = -145._ Ω

Computed Results: Zm = 108.266_Ω, **θ** = -.069443_rad

Chapter 24 Polyphase Circuits

This chapter covers equations used in Polyphase circuits. The equations have been divided into three sections.

- ❖ Balanced Δ Network
- ❖ Balanced Wye Network
- ❖ Power Measurements

Variables

All the variables are listed below with a brief description and units.

Variable	Description	Unit
IL	Line current	A
Ip	Phase current	A
P	Power per phase	W
PT	Total power	W
θ	Impedance angle	rad
VL	Line voltage	V
Vp	Phase voltage	V
W1	Wattmeter 1	W
W2	Wattmeter 2	W

24.1 Balanced Δ Network

These equations describe the essential features of a *Balanced Δ Network*. The line voltage **VL** is defined in terms of phase voltage **Vp**. The second equation expresses the line current **IL** using the phase current **Ip**. The third equation computes the power in each phase **P** from **Vp**, **Ip** and the phase delay **θ** between voltage and current. The last two equations represent the total power **PT** delivered to the system in terms of **IL, VL Vp** and **Ip**.

$$VL = Vp \qquad \textbf{Eq. 24.1.1}$$

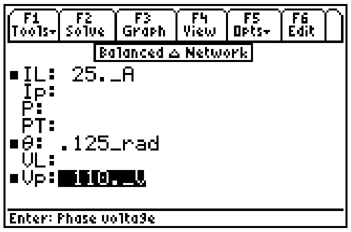
$$IL = \sqrt{3} \cdot Ip \qquad \textbf{Eq. 24.1.2}$$

$$P = Vp \cdot Ip \cdot \cos(\theta) \qquad \textbf{Eq. 24.1.3}$$

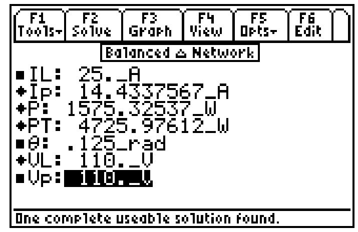
$$PT = 3 \cdot Vp \cdot Ip \cdot \cos(\theta) \qquad \textbf{Eq. 24.1.4}$$

$$PT = \sqrt{3} \cdot VL \cdot IL \cdot \cos(\theta) \qquad \textbf{Eq. 24.1.5}$$

Example 24.1 - Given a line current of 25 A, a phase voltage of 110 V, and a phase angle of 0.125 rad, find the phase current, power, total power and line voltage.



Input variables



Computed results

Solution - Upon examining the problem, all equations are needed. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation set. The computed results are shown in the screen display above.

Known Variables: IL = 25._A, **θ** = .125_rad, **Vp** = 110._V

Computed Results: Ip = 14.4337567_A, **P** = 1575.32537_W, **PT** = 4725.97612_W, **VL** = 110._V

24.2 Balanced Wye Network

These equations describe the relationship for a *Balanced Wye Network*. The first equation computes the line voltage **VL** from the phase voltage **Vp**. The second equation calculates the line current **IL** from the phase current **Ip**. The power/phase **P**, is defined in terms of **Vp**, **Ip** and phase delay **θ**. The last two equations are used to estimate the total power **PT** delivered to the system from the parameters **VL**, **IL** or **Vp** and **Ip.**

$$VL = \sqrt{3} \cdot Vp \qquad \textbf{Eq. 24.2.1}$$

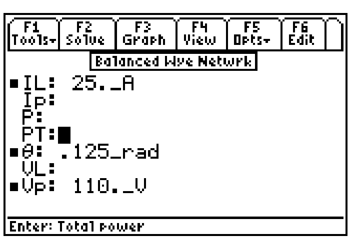
$$IL = Ip \qquad \textbf{Eq. 24.2.2}$$

$$P = Vp \cdot Ip \cdot \cos(\theta) \qquad \textbf{Eq. 24.2.3}$$

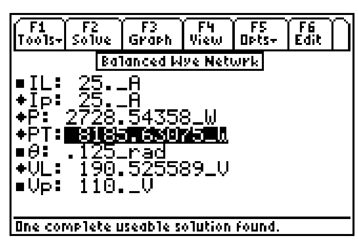
$$PT = 3 \cdot Vp \cdot Ip \cdot \cos(\theta) \qquad \textbf{Eq. 24.2.4}$$

$$PT = \sqrt{3} \cdot VL \cdot IL \cdot \cos(\theta) \qquad \textbf{Eq. 24.2.5}$$

Example 24.2 - Using the known parameters in the previous example for the *Balanced Δ Network*, find the phase current, power, total power and line voltage.



Input variables

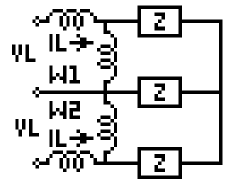


Computed results

Solution - All of the equations are needed to compute the solution. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation set. The computed results are shown in the screen display above.

Known Variables: IL = 25._A, **θ** = .125_rad, **Vp** = 110._V
Computed Results: Ip = 25._A, **P** = 2728.54358_W, **PT** = 8185.63075_W, **VL** = 190.525589_V

24.3 Power Measurements



These three equations for a two-watt meter connection are used to measure the total power of a balanced network. The first two equations determine the watt meter readings **W1** and **W2** are expressed from the line current **IL**, line voltage **VL**, and phase delay **θ** between the voltage and the current. The final equation represents the total power, **PT,** delivered to the three-phase load.

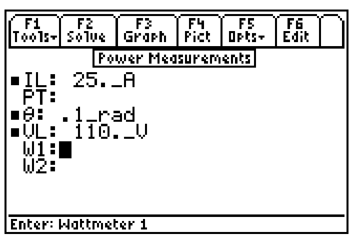
$$W1 = VL \cdot IL \cdot \cos\left(\theta + \frac{\pi}{6}\right)$$ **Eq.**

24.3.1

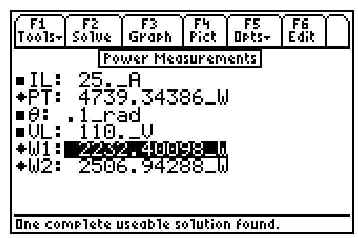
$$W2 = VL \cdot IL \cdot \cos\left(\theta - \frac{\pi}{6}\right)$$ **Eq. 24.3.2**

$$PT = \sqrt{3} \cdot VL \cdot IL \cdot \cos(\theta)$$ **Eq. 24.3.3**

Example 24.3 - Given a line voltage of 110 V and a line current of 25 A and a phase angle of 0.1 rad, find the wattmeter readings in a 2 wattmeter meter system.



Input variables



Computed results

Solution - All of the equations are needed to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation set. The computed results are shown in the screen display above.

Known Variables: IL = 25._A, **θ** = .1_rad, **VL** = 110._V

Computed Results: PT = 4739.34386_W, **W1** = 2232.40098_W, **W2** = 2506.94288_W

Chapter 25 Electrical Resonance

The equations in this section describe the electrical properties of resonance in circuits composed of ideal circuit elements. The section is organized under four topics:

- Parallel Resonance I
- Parallel Resonance II
- Resonance in Lossy Inductor
- Series Resonance

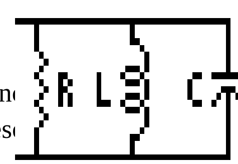
Variables

The following variables are listed with a brief description and their appropriate units.

Variable	**Description**	**Unit**
α	Damping coefficient	r/s
β	Bandwidth	r/s
C	Capacitance	F
Im	Current	A
L	Inductance	H
θ	Phase angle	rad
Q	Quality factor	unitless
R	Resistance	Ω
Rg	Generator resistance	Ω
Vm	Maximum voltage	V
ω	Radian frequency	r/s
ω0	Resonant frequency	r/s
ω1	Lower cutoff frequency	r/s
ω2	Upper cutoff frequency	r/s
ωd	Damped resonant frequency	r/s
ωm	Frequency for maximum amplitude	r/s
Yres	Admittance at resonance	S
Z	Impedance	Ω
Zres	Impedance at resonance	Ω

25.1 Parallel Resonance I

These ten equations describe resonance properties in parallel resonance circuits. The first equation expresses **Vm**, the voltage across the circuit, in terms of **Im**, the magnitude of the supplied current and the equivalent impedance of the parallel circuit consisting of an inductor **L**, a capacitor **C** and a resistor **R** at the radian frequen uation computes the phase angle, θ, between **Vm** and **Im**. The third equation defines the res rom the



reactive parameters **L** and **C**. The terms **ω1** and **ω2** represent the lower and upper cutoff frequencies beyond **ω0**, where the impedance is half the impedance at resonance. The bandwidth, **β,** is the difference between **ω1** and **ω2**. The last three equations calculate the quality factor **Q** in terms of **R**, **C**, **L** and **ω0**.

$$Vm = \frac{\mathrm{Im}}{\sqrt{\left(\frac{1}{R^2} + \left(\omega \cdot C - \frac{1}{(\omega \cdot L)}\right)^2\right)}} \qquad \textbf{Eq. 25.1.1}$$

$$\theta = \tan^{-1}\left(\left(\omega \cdot C - \frac{1}{\omega \cdot L}\right) \cdot R\right) \qquad \textbf{Eq. 25.1.2}$$

$$\omega 0 = \frac{1}{\sqrt{L \cdot C}} \qquad \textbf{Eq. 25.1.3}$$

$$\omega 1 = \frac{-1}{2 \cdot R \cdot C} + \sqrt{\frac{1}{(2 \cdot R \cdot C)^2} + \frac{1}{L \cdot C}} \qquad \textbf{Eq. 25.1.4}$$

$$\omega 2 = \frac{1}{2 \cdot R \cdot C} + \sqrt{\frac{1}{(2 \cdot R \cdot C)^2} + \frac{1}{L \cdot C}} \qquad \textbf{Eq. 25.1.5}$$

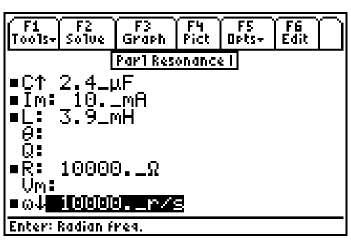
$$\beta = \omega 2 - \omega 1 \qquad \textbf{Eq. 25.1.6}$$

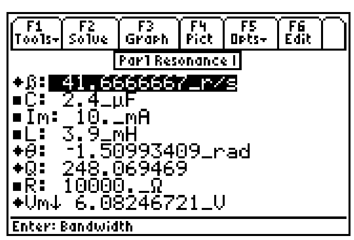
$$Q = \frac{\omega 0}{\beta} \qquad \textbf{Eq. 25.1.7}$$

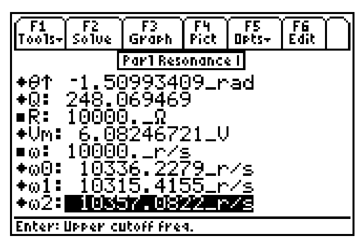
$$Q = R \cdot \sqrt{\frac{C}{L}} \qquad \textbf{Eq. 25.1.8}$$

$$Q = \omega 0 \cdot R \cdot C \qquad \textbf{Eq. 25.1.9}$$

Example 25.1 - Calculate the resonance parameters of a parallel resonant circuit containing a 10,000 Ω resistor, a 2.4 μF capacitor and a 3.9 mH inductor. The amplitude of the current is 10 mA at a radian frequency of 10,000 rad/s.







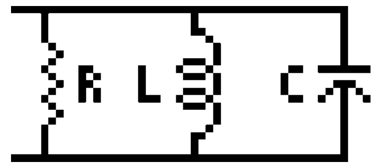
Input Values *Calculated Results (Upper and Lower Screens)*

Solution - All of the equations are needed to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the set of equations. The computed results are shown in the screen displays above.

Known Variables: **C** = 2.4_μF, **Im** = 10._mA, **R** = 10,000._Ω, **L** = 3.9 mH, **ω** = 10000_r/s

Computed Results: **β** = 41.6666667_r/s, **θ** = -1.50993409_rad, **Q** = 248.069469,
Vm = 6.08246721_V, **ω0** = 10336.2279_r/s, **ω1** = 10315.4155_r/s, **ω2** = 10357.0822_r/s

25.2 Parallel Resonance II



These equations represent an alternative method of expressing the properties of a resonant circuit in terms of the quality factor **Q**. The first equation links **Q** with the resonant frequency **ω0** and the bandwidth **β**. The lower and upper cutoff frequencies, **ω1** and **ω2** are defined in terms of **ω0** and **Q**. The fourth and fifth equations compute **α**, the damping coefficient, either from **R** and **C,** or **ω0** and **Q**. The final two equations express the damped resonant frequency **ωd** in terms of **α** and **ω0** or **ω0** and **Q**.

$$Q = \frac{\omega 0}{\beta} \qquad \textbf{Eq. 25.2.1}$$

$$\omega 1 = \omega 0 \cdot \left(\frac{-1}{2 \cdot Q} + \sqrt{\frac{1}{(2 \cdot Q)^2} + 1} \right) \qquad \textbf{Eq. 25.2.2}$$

$$\omega 2 = \omega 0 \cdot \left(\frac{1}{2 \cdot Q} + \sqrt{\frac{1}{(2 \cdot Q)^2} + 1} \right) \qquad \textbf{Eq. 25.2.3}$$

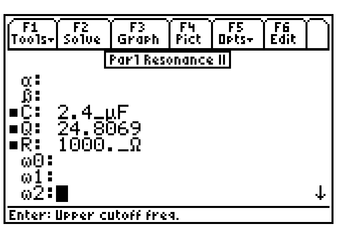
$$\alpha = \frac{1}{2 \cdot R \cdot C} \qquad \textbf{Eq. 25.2.4}$$

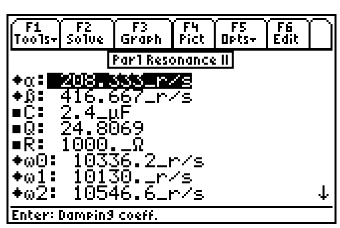
$$\alpha = \frac{\omega 0}{2 \cdot Q} \qquad \textbf{Eq. 25.2.5}$$

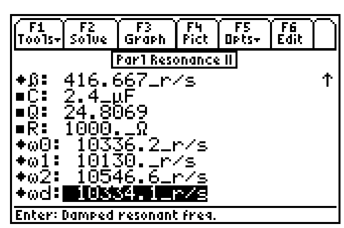
$$\omega d = \sqrt{\omega 0^2 - \alpha^2} \qquad \textbf{Eq. 25.2.6}$$

$$\omega d = \omega 0 \cdot \sqrt{1 - \frac{1}{4 \cdot Q^2}} \qquad \textbf{Eq. 25.2.7}$$

Example 25.2 - A parallel resonant circuit has a 1000 Ω resistor and a 2 μF capacitor. The *Quality Factor* for this circuit is 24.8069. Find the band-width, damped and resonant frequencies.







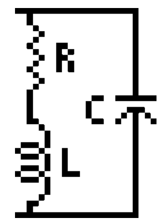
Input Values *Calculated Results (Upper and Lower Screens)*

Solution - All of the equations are needed to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the set of equations. The computed results are shown in the screen displays above.

Known Variables: **C** = 2.4_μF, **Q** = 24.8069, **R** = 1000._Ω

Computed Results: α = 208.33, β = 416.667._r/s, **ω0** = 10336.2_r/s, **ω1** = 10130._r/s, **ω2** = 10546.6_r/s, **ωd** = 10334.1_r/s

25.3 Resonance in Lossy Inductor



These equations characterize the properties of a lossy inductor in parallel with an ideal capacitor and a current source with an impedance of **Rg**. At the resonant frequency **ω0,** the admittance of the parallel circuit is purely conductive. **Yres** and **Zres** represent the impedance and admittance of the circuit at resonance. **ωm** represents the frequency that occurs when the amplitude of the voltage across the resonant circuit is at maximum.

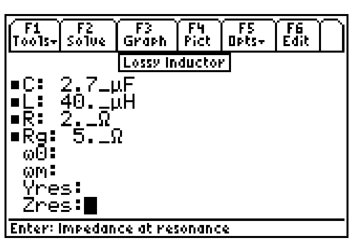
$$\omega 0 = \sqrt{\frac{1}{L \cdot C} - \left(\frac{R}{L}\right)^2}$$ **Eq. 25.3.1**

$$Yres = \frac{L + Rg \cdot R \cdot C}{L \cdot Rg}$$ **Eq. 25.3.2**

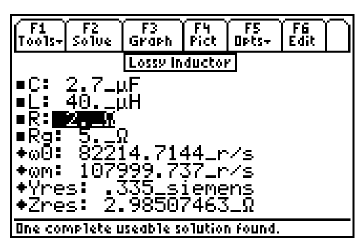
$$Zres = \frac{1}{Yres}$$ **Eq. 25.3.3**

$$\omega m = \sqrt{\sqrt{\left(\frac{1}{L \cdot C}\right)^2 \cdot \left(1 + \frac{2 \cdot R}{Rg}\right) + \left(\frac{R}{L}\right)^2 \cdot \frac{2}{L \cdot C}} - \left(\frac{R}{L}\right)^2}$$ **Eq. 25.3.4**

Example 25.3 - A power source with an impedance **Rg** of 5 Ω is driving a parallel combination of a lossy 40 μH inductor with a 2 Ω loss resistance, and a capacitor of 2.7 μF. Find the frequency of resonance and the frequency for maximum amplitude.



Entered Values



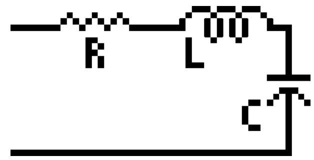
Calculated Results

Solution - Upon examining the problem, all equations are needed to solve for a solution. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the set of equations. The computed results are shown in the screen displays above.

Known Variables: **C** = 2.7_μF, **R** = 2._Ω, **L** = 40._μH, **Rg** = 5._Ω

Computed Results: **ω0** = 82214.7144_r/s, **ωm** =107999.737_r/s, **Yres** = .335_siemens, **Zres** = 2.98507463_Ω

25.4 Series Resonance



These equations characterize the properties of a series resonance circuit. The first equation connects the resonant frequency **ω0** and the reactive elements, the inductance **L,** and the capacitance, **C**. The second and third equations compute the magnitude **Z** and phase **θ** of the impedance, respectively.. The equations for **ω1** and **ω2** represent the upper and lower cutoff frequencies beyond resonance, where the impedance is half the impedance at resonance. The expressions for **β** represents the bandwidth of the resonant circuit.
The last equation determines the quality factor **Q** in terms of **R**, **C**, **L**, and **ω0**.

$$\omega 0=\frac{1}{\sqrt{L\cdot C}}$$ **Eq. 25.4.1**

$$Z=\sqrt{R^2+\left(\omega\cdot L-\frac{1}{\omega\cdot C}\right)^2}$$ **Eq. 25.4.2**

$$\theta=\tan^{-1}\left(\frac{\omega\cdot L-\frac{1}{\omega\cdot C}}{R}\right)$$ **Eq. 25.4.3**

$$\omega 1=\frac{-R}{2\cdot L}+\sqrt{\left(\frac{R}{2\cdot L}\right)^2+\frac{1}{L\cdot C}}$$ **Eq. 25.4.4**

$$\omega 2=\frac{R}{2\cdot L}+\sqrt{\left(\frac{R}{2\cdot L}\right)^2+\frac{1}{L\cdot C}}$$ **Eq. 25.4.5**

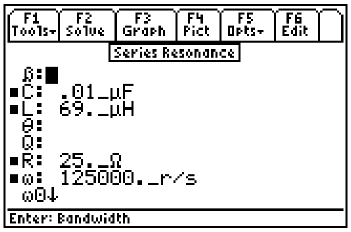
$$\beta=\omega 2-\omega 1$$ **Eq. 25.4.6**

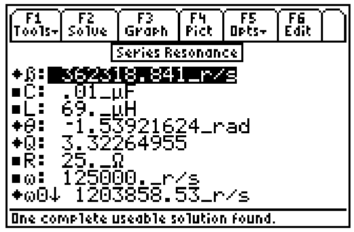
$$\beta=\frac{R}{L}$$ **Eq. 25.4.7**

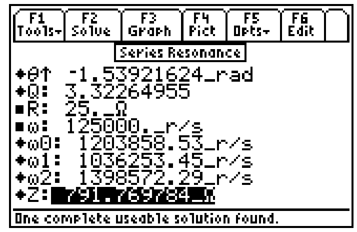
$$Q=\frac{\omega 0\cdot L}{R}$$ **Eq. 25.4.8**

$$Q=\frac{1}{R}\cdot\sqrt{\frac{L}{C}}$$ **Eq. 25.4.9**

Example 25.4 - Find the characteristic parameters of a series-resonant circuit with **R** = 25Ω, **L** = 69 μH, **C** = 0.01 μF and a radian frequency of 125,000 rad/s.







Entered Values *Calculated Results (Upper and Lower Screens)*

Solution - Upon examining the problem, all equations are needed to solve the problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the set of equations. The computed results are shown in the screen displays above.

Known Variables: C=.01_µF, **R** = 2.5_Ω, **L** = 69._µH, **R** = 25._Ω, **ω** = 125000._r/s

Computed Results: **ω0** = 1203858.53_r/s, **ω1** =1036253.45_r/s, **ω2** = 1398572.29_r/s, **Z** = 791.769784_Ω

Chapter 26 OpAmp Circuits

Seven commonly-used OpAmp circuits are presented in this section. An OpAmp is a direct-coupled high-gain amplifier that can be configured with the use of feedback to circuit elements to achieve overall performance characteristics. There are two inputs labeled '+' and '-'. The manner in which input signals are connected to these terminals defines the inverting or non-inverting properties of the circuit.

- Basic Inverter
- Non-Inverting Amplifier
- Current Amplifier
- Transconductance Amplifier
- Level Detector (Inverting)
- Level Detector (Non-Inverting)
- Differentiator
- Differential Amplifier

Variables

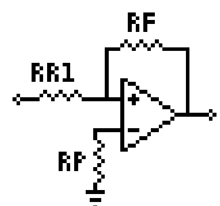
All the variables used here are listed with a brief description and proper units.

Variable	**Description**	**Unit**
Acc	Common Mode current gain	unitless
Aco	Common Mode gain from real OpAmp	unitless
Ad	Differential mode gain	unitless
Agc	Transconductance	S
Aic	Current gain	unitless
Av	Voltage gain	unitless
CC1	Input capacitor	F
Cf	Feedback capacitor	F
CMRR	CM rejection ratio	unitless
Cp	Bypass capacitor	F
fcp	3dB bandwidth, circuit	Hz
fd	Characteristic frequency	Hz
f0	Passband, geometric center	Hz
fop	3dB bandwidth, OpAmp	Hz
IIf	Maximum current through Rf	A
RR1	Input resistor	Ω
RR2	Current stabilizor	Ω
RR3	Feedback resistor	Ω
RR4	Resistor	Ω
Rf	Feedback resistor	Ω
Rin	Input resistance	Ω
Rl	Load resistance	Ω
Ro	Output resistance, OpAmp	Ω
Rout	Output resistance	Ω
Rp	Bias current resistor	Ω

Rs	Voltage divide resistor	Ω
tr	10-90% rise time	s
ΔVH	Hysteresis	V
VL	Detection threshold, low	V
Vomax	Maximum circuit output	V
VR	Reference voltage	V
Vrate	Maximum voltage rate	V/s
VU	Detection threshold, high	V
Vz1	Zener breakdown 1	V
Vz2	Zener breakdown 2	V

26.1 Basic Inverter

These equations define the properties of a basic inverter. The first equation relates the voltage gain **Av** to the feedback resistance **Rf** and input resistance **RR1**. The optimum value of **Rp** is defined by the second equation to minimize output-voltage offset due to input bias current. The first pole frequency **fcp** is defined by the third equation. Small signal rise time **tr** (10 to 90%) is defined by the fourth equation.



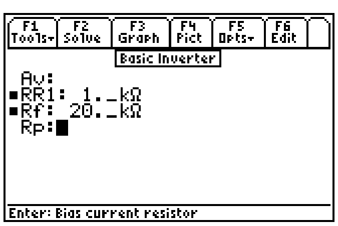
$$Av = \frac{-Rf}{RR1}$$ **Eq. 26.1.1**

$$Rp = \frac{RR1 \cdot Rf}{RR1 + Rf}$$ **Eq. 26.1.2**

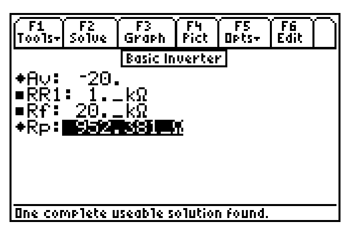
$$fcp = fop \cdot (-Av) \cdot \left(\frac{RR1}{Rf} \right)$$ **Eq. 26.1.3**

$$tr = \frac{.35 \cdot Rf}{fop \cdot (-Av) \cdot RR1}$$ **Eq. 26.1.4**

Example 26.1 - Find the gain of an inverter and its optimum value for bias resistance given an input resistance of 1 kΩ and a feedback resistance of 20 kΩ.



Entered Values



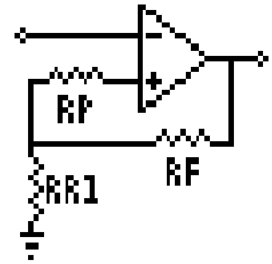
Calculated Results

Solution - Use the first and second equations to compute the solution for this problem. Select these by highlighting each equation and pressing the ENTER key. Press F2 to display the input screen, enter all the known variables and press F2 to solve the equation. The computed results are shown in the screen displays above.

Known Variables: RR1 = 1._kΩ, **Rf**=20._kΩ

Computed Results: **Av** = -20., **Rp** = 952.381._ Ω

26.2 Non-Inverting Amplifier

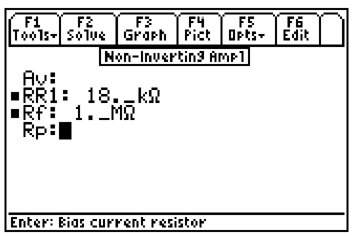


These equations define the properties of a non-inverting amplifier. The first equation expresses the voltage gain **Av** in terms of the feedback resistor **Rf** and resistor **RR1**. The second equation gives the value of **Rp** needed in the input circuit to minimize offset current effects.

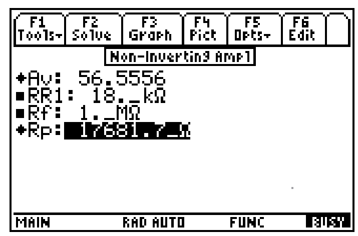
$$Av = 1 + \frac{Rf}{RR1}$$ **Eq. 26.2.1**

$$Rp = \frac{RR1 \cdot Rf}{RR1 + Rf}$$ **Eq. 26.2.2**

Example 26.2 - Find the DC gain of a non-inverting amplifier with a feedback resistance of 1 MΩ and a resistance to the load of 18 kΩ. Find the gain and the optimum value for a bias resistor.



Entered Values



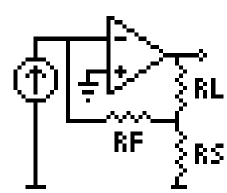
Calculated Results

Solution - Use the first and second equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: Rf = 1._MΩ, **RR1** = 18._kΩ

Computed Results: **Av** = 56.5556, **Rp** = 17681.7_Ω

26.3 Current Amplifier



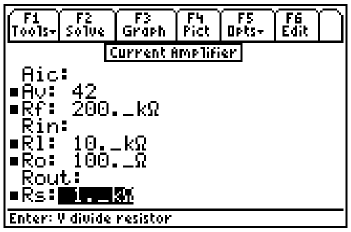
This section describes the properties of a current amplifier. The first equation shows the relationship between the current gain **Aic** with feedback resistance **Rf**, load resistance **Rl**, output resistance of OpAmp **Ro**, voltage divide resistor **Rs**, and voltage gain **Av**. The remaining equations define the input resistance **Rin** and output resistance **Rout** of the system.

$$Aic = \frac{(Rs + Rf) \cdot Av}{Rl + Ro + Rs \cdot (1 + Av)}$$ **Eq. 26.3.1**

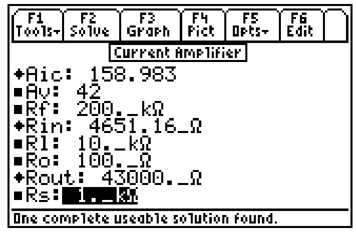
$$Rin = \frac{Rf}{1 + Av}$$ **Eq. 26.3.2**

$$Rout = Rs \cdot (1 + Av) \qquad \textbf{Eq. 26.3.3}$$

Example 26.3 - A current amplifier with a 200 kΩ feedback resistance has a voltage gain of 42. If the source resistance is 1 kΩ, the load resistance is 10 kΩ and the output resistance of the OpAmp is 100 Ω, find the current gain, input and output resistances.



Entered Values



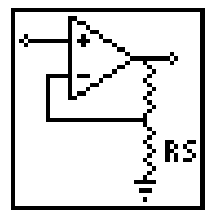
Calculated Results

Solution - Use all of the equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: **Av** = 42, **Rf** = 200._kΩ, **Rl** = 10._kΩ, **Ro** = 100._Ω, **Rs** = 1._kΩ

Computed Results: **Aic** = 158.983, **Rin** = 4651.16_Ω, **Rout** = 43000._ Ω

26.4 Transconductance Amplifier

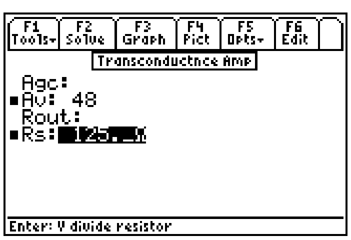


The two equations in this section specify a closed loop transconductance **Agc** and output resistance **Rout** in terms of the resistance **Rs** and voltage gain **Av**.

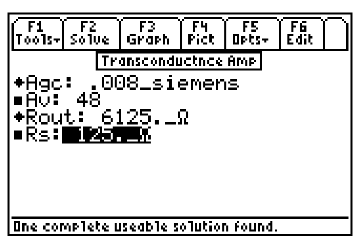
$$Agc = \frac{1}{Rs} \qquad \textbf{Eq. 26.4.1}$$

$$Rout = Rs \cdot (1 + Av) \qquad \textbf{Eq. 26.4.2}$$

Example 26.4 - Find the transconductance and output resistance for a transconductance amplifier with a voltage gain of 48 and an external resistance of 125 Ω.



Entered Values



Calculated Results

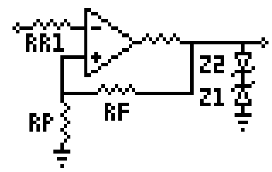
Solution - Use both equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen display above.

Known Variables: **Rs** = 125._Ω, **Av** = 48

Computed Results: **Agc** = .008_siemens, **Rout** = 6125._ Ω

26.5 Level Detector (Inverting)

The first equation in this section computes the value of the resistor **RR1** attached to an OpAmp inverting input. The second equation calculates the hysteresis (or memory) **ΔVH** of the level detector circuit. The third and fourth equations define the upper and lower trip voltages **VU** and **VL** for an ideal inverting level detector, assuming a reference voltage **VR** and breakdown voltages **Vz1** and **Vz2**, and in terms of **Rp** and **Rf**.



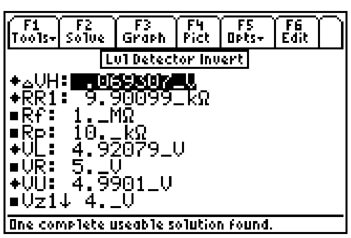
$$RR1 = \frac{Rp \cdot Rf}{Rp + Rf}$$ **Eq. 26.5.1**

$$\Delta VH = \frac{(Vz1 + Vz2)}{Rp + Rf} \cdot Rp$$ **Eq. 26.5.2**

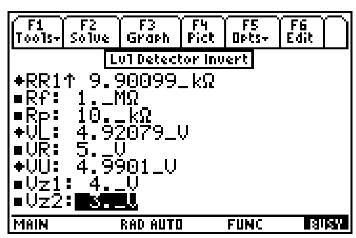
$$VU = \frac{VR \cdot Rf + Rp \cdot Vz1}{Rf + Rp}$$ **Eq. 26.5.3**

$$VL = \frac{VR \cdot Rf - Rp \cdot Vz2}{Rf + Rp}$$ **Eq. 26.5.4**

Example 26.5. - An inverting level detector possesses two zener diodes to set the trip level. The setting levels are 4 V and 3 V, respectively, for the first and second diodes. The reference voltage is 5 V, the OpAmp is supported by a 10 kΩ bias resistor and a 1 MΩ feedback resistor. Find the hysteresis, the upper and lower detection thresholds, and the input resistance.



Upper Display



Lower Display

Solution - Use all of the equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: **Rf** = 1._MΩ, **Rp** = 10._kΩ, **VR** = 5._V, **Vz1** = 4._V, **Vz2** = 3._V

Computed Results: **ΔVH** = .069307_V, **RR1** = 9.90099_kΩ, **VL** = 4.92079_V, **VU** = 4.9901_V

26.6 Level Detector (Non-Inverting)

This section computes the value of the resistor **RR1** attached to an OpAmp non-inverting input. The next equation calculates the hysteresis (or memory) **ΔVH** of the level detector circuit. The next two equations define the upper and lower trip voltages **VU** and **VL** for an ideal inverting level detector, a reference voltage **VR** and breakdown voltages **Vz1** and **Vz2**, in terms of **Rp** and **Rf**.

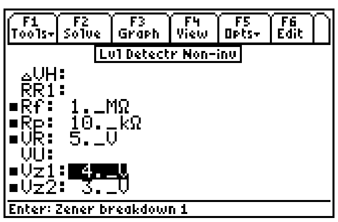
$$RR1 = \frac{Rp \cdot Rf}{Rp + Rf}$$ **Eq. 26.6.1**

$$\Delta VH = \frac{(Vz1 + Vz2)}{Rp + Rf} \cdot Rp$$ **Eq. 26.6.2**

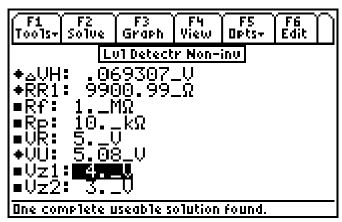
$$VU = \frac{VR \cdot (Rf + Rp) + Rp \cdot Vz2}{Rf}$$ **Eq. 26.6.3**

$$VL = \frac{VR \cdot (Rp + Rf) - Rp \cdot Vz1}{Rf}$$ **Eq. 26.6.4**

Example 26.6 - For a non-inverting level detector with the same specifications as the inverting level detector in the previous example, compute the hysteresis, the upper and lower detection thresholds, and the input resistance.



Entered Values



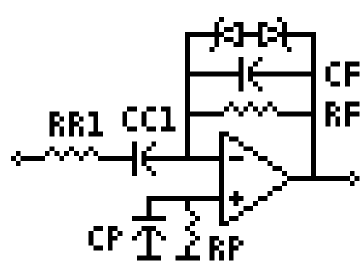
Calculated Results

Solution - Use the first three equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: Rf = 1._MΩ, **Rp** = 10._kΩ, **VR** = 5._V, **Vz1** = 4._V, **Vz2** = 3._V

Computed Results: **ΔVH** = .069307_V, **RR1** = 9900.99_Ω, **VU** = 5.08_V

26.7 Differentiator



These equations define all the components required for a differentiator. The first equation defines the feedback resistor **Rf** in terms of the maximum output voltage **Vomax** and current **IIf**. Typically, **IIf** is of the order of 0.1 - 0.5 mA. The second equation computes the value for the resistor **Rp** used to cancel the effects of OpAmp input bias current. **CC1** is the input capacitor required for the differentiator, and **RR1** is the resistor utilized for stability. The characteristic frequency of the differentiator **fd** is expressed by the fifth equation. The last two equations compute the bypass capacitor **Cp** and the feedback capacitor **Cf**.

$$Rf = \frac{Vo\max}{IIf}$$ **Eq. 26.7.1**

$$Rp = Rf$$ **Eq. 26.7.2**

$$CC1 = \frac{Vo\max}{Rf \cdot Vrate}$$ **Eq. 26.7.3**

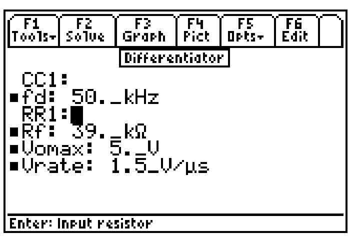
$$RR1 = \frac{1}{2 \cdot \pi \cdot fd \cdot CC1}$$ **Eq. 26.7.4**

$$fd = \frac{1}{2 \cdot \pi \cdot Rf \cdot CC1}$$ **Eq. 26 7.5**

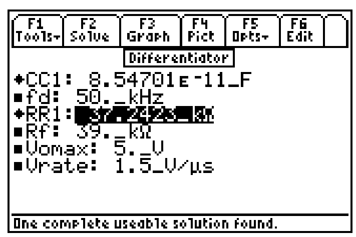
$$Cp = \frac{10}{2 \cdot \pi \cdot f0 \cdot Rp}$$ **Eq. 26.7.6**

$$Cf = \frac{1}{4 \cdot \pi \cdot f0 \cdot Rf}$$ **Eq. 26.7.7**

Example 26.7 - A differentiator circuit designed with an OpAmp has a slew rate of 1.5 V/µs. If the maximum output voltage is 5 V, and the feedback resistor is 39 kΩ, what input capacitor and resistor are needed for the amplifier with a characteristic frequency of 50 kHz?



Entered Values



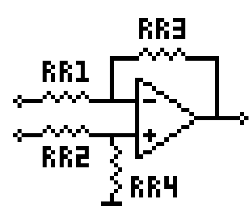
Calculated Results

Solution - Use the third and fourth equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: fd = 50._kHz, **Vrate** = 1.5_V/µs, **Vomax** = 5._V, **Rf** = 39._kΩ,

Computed Results: **CC1** = 8.54701E-11_F, **RR1** = 37.2423_kΩ

26.8 Differential Amplifier



These four equations describe the primary relationships used in designing of a differential amplifier. The first equation computes the differential gain **Ad** in terms of the input and feeback resistors **RR1** and **RR3**. The second equation shows the common-mode gain **Aco** in terms of **RR3**, **RR1**, and the common-mode rejection ratio **CMRR**. The third equation expands the definition of **Ad** from the first equation to accomodate a practical OpAmp with a finite voltage gain **Av**. The final equation shows the common-mode gain due to resistor mismatching **Acc**.

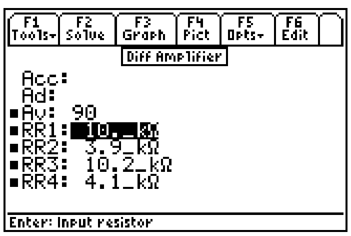
$$Ad = \frac{RR3}{RR1} \qquad \textbf{Eq. 26.8.1}$$

$$Aco = \frac{RR3^2}{RR3 \cdot (RR1 + RR3) \cdot CMRR} \qquad \textbf{Eq. 26.8.2}$$

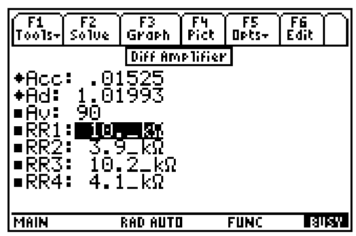
$$Ad = \frac{Av \cdot RR3}{\sqrt{RR1^2 \cdot Av^2 + RR3^2}} \qquad \textbf{Eq. 26.8.3}$$

$$Acc = \frac{RR4 \cdot RR1 - RR2 \cdot RR3}{RR1 \cdot (RR2 + RR4)} \qquad \textbf{Eq. 26.8.4}$$

Example 26.8 - Find the differential mode gain and the current gain for a differential amplifier with bridge resistors RR1, RR2, RR3 and RR4 of 10 kΩ, 3.9 kΩ, 10.2 kΩ and 4.1 kΩ, respectively. Assume a voltage gain of 90.



Entered Values



Calculated Results

Solution - Use the third and fourth equations to compute the solution for this problem. Select these by highlighting each equation and pressing the ENTER key. Press F2 to display the input screen, enter all the known variables and press F2 to solve the equation. The computed results are shown in the screen displays above.

Known Variables: **Av** = 90, **RR1** = 10._kΩ, **RR2** = 3.9_kΩ, **RR3** = 10.2_kΩ, **RR4** = 4.1_kΩ,

Computed Results: **Acc** = .01525, **Ad** = 1.01993

Chapter 27 Solid State Devices

This section covers a variety of topics in solid state electronics.

Read this!

Note: The equations in this section are grouped under topics which describe general properties of semiconductors or devices. Equations for a variety of specific cases and are listed together under a sub-topic heading and are not necessarily a set of consistent equations which can be solved together. Choosing equations in a subtopic w/o regard as to whether the equations represent actual relationships could generate erroneous results or no solution at all. Read the description of each equation set to determine which equations in a sub-topic form a consistent subset before attempting to compute a solution.

- Semiconductor Basics
- PN Junctions
- PN Junction Currents
- Transistor Currents
- Ebers-Moll Equations
- Ideal Currents - pnp
- Switching Transients
- MOS Transistor I
- MOS Transistor II
- MOS Inverter (Resistive)
- MOS Inverter (Saturated)
- MOS Inverter (Depletion)
- CMOS Transistor Pair
- Junction FET

Variables

A complete list of all the variables used in this section along with a brief description and appropriate units is given below.

Variable	Description	Unit
α	CB current gain	unitless
aLGJ	Linearly graded junction parameter	$1/m^4$
A	Area	m^2
A1	EB junction area	m^2
A2	CB junction area	m^2
αf	Forward α	unitless
Aj	Junction area	m^2
αr	Reverse α	unitless
β	CE current gain	unitless
b	Channel width	m
βf	Forward β	unitless
βr	Reverse β	unitless
Cj	Junction capacitance	F

CL	Load capacitance	F
Cox	Oxide capacitance per unit area	F/m^2
D	Diffusion coefficient	m^2/s
DB	Base diffusion coefficient	m^2/s
DC	Collector diffusion coefficient	m^2/s
DE	Emitter diffusion coefficient	m^2/s
Dn	n diffusion coefficient	m^2/s
Dp	p diffusion coefficient	m^2/s
εox	Oxide permittivity	unitless
εs	Silicon Permittivity	unitless
Ec	Conduction band	J
EF	Fermi level	J
Ei	Intrinsic Fermi level	J
Ev	Valence band	J
ffmax	Maximum frequency	Hz
γ	Body coefficient	$V^{.5}$
gd	Drain conductance	S
gm	Transconductance	S
gmL	Transconductance, load device	S
Go	Conductance	S
I	Junction current	A
I0	Saturation current	A
IB	Base current	A
IC	Collector current	A
ICB0	CB leakage, E open	A
ICE0	CE leakage, B open	A
ICsat	Collector I at saturation edge	A
ID	Drain current	A
IDmod	Channel modulation drain current	A
ID0	Drain current at zero bias	A
IDsat	Drain saturation current	A
IE	Emitter current	A
IIf	Forward current	A
Ir	Reverse current	A
Ir0	E-M reverse current component	A
IRG	G-R current	A
IRG0	Zero bias G-R current	A
Is	Saturation current	A
λ	Modulation parameter	1/V
Is	Saturation current	A
kD	MOS constant, driver	A/V^2
kL	MOS constant, load	A/V^2
kn	MOS constant	A/V^2
kn1	MOS process constant	A/V^2
kN	MOS constant, n channel	A/V^2
kP	MOS constant, p channel	A/V^2
KR	Ratio	unitless
L	Transistor length	m
LC	Diffusion length, collector	m
LD	Drive transistor length	m
LE	Diffusion length, emitter	m
LL	Load transistor length	m

LLn	Diffusion length, n	m
lNN	n-channel length	m
Lp	Diffusion length, p	m
lP	p-channel length	m
μn	n (electron) mobility	$m^2/(V*s)$
μp	p (positive charge) mobility	$m^2/(V*s)$
mn	n effective mass	unitless
mp	p effective mass	unitless
N	Doping concentration	$1/m^3$
Na	Acceptor density	$1/m^3$
nnC	n density, collector	$1/m^3$
Nd	Donor density	$1/m^3$
nE	n density, emitter	$1/m^3$
ni	Intrinsic density	$1/m^3$
N0	Surface concentration	$1/m^3$
npo	n density in p material	$1/m^3$
p	p density	$1/m^3$
pB	p density, base	$1/m^3$
φF	Fermi potential	V
φGC	Work function potential	V
pno	p density in n material	$1/m^3$
Qtot	Total surface impurities	unitless
Qb	Bulk charge at bias	C/m^2
Qb0	Bulk charge at 0 bias	C/m^2
Qox	Oxide charge density	C/m^2
Qsat	Base Q, transition edge	C
ρn	n resistivity	Ω*m
ρp	p resistivity	Ω*m
Rl	Load resistance	Ω
τB	lifetime in base	s
τD	Time constant	s
τL	Time constant	s
τo	Lifetime	s
τp	Minority carrier lifetime	s
τt	Base transit time	s
t	Time	s
TT	Temperature	K
tch	Charging time	s
tdis	Discharge time	s
tox	Gate oxide thickness	m
tr	Collector current rise time	s
ts	Charge storage time	s
tsd1	Storage delay, turn off	s
tsd2	Storage delay, turn off	s
Ttr	Transit time	s
V1	Input voltage	V
Va	Applied voltage	V
Vbi	Built-in voltage	V
VBE	BE bias voltage	V
VCB	CB bias voltage	V
VCC	Collector supply voltage	V

VCEs	CE saturation voltage	V
VDD	Drain supply voltage	V
VDS	Drain voltage	V
VDsat	Drain saturation voltage	V
VEB	EB bias voltage	V
VG	Gate voltage	V
VGS	Gate to source voltage	V
VIH	Input high	V
Vin	Input voltage	V
VIL	Input low voltage	V
VL	Load voltage	V
VM	Midpoint voltage	V
VOH	Output high	V
VOL	Output low	V
Vo	Output voltage	V
Vp	Pinchoff voltage	V
VSB	Substrate bias	V
VT	Threshold voltage	V
VT0	Threshold voltage at 0 bias	V
VTD	Depletion transistor threshold	V
VTL	Load transistor threshold	V
VTL0	Load transistor threshold	V
VTN	n channel threshold	V
VTP	p channel threshold	V
W	MOS transistor width	m
WB	Base width	m
WD	Drive transistor width	m
WL	Load transistor width	m
WN	n-channel width	m
WP	p-channel width	m
x	Depth from surface	m
xd	Depletion layer width	m
xn	Depletion width, n side	m
xp	Depletion width, p side	m
Z	JFET width	m

27.1 Semiconductor Basics

The nine equations listed under this sub-topic describe the basic properties used semiconductor technology. The first four equations are a subset which describes the basic properties of free carriers in semiconductors such as resistivity, mobility and diffusion properties. Since the main semiconductor material of commercial use is silicon, a special function **ni(TT)** was developed to calculate the intrinsic carrier density as a function of temperature TT. The first two equations define the resistivities **ρn** and **ρp** of n and p-type semiconductors in terms of the electron and hole mobilities, **μn** and **μp**, and doping densities, **Nd** and **Na.** The next two equations are often called the Einstein equations connecting the electron and hole diffusion coefficients **Dn** and **Dp,** to their mobilities **μn** and **μp** and the temperature **TT.**

$$\rho n = \frac{1}{q \cdot \mu n \cdot Nd} \qquad \textbf{Eq. 27.1.1}$$

$$\rho p = \frac{1}{q \cdot \mu p \cdot Na} \qquad \textbf{Eq. 27.1.2}$$

$$Dn = \frac{k \cdot TT}{q} \cdot \mu n$$ **Eq. 27.1.3**

$$Dp = \frac{k \cdot TT}{q} \cdot \mu p$$ **Eq. 27.1.4**

The Fermi level **EF** is a measure of the chemical potential in silicon and is used to estimate the doping density. For instance in a n-type semiconductor, equation 27.1.5 is used to determine the location of the Fermi level, while in a p-type material equation 27.1.6 is used to establish the Fermi level. In some cases, when both donor and acceptor levels are specified, one has to choose either equation 27.1.5 or 27.1.6 whether **Nd>Na**. At normal temperatures, if **Nd>Na**, the material is defined as n-type and 27.1.6 would be used provided **Nd** in the equation is replaced by **Nd-Na**. The equation 27.1.5 would be used if **Nd<Na**. The intrinsic Fermi level is always defined by the equation 21.1.7. The Fermi level equations define the relative location of **EF**, with respect to the intrinsic Fermi Level **Ei**, in terms of temperature **TT**, **Na** or **Nd**, and the intrinsic carrier density function **ni(TT)**. **Ei** is calculated in the seventh equation in terms of the conduction and valence band levels **Ec** and **Ev**, temperature **TT**, the effective mass of electrons **mn** and holes **mp**.

$$Ei = EF + k \cdot TT \cdot \ln\left(\frac{Na}{ni(TT)}\right)$$ **Eq. 27.1.5**

$$EF = Ei + k \cdot TT \cdot \ln\left(\frac{Nd}{ni(TT)}\right)$$ **Eq. 27.1.6**

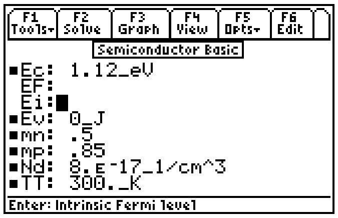
$$Ei = \frac{(Ec + Ev)}{2} + \frac{3}{4} \cdot k \cdot TT \cdot \ln\left(\frac{mp}{mn}\right)$$ **Eq. 27.1.7**

The final two equations are diffusion properties of dopants in silicon based on two distinctly different conditions. The equation 27.1.8 covers the diffusion from an infinite source while the equation 27.1.9 covers diffusion from a finite source. The diffusion of impurities in a semiconductor subject to an infinite source with a surface concentration **N0** at a depth **x** below the surface after a time **t**, given the diffusion coefficient **D** is shown in the next equation. The final equation details the diffusion from a finite impurity source **Q** over a surface area **A** with a classic Gaussian distribution.

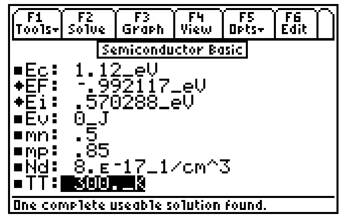
$$\frac{N}{N0} = erfc\left(\frac{x}{2 \cdot \sqrt{D \cdot t}}\right)$$ **Eq. 27.1.8**

$$N = \frac{Qtot}{A \cdot \sqrt{\pi \cdot D \cdot t}} \cdot e^{-\frac{x^2}{4 \cdot D \cdot t}}$$ **Eq. 27.1.9**

Example 27.1.1 - Find the intrinsic and actual Fermi levels for silicon at 300_°K if the conduction band is 1.12 eV above the valence band. The donor density is 8 x 10^{-17} cm^{-3}. The effective masses for electrons and holes are 0.5 and 0.85.



Entered Values



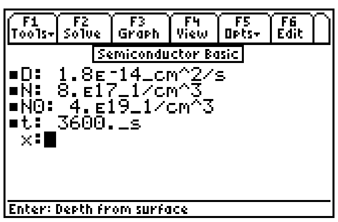
Computed Results

Solution - Since the dopant is a donor, use equations 27.1.6 and 27.1.7 to find compute a solution. Select these equations and press [F2] to display the input screen, enter all the known variables and press [F2] to solve the set of equations. To convert the results of **Ef** and **Ei** to units of electron volts, highlight each value press [F5]/**Opts** and [4]/**Conv** to display the unit menu in the tool bar. The computed results are shown in the screen displays above.

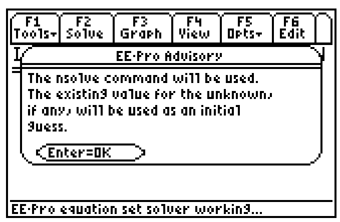
Known Variables: Ec = 1.12_eV, **Ev** = 0_J, **TT** = 300_K, **mn** = .5, **mp** = 0.85,
Nd = 8 x 10E17_cm^-3.

Computed Results: **EF** = -.992117_eV, and **Ei** = .570288_eV

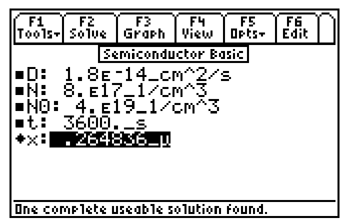
Example 27.1.2 - Find the diffusion penetration depth after one hour for phosphorus atoms with a diffusion coefficient of 1.8 x 10^{-14} cm^2/s. The carrier density at the desired depth is 8 x 10^{17} cm^{-3} while the surface density is 4 x 10^{19} cm^{-3}.



Entered Values



Notice of nsolve routine



Calculated Results

Solution - Equation 21.1.8 is needed to compute the solution for this problem. Select it by highlighting and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation.

The *nsolve* routine is used since **x** is an input for the user defined function *erfc* (see Chapter 15: *Introduction to Equations* for more information about *nsolve* and user-defined functions). The computed results are shown in the screen displays above.

Known Variables: D = 1.8 E-14_cm^2/s, **N** = 8. E17_1/cm^3, **N0** = 4. E19_1/cm^3,
t = 3600._s

Computed Results: **x** = .264836E-7_μ

27.2 PN Junctions

These equations describe the properties of PN junctions. They can be classified in two four distinct categories.

The first equation calculates the built-in voltage **Vbi** for a step junction in terms of temperature **TT**, the doping densities **Nd** and **Na,** and the intrinsic density **ni(TT)**.

$$Vbi = \frac{k \cdot TT}{q} \cdot \ln\left(\frac{Nd \cdot Na}{ni(TT)^2}\right) \qquad \textbf{Eq. 27.2.1}$$

Equations 27.2.2 - 27.2.4 compute the depletion layer widths **xn** and **xp** in the p and the n regions of the junction in terms of the dielectric constant **εs**, doping densities **Nd** and **Na**, built-in voltage **Vbi** and the applied voltage **Va; xd** is the total depletion region width for a given applied voltage.

$$xn = \sqrt{\frac{2 \cdot \varepsilon s \cdot \varepsilon 0 \cdot |Vbi - Va| \cdot Na}{q \cdot Nd \cdot (Na + Nd)}} \qquad \textbf{Eq. 27.2.2}$$

$$xp = \frac{Nd}{Na} \cdot xn \qquad \textbf{Eq. 27.2.3}$$

$$xd = xn + xp \qquad \textbf{Eq. 27.2.4}$$

Equation 27.2.5 calculates the capacitance **Cj** of a PN junction in terms of **εs**, junction area **Aj** and **xd**.

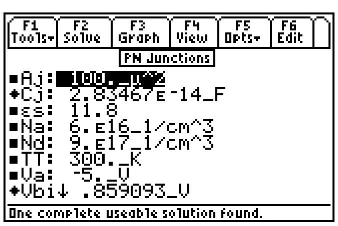
$$Cj = \frac{\varepsilon s \cdot \varepsilon 0}{xd} \cdot Aj \qquad \textbf{Eq. 27.2.5}$$

The last two equations (27.2.6 and 27.2.7) calculate the built-in voltage **Vbi** and depletion layer width **xd** for a linearly-graded junction with a gradient parameter **aLGJ.**

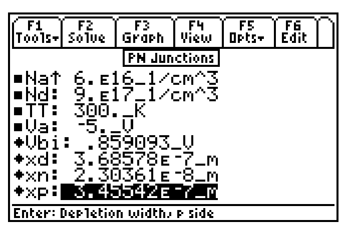
$$Vbi = \frac{2 \cdot k \cdot TT}{q} \cdot \ln\left(\frac{aLGJ \cdot xd}{2 \cdot ni(TT)}\right) \qquad \textbf{Eq. 27.2.6}$$

$$xd = \left(\frac{12 \cdot \varepsilon s \cdot \varepsilon 0}{q \cdot aLGJ} \cdot |Vbi - Va|\right)^{\frac{1}{3}} \qquad \textbf{Eq. 27.2.7}$$

Example 27.2.1 - A PN step junction is characterized by an acceptor doping density of 6 x 10^{16} cm^{-3} and a donor doping density of 9 x 10^{17} cm^{-3}. The junction area is 100 μm^2 at room temperature. For an applied voltage of -5 V, find the built-in potential and junction capacitance. Use a value of 11.8 for the relative permittivity of silicon.



Results: Upper Half



Results: Lower Half

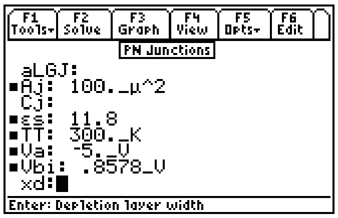
Solution - Use the first five equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: Aj = 100._μ^2, **εs** = 11.8, **Na** = 6E16_1/cm^3, **Nd** = 9.E17_1/cm^3,

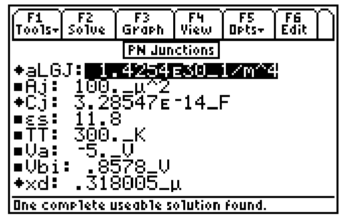
TT = 300._K, **Va** = -5._V

Computed Results: **Cj** = 2.83467E-14_F, **Vbi** = .859093_V, **xd** = 3.68578E-7_m, **xn** = 2.30361E-8_m, **xp** = 3.45542E-7_m

Example 27.2.2 - A linearly graded junction has an area of 100 μ^2, a built-in voltage of 0.8578 V, and an applied voltage of -5.V. The relative permittivity of silicon is 11.8. Under room temperature conditions, what is the junction capacitance, depletion layer width, and the linear-graded junction parameter?



Entered Values



Calculated Results

Solution - Use equations 27.2.5-7 to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: Va = -5_V, **Vbi** = .8578_V, **Aj** = 100._µ^2, **εs** = 11.8, **TT** = 300._°K,

Computed Results: **aLGJ** = 1.4254E30_1/m^4, **Cj** = 3.28547E-14_F, **xd** = .318005_µ

27.3 PN Junction Currents

These equations characterize the relationships for computing currents in PN junctions. They can be classified into four categories.

The first three equations define the junction currents. First, the junction current **I** is expressed in terms of the junction area **Aj**, diffusion coefficients **Dn** and **Dp,** diffusion lengths **LLn** and **Lp**, equilibrium densities of minority carriers **npo** and **pno**, applied bias **Va**, and temperature **TT**. The second equation is a simplified form the first equation where the current **I0** is defined as the multiplier of the exponential term. In this form, it is often called Shockley equation. The third equation calculates this saturation current **I0** in terms of the junction area **Aj**, diffusion coefficients **Dn** and **Dp,** diffusion lengths **LLn** and **Lp**, equilibrium densities of minority carriers **npo** and **pno.** It is used to simplify the first equation.

$$I = q \cdot Aj \cdot \left(\frac{Dn}{LLn} \cdot npo + \frac{Dp}{Lp} \cdot pno \right) \cdot \left(e^{\frac{q \cdot Va}{k \cdot TT}} - 1 \right) \qquad \textbf{Eq. 27.3.1}$$

$$I = I0 \cdot \left(e^{\frac{q \cdot Va}{k \cdot TT}} - 1 \right) \qquad \textbf{Eq. 27.3.2}$$

$$I0 = q \cdot Aj \cdot \left(\frac{Dn}{LLn} \cdot npo + \frac{Dp}{Lp} \cdot pno \right) \qquad \textbf{Eq. 27.3.3}$$

The so-called Generation-Recombination current **IRG0** at 0 bias is calculated by the fourth equation in terms of **Aj**, average recombination time **τo**, intrinsic density **ni**, depletion width **xd**. The fifth equation shows that applying an external voltage **Va**, the generation recombination current **IRG** increases exponentially.

$$IRG0 = \frac{-q \cdot Aj \cdot ni(TT) \cdot xd}{2 \cdot \tau o} \qquad \textbf{Eq. 27.3.4}$$

$$IRG = \frac{q \cdot Aj \cdot ni(TT) \cdot xd}{2 \cdot \tau o} \cdot \left(e^{\frac{q \cdot Va}{2 \cdot k \cdot TT}} - 1 \right) \qquad \textbf{Eq. 27.3.5}$$

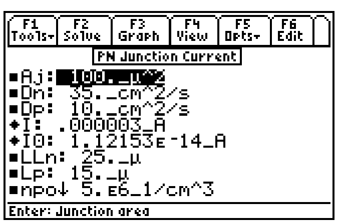
The small signal conducatnce of the junction is defined as **Go**, and is computed in terms of temperature **TT** and currents **I** and **I0**. The last two equations compute the charge storage time **ts** when the diode current is switched externally from **IIf** to **Ir**. It is seen from these two equations that **ts** depends strongly upon the minority carrier lifetime **τp**.

$$Go = \frac{q}{k \cdot TT} \cdot (I + I0) \qquad \textbf{Eq. 27.3.6}$$

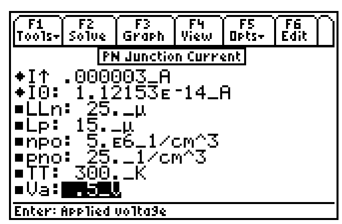
$$ts = \tau p \cdot \ln\left(1 + \frac{IIf}{Ir}\right) \qquad \textbf{Eq. 27.3.7}$$

$$\frac{1}{1 + \frac{Ir}{IIf}} = erf\left(\sqrt{\frac{ts}{\tau p}}\right) \qquad \textbf{Eq. 27.3.8}$$

Example 27.3.1 - A PN Junction is characterized as having a junction area of 100 μm^2, an applied voltage of 0.5 V, and diffusion coefficients for electrons and holes of 35 cm^2/s and 10 cm^2/s, respectively. The diffusion lengths for electrons and holes are 25 μm and 15 μm. The minority carrier densities are 5 x 10^6 cm^{-3} (electrons) and 25 cm^{-3} (holes). Find the junction current and the saturation current for room temperature conditions.



Entered Values



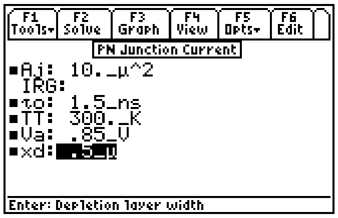
Calculated Results

Solution - Use the equations 27.3.1 and 27.3.2 or 27.3.1 and 27.3.3 to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

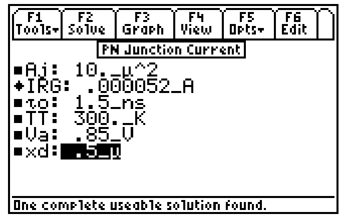
Known Variables: Aj = 100._μ^2, **Dn** = 35._cm^2/s, **Dp** = 10._cm^2/s, **Lln** = 25._μ, **Lp** = 15._ μ, **npo** = 5.E6_1/cm^3, **pno** = 25._1/cm^3, **TT** = 300._°K, **Va** = .5_V

Computed Results: **I** = .000003_A, **I0** = 1.12153E-14_A

Example 27.3.2 -Find the generation-recombination current at room temperature for a pn junction biased at 0.85 V, a junction area of 10 μm^2, a depletion layer width of 0.5 μm, a carrier life time of 1.5 x 10^{-9} s.



Entered Values



Calculated Results

Solution - Use the fifth equation to solve this problem. Select this by highlighting the equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: Aj = 10._ μ^2, **τ0** = 1.5_ns**, TT** = 300_K, **Va** = 0.85, **xd** = .5_μ

Computed Results: **IRG** = .000052_A

27.4 Transistor Currents

The seven equations describe top-level relationships between the emitter, base and collector currents **IE, IB** and **IC**, respectively.

The first equation defines the common base current gain α as the ratio of **IC** to **IE**. The second equation defines the common emitter current gain β in terms of **α.**

$$\alpha = \frac{IC}{IE}$$ **Eq. 27.4.1**

$$\beta = \frac{\alpha}{1-\alpha}$$ **Eq. 27.4.2**

The third equation represents Kirchoff's current law for the bipolar junction transistor.

$$IE = IB + IC$$ **Eq. 27.4.3**

The next three equations represent alternate forms of the collector current in terms of **α, IE, IB, β** and the leakage currents **ICE0**, and **ICB0**.

$$IC = \alpha \cdot IE + ICB0$$ **Eq. 27.4.4**

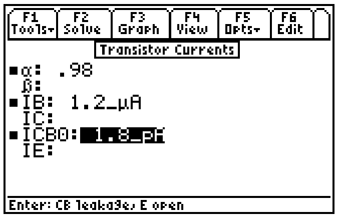
$$IC = \frac{\alpha}{1-\alpha} \cdot IB + \frac{ICB0}{1-\alpha}$$ **Eq. 27.4.5**

$$IC = \beta \cdot IB + ICE0$$ **Eq. 27.4.6**

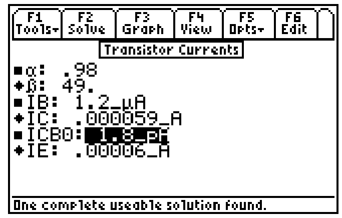
The final equation links **ICE0** and **ICB0** in terms of β.

$$ICE0 = ICB0 \cdot (\beta + 1)$$ **Eq. 27.4.7**

Example 27.4 - A junction transistor has the following parameters: α is 0.98, the base current is 1.2 μA while ICBO is 1.8 pA. Find the β, emitter and collector currents.



Entered Values



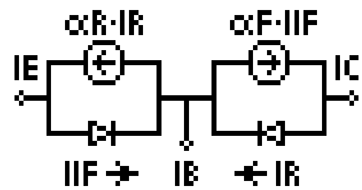
Calculated Results

Solution - A few different choices are available, however the results might differ slightly due to the combination of equations used. The second, third and fourth equations can be used to solve this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: $\alpha = .98$, **IB** $= 1.2\_\mu A$, **ICB0** $= 1.8\_pA$

Computed Results: $\beta = 49.$, **IC** $= .000059\_A$, **IE** $= .00006\_A$

27.5 Ebers-Moll Equations



These ten equations show a collection of relevant relationships developed by J. J. Ebers and J. L. Moll in the mid-1950s recognizing the reciprocal behavior of bipolar function transistors.

The first three equations connect the emitter, collector and base currents **IE, IC** and **IB** in terms of forward and reverse current gain **αf** and **αr** and the forward and reverse currents **IIf** and **Ir.**

$$IE = IIf - \alpha r \cdot Ir$$ **Eq. 27.5.1**

$$IC = \alpha f \cdot IIf - Ir$$ **Eq. 27.5.2**

$$IB = (1 - \alpha f) \cdot IIf + (1 - \alpha r) \cdot Ir$$ **Eq. 27.5.3**

The corresponding common emitter current gains in the forward and reverse directions are given by **βf** and **βr**, in terms of **αf** and **αr** in the fourth and fifth equations.

$$\beta f = \frac{\alpha f}{1 - \alpha f}$$ **Eq. 27.5.4**

$$\beta r = \frac{\alpha r}{1 - \alpha r}$$ **Eq. 27.5.5**

The reciprocity relationships between **αf** and **αr**, **IIf** and **Ir**, and the saturation current **Is** are defined by the next two equations. The recognition of this reciprocity relationship has been the basis of computing switching characteristics of a transistor.

$$\alpha f \cdot IIf = Is$$ **Eq. 27.5.6**

$$\alpha r \cdot Ir = Is \qquad \textbf{Eq. 27.5.7}$$

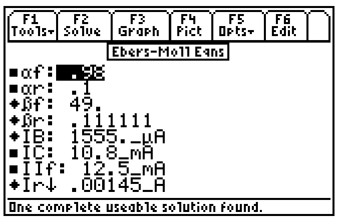
The last three equations define **ICE0** and **ICB0** in terms of **αf , αr**, **βf** and **Ir0.**

$$ICB0 = (1 - \alpha r \cdot \alpha f) \cdot Ir0 \qquad \textbf{Eq. 27.5.8}$$

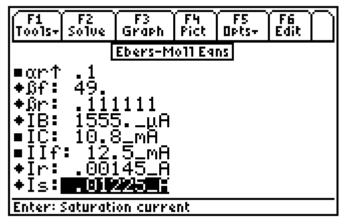
$$ICE0 = ICB0 \cdot (\beta f + 1) \qquad \textbf{Eq. 27.5.9}$$

$$ICE0 = \frac{Ir0 \cdot (1 - \alpha f \cdot \alpha r)}{1 - \alpha f} \qquad \textbf{Eq. 27.5.10}$$

Example 27.5.1 - A junction transistor has a forward and reverse α of 0.98 and 0.10 respectively. The collector current is 10.8 mA while the forward current is 12.5 mA. respectively. Compute the base, saturation and reverse currents, in addition to the forward and the reverse β.



Display (Upper-half)



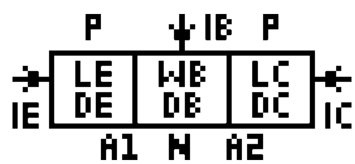
Display (Lower-half)

Solution - The second through sixth equations are needed to solve this problem. Select these using the highlight bar and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation set. The computed results are shown in the screen displays above.

Known Variables: **αf** = .98, **αr** = .1, **IC** = 10.8_mA, **IIf** = 12.5_mA

Computed Results: **βf** = 49., **βr** = .111111, **IB** = 1555.μA, **Ir** = .00145_A, **Is** = .01225._A

27.6 Ideal Currents - pnp



The four equations in this set form the basis of transistor action resulting in emitter, base and collector currents in a pnp transistor. The first three equations show the emitter, collector and base currents **IE, IC**, and **IB** in terms of emitter base area **A1,** diffusion coefficients **DE, DB**, and **DC,** the minority carrier densities **nE, pB**, and **nC,** emitter and collector diffusion lengths **LE** and **LC,** base width **WB,** emitter-base and collector base voltages **VEB** and **VCB,** base collection junction **A2** and temperature **TT.** The last equation shows the relationship between α, **DB, pB, WB, DE, nE** and **LE**. The corresponding equations for an npn transistor can be derived from this equation set by proper use of sign conventions.

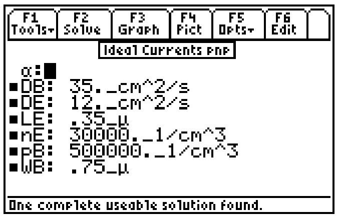
$$IE = q \cdot A1 \cdot \left(\frac{DE \cdot nE}{LE} + \frac{DB \cdot pB}{WB}\right) \cdot \left(e^{\frac{q \cdot VEB}{k \cdot TT}} - 1\right) - \frac{q \cdot A2 \cdot DB}{WB} \cdot pB \left(e^{\frac{q \cdot VCB}{k \cdot TT}} - 1\right) \qquad \textbf{Eq. 27.6.1}$$

$$IC = \frac{q \cdot A1 \cdot DB \cdot pB}{WB} \cdot \left(e^{\frac{q \cdot VEB}{k \cdot TT}} - 1\right) - q \cdot A2 \cdot \left(\frac{DC \cdot nnC}{LC} + \frac{DB \cdot pB}{WB}\right) \cdot \left(e^{\frac{q \cdot VCB}{k \cdot TT}} - 1\right) \qquad \textbf{Eq. 27.6.2}$$

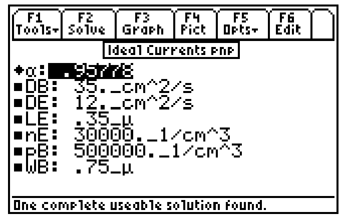
$$IB = \frac{q \cdot A1 \cdot DE}{LE} \cdot nE \cdot \left(e^{\frac{q \cdot VBE}{k \cdot TT}} - 1 \right) + \frac{q \cdot A2 \cdot DC}{LC} \cdot nnC \left(e^{\frac{q \cdot VCB}{k \cdot TT}} - 1 \right)$$ **Eq. 27.6.3**

$$\alpha = \frac{\frac{DB \cdot pB}{WB}}{\frac{DB \cdot pB}{WB} + \frac{DE \cdot nE}{LE}}$$ **Eq. 27.6.4**

Example 27.6 - Find the emitter current gain α for a transistor with the following properties: base width of 0.75 μm, base diffusion coefficient of 35 cm^2/s, emitter diffusion coefficient of 12 cm^2/s, and emitter diffusion length of 0.35 μm. The emitter electron density is 30,000 cm^{-3} and the base density is 500,000 cm^{-3}.



Entered Values



Calculated Results

Solution - Use the last equation to compute the solution for this problem. Select this by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: **DB** = 35._cm^2/s, **DE** = 12.cm^2/s, **LE** = .35_μ, **nE** = 30000._1/cm^3, **pB** = 500000._1/cm^3, **WB** = .75_μ.

Computed Results: α = .95778

27.7 Switching Transients

These six equations compute the key relationships in determining switching response times of bipolar transistors. The work of Ebers and Moll was supplemented by Gummel to model transistor behavior in several different ways. The concept of charge in the base of the transistor controlling switching times became an important contribution to switching theory.

The first equation expresses the base charge at the edge of saturation **Qsat** in terms of the collector saturation current **ICsat** and the base transit time **τt**. The collector saturation is determined (approximately) by the second equation in terms of supply voltage **VCC** and load resistance **Rl**.

$$Qsat = ICsat \cdot \tau t$$ **Eq. 27.7.1**

$$ICsat = \frac{Vcc}{Rl}$$ **Eq. 27.7.2**

The third equation calculates the turn-on transient time **tr** in terms of base recombination time **τB**, **ICsat**, base current **IB** and base transit time **τt**. The fourth equation computes the storage delay **tsd1** when the bipolar transistor is switched from the saturation region to cutoff by changing the base current from **IB** to 0. The penultimate equation shows the storage delay **tsd2** when the base current is switched from **IB** to **-IB**. The final equation computes the so called saturation voltage **VCEs**, the voltage drop between the collector and the emitter under full saturation, in terms of the collector and base currents **IC** and **IB** and the forward and reverse α's **αf** and **αr**.

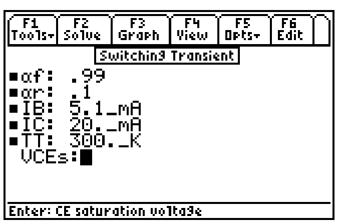
$$tr = \tau B \cdot \ln\left(\frac{1}{1-\frac{ICsat \cdot \tau t}{IB \cdot \tau B}}\right) \qquad \textbf{Eq. 27.7.3}$$

$$tsd1 = \tau B \cdot \ln\left(\frac{IB \cdot \tau B}{ICsat \cdot \tau t}\right) \qquad \textbf{Eq. 27.7.4}$$

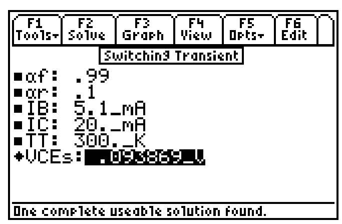
$$tsd2 = \tau B \cdot \ln\left(\frac{2 \cdot IB \cdot \tau B}{ICsat \cdot \tau t \cdot \left(1+\frac{IB \cdot \tau B}{ICsat \cdot \tau t}\right)}\right) \qquad \textbf{Eq. 27.7.5}$$

$$VCEs = \frac{k \cdot TT}{q} \cdot \ln\left(1+\frac{\frac{IC}{IB} \cdot (1-\alpha r)}{\alpha r \cdot \left(1-\frac{\frac{IC}{IB} \cdot (1-\alpha f)}{\alpha f}\right)}\right) \qquad \textbf{Eq. 27.7.6}$$

Example 27.7 - Find the saturation voltage for a switching transistor at room temperature when a base current of 5.1 mA is used to control a collector current of 20 mA. The forward and reverse α's are 0.99 and 0.1 respectively.



Entered Values



Calculated Results

Solution - Use the last equation to solve this problem. Select the equation by highlighting and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed result is shown in the screen display above.

Known Variables: **αf** = .99, **αr** = .1, **IB** = 5.1_mA, **IC** = 20._mA **TT** = 300._K

Computed Results: **VCEs** = .093869_V

27.8 MOS Transistor I

The seven equations in this section form the basic equations of charge, capacitance and threshold voltage for a MOS transistor. The first equation shows the Fermi potential **ϕF** defined in terms of temperature **TT**, the intrinsic carrier density **ni**, and the hole density **p**.

$$\phi F = \frac{k \cdot TT}{q} \cdot \ln\left(\frac{ni(TT)}{p}\right) \qquad \textbf{Eq. 27.8.1}$$

The second equation shows the depletion layer **xd** at the surface of a p-type semiconductor in terms of the relative dielectric constant **εs**, Fermi potential **ϕF**, and doping density **Na**.

$$xd = \sqrt{\frac{2 \cdot \varepsilon s \cdot \varepsilon 0 \cdot (2 \cdot \phi F)}{q \cdot Na}} \qquad \textbf{Eq. 27.8.2}$$

The third equation computes the charge density **Qb0** accumulated at the surface of the semiconductor due to band bending at a substrate bias of 0_V. The fourth equation shows how surface charge density **Qb** is influenced by the substrate bias **VSB**.

$$Qb0 = -\sqrt{2 \cdot q \cdot Na \cdot \varepsilon s \cdot \varepsilon 0 \cdot \left|2 \cdot \phi F\right|} \qquad \textbf{Eq. 27.8.3}$$

$$Qb = -\sqrt{2 \cdot q \cdot Na \cdot \varepsilon s \cdot \varepsilon 0 \cdot \left|-2 \cdot \phi F + VSB\right|} \qquad \textbf{Eq. 27.8.4}$$

A thin oxide layer with a thickness **tox** on the surface of the semiconductor results in a capacitance **Cox** per unit area in the fifth equation.

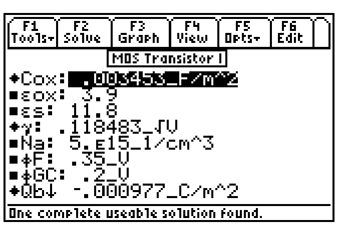
$$Cox = \frac{\varepsilon ox \cdot \varepsilon 0}{tox} \qquad \textbf{Eq. 27.8.5}$$

The sixth equation defines the body coefficient **γ** in terms of **Cox**, **Na**, and **εs**. The final equation computes the threshold voltage for a MOS system with a work function potential of **ϕGC** and residual oxide charge density **Qox**.

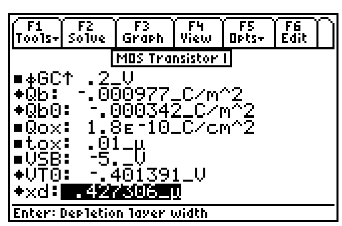
$$\gamma = \frac{1}{Cox} \cdot \sqrt{2 \cdot q \cdot Na \cdot \varepsilon s \cdot \varepsilon 0} \qquad \textbf{Eq. 27.8.6}$$

$$VT0 = \phi GC - 2 \cdot \phi F - \frac{Qb0}{Cox} - \frac{Qox}{Cox} \qquad \textbf{Eq. 27.8.7}$$

Example 27.8 - A p-type silicon with a doping level of 5 x 10^{15} cm^{-3} has an oxide thickness of 0.01 μm and oxide charge density of 1.8 x 10^{-10}_C/cm^2. A -5 V bias is applied to the substrate which has a Fermi potential of 0.35 V. Assume the relative permittivity of silicon and silicon dioxide is 11.8 and 3.9, respectively, and the work function is 0.2 V.



Display (Upper-half)



Display (Lower-half)

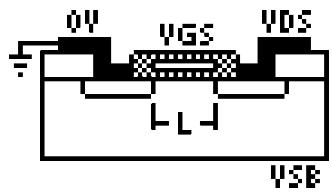
Solution - Use the second through last equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: **εox** = 3.9, **εs** = 11.8, **Na** = 5.E15_1/cm^3, **φF** = .35_V, **φGC** = .2V, **Qox** = 1.8E-10_C/cm^2, **tox** = .01_μ, **VSB** = -5._V

Computed Results: **Cox** = .003453_F/m^2, **γ** = .118483_√V, **Qb** = -.000977_C/m^2, **Qb0** = -.000342_C/m^2, **VT0** = -.401391_V, **xd** = .427306_μ

27.9 MOS Transistor II

These equations describe the performance characteristics of a MOS transistor. The first two equations give two alternate forms for the process constant **kn1** in terms of electron mobility **μn**, oxide capacitance per unit area **Cox**, relative oxide permittivity **εox**, and oxide thickness **tox**. The third equation links the process constant **kn1** to the device constant **kn**, device length **L**, and width **W**.



$$kn1 = \mu n \cdot Cox$$ **Eq. 27.9.1**

$$kn1 = \frac{\mu n \cdot \varepsilon ox \cdot \varepsilon 0}{tox}$$ **Eq. 27.9.2**

$$kn = kn1 \cdot \frac{W}{L}$$ **Eq. 27.9.3**

The fourth equation defines **IDmod** the drain current, when the transistor is operating under saturation, in terms of **kn**, gate voltage **VGS**, threshold voltage **VT**, modulation parameter **λ**, and drain voltage **VDS**. The basic physics behind the increase in drain current comes from the channel widths being non-uniform under the gate because f a finite potential difference between the source and the drain terminals.

$$ID\text{mod} = \frac{kn}{2} \cdot (VGS - VT)^2 \cdot (1 + \lambda \cdot VDS)$$ **Eq. 27.9.4**

The fifth equation computes the drain current **ID** under linear or saturated conditions in terms of **kn**, **VGS**, **VT**, and **VDS**.

$$ID = \left\{ \begin{array}{l} \frac{kn}{2} \cdot \left(2 \cdot (VGS - VT) \cdot VDS - VDS^2\right), VGS - VT \le VDS \\ \frac{kn}{2} \cdot (VGS - VT)^2, else \end{array} \right\}$$ **Eq. 27.9.5**

The expression for the threshold voltage **VT** is defined in terms of zero substrate bias threshold voltage **VTO**, body coefficient **γ**, substrate bias **VSB**, and Fermi potential **φF**.

$$VT = VT0 + \gamma \cdot \left(\sqrt{|-2 \cdot \phi F + VSB|} - \sqrt{2 \cdot \phi F}\right)$$ **Eq. 27.9.6**

The last four equations calculate performance parameters transconductance **gm**, transit time through the channel **Ttr**, maximum frequency of operation **ffmax**, and drain conductance **gd**.

The last four equations calculate performance parameters transconductance **gm**, transit time through the channel **Ttr**, maximum frequency of operation **ffmax**, and drain conductance **gd**.

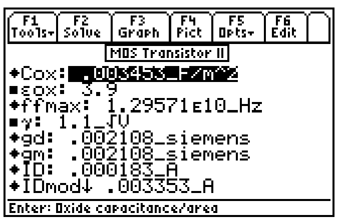
$$gm = kn \cdot (VGS - VT) \qquad \textbf{Eq. 27.9.7}$$

$$Ttr = \frac{\frac{4}{3} \cdot L^2}{\mu n \cdot (VGS - VT)} \qquad \textbf{Eq. 27.9.8}$$

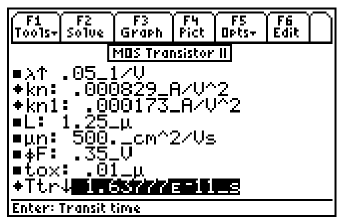
$$ff\ \max = \frac{gm}{2 \cdot \pi \cdot Cox \cdot W \cdot L} \qquad \textbf{Eq. 27.9.9}$$

$$gd = kn \cdot (VGS - VT) \qquad \textbf{Eq. 27.9.10}$$

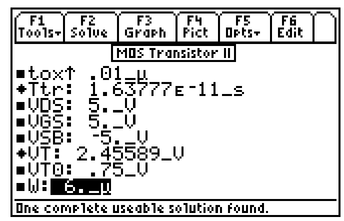
Example 27.9 - An nMOS transistor has a 6 μ width and 1.25μ gate length. The electron mobility is 500 cm^2/V/s. The gate oxide thickness is 0.01μm. The oxide permittivity is 3.9. The zero bias threshold voltage is 0.75 V. The bias factor is 1.1 $V^{1/2}$. The drain and gate voltages are 5 V, and the substrate bias voltage is -5 V. Assuming that λ is 0.05 V^{-1} and ϕF is 0.35 V, find all the relevant performance parameters.



Upper Display



Middle Display



Lower Display

Solution - Use all of the equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: **εox** = 3.9, **γ** = 1.1_√V, **λ** = .05_1/V, **L** = 1.25 μ, **μn** = 500_cm^2/Vs, **ϕF** = .35_V, **tox** = .01_μ, **VDS** = 5._V, **VGS** = 5._V, **VSB** = -5._V, **VT0** = .75_V, **W** = 6._μ

Computed Results: **Cox** = .003453_F/m^2, **ffmax** = 1.29571E10_Hz, **gd** = .002108_siemens, **gm** = .002108_siemens, **ID** = .000183_A, **IDmod** = .003353_A, **kn** = .000829_A/V^2, **kn1** = .000173_A/V^2, **Ttr** = 1.63777E-11_s, **VT** = 2.45589_V

27.10 MOS Inverter (Resistive Load)

This section lists the design equations for a MOS inverter with a resistive load.

The first equation specifies the device constant **kD** for the driver transistor in terms of its gate capacitance **Cox**, mobility **μn**, width **WD**, and channel length **LD**.

$$kD = \frac{\mu n \cdot Cox \cdot WD}{LD} \qquad \textbf{Eq. 27.10.1}$$

The second equation specifies the output high voltage **VOH** when the input to the driver **VDD** is below the threshold voltage **VT**. The third equation determines **VOL**, the output low voltage, **Vo** when the input is driven high. This equation is a quadratic in **VOL**, and the solution is meaningful for positive values of **VOL**. The next equation computes **VIH** in the linear region of the drain current equation.

$$VOH = VDD \qquad \textbf{Eq. 27.10.2}$$

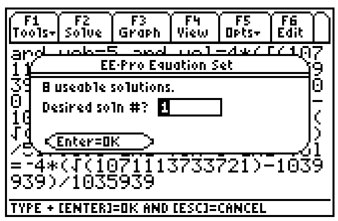
$$VOL^2 - 2\cdot\left(\frac{1}{kD\cdot Rl} + VDD - VT\right)\cdot VOL + \frac{2VDD}{kD\cdot Rl} = 0 \qquad \textbf{Eq. 27.10.3}$$

$$\frac{kD}{2}\cdot\left(2\cdot(VIH - VT)\cdot Vo - Vo^2\right) = \frac{(VDD - Vo)}{Rl} \qquad \textbf{Eq. 27.10.4}$$

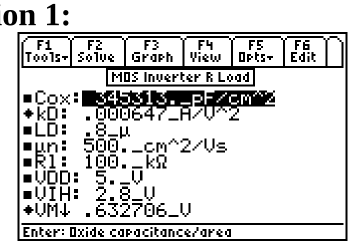
The final equation computes the midpoint voltage **VM** for which the driver transistor is in saturation.

$$\frac{kD}{2}\cdot(VM - VT)^2 = \frac{(VDD - VM)}{Rl} \qquad \textbf{Eq. 27.10.5}$$

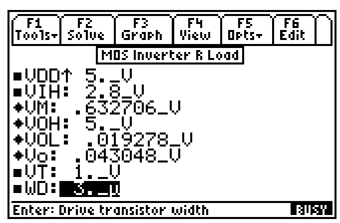
Example 27.10.1 - Find the driver device constant, output and mid-point voltages for a MOS inverter driving a 100_kΩ resistive load. Driver properties include a 3 μm wide gate, a length of 0.8 μm, **Cox** of 345313 pF/cm^2. The electron mobility is 500 cm^2/V/s, **VIH**=2.8 V, **VT** = 1_V and **VDD** = 5_V.



Solution 1:

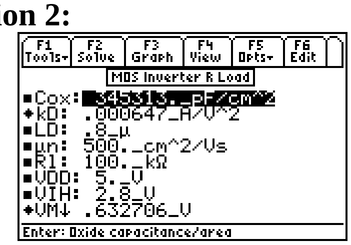


Upper Display

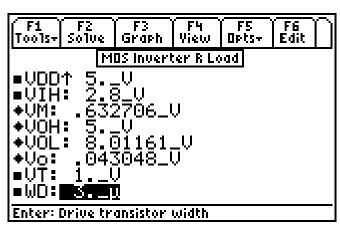


Lower Display

Solution 2:

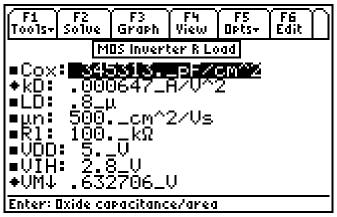


Upper Display

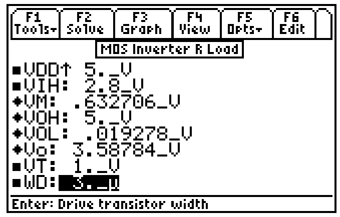


Lower Display

Solution 3:

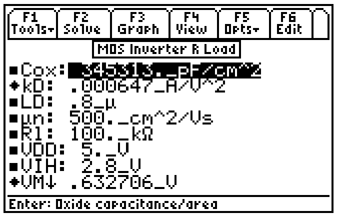


Upper Display

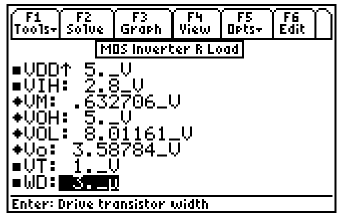


Lower Display

Solution 4:

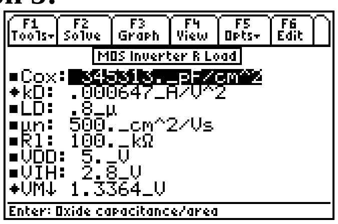


Upper Display

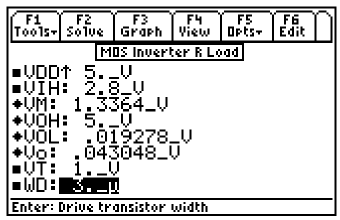


Lower Display

Solution 5:

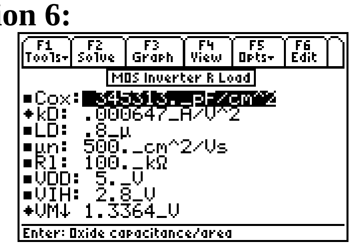


Upper Display

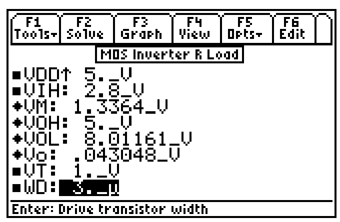


Lower Display

Solution 6:

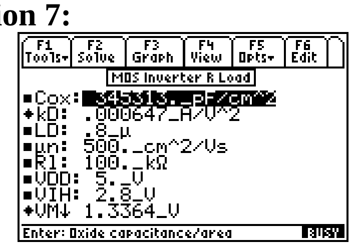


Upper Display

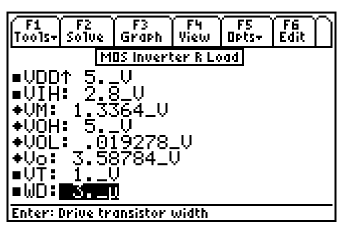


Lower Display

Solution 7:

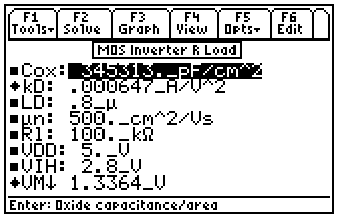


Upper Display

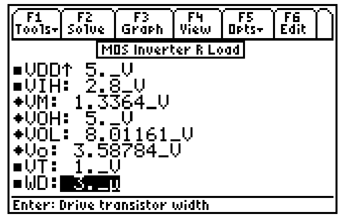


Lower Display

Solution 8:



Upper Display



Lower Display

Solution - Use all of the equations to solve for the problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation set. Eight complete solutions are generated, in this case, requiring the user to select an answer most relavent to the situation (ie: physical significance, realistic values for components, currents, etc). Mathematically setting up and solving the problem takes some time. Anticipate about 20-30 seconds for *EE·Pro* to display a dialogue box prompting the user to select a solution set to be displayed. Select the number of a solution to be viewed (ie: 1, 2, 3...etc.) and press [ENTER] twice.

To view another solution, press [F2] to resolve the problem and select the number of another available solution. The computed results for all four solutions are shown in the screen displays above. In this example **VOH, VOL, VIL, Vo** and **VM** have to be positive and between 0 and **VDD**.

Known Variables: Cox = 345313_pF/cm^2, **LD** = .8_µ, **µN** = 500._cm^2/Vs, **R1** = 100._kΩ, **VDD** = 5._V, **VIH** = 2.8_V, **VT** = 1_V, **WD** = 3._µ

Computed Results:
Solution 1: **kD** = .000647_A/V^2, **VM** = .632706_V, **VOH** = 5._V, **VOL** = .019278_V, **Vo** = .043048_V
Solution 2: **kD** = .000647_A/V^2, **VM** = .632706_V, **VOH** = 5._V, **VOL** = 8.01161_V, **Vo** = .043048_V
Solution 3: **kD** = .000647_A/V^2, **VM** = .632706_V, **VOH** = 5._V, **VOL** = .019278_V, **Vo** = 3.58784_V
Solution 4: **kD** = .000647_A/V^2, **VM** = .632706_V, **VOH** = 5._V, **VOL** = 8.01161_V, **Vo** = 3.58784_V
Solution 5: **kD** = .000647_A/V^2, **VM** = 1.3364_V, **VOH** = 5._V, **VOL** = .019278_V, **Vo** = .043048_V
Solution 6: **kD** = .000647_A/V^2, **VM** = 1.3364_V, **VOH** = 5._V, **VOL** = 8.01161_V, **Vo** = .043048_V
Solution 7: **kD** = .000647_A/V^2, **VM** = 1.3364_V, **VOH** = 5._V, **VOL** = .019278_V, **Vo** = 3.58784_V
Solution 8: **kD** = .000647_A/V^2, **VM** = 1.3364_V, **VOH** = 5._V, **VOL** = 8.01161_V, **Vo** = 3.58784_V

27.11 MOS Inverter (Saturated Load)

The features of a MOS inverter with a saturated enhancement transistor load are described in this section.

The first two equations define the device constants for the load transistor (**kL**, **WL**, **LL**) and the driver transistor (**kD**, **WD**, **LD**) in terms of the process parameters, namely mobility **µn** and gate capacitance per unit area **Cox**. The third equation defines the geometry ratio **KR** of the load and drive transistors.

$$kL = \frac{\mu n \cdot Cox \cdot WL}{LL}$$ **Eq. 27.11.1**

$$kD = \frac{\mu n \cdot Cox \cdot WD}{LD}$$ **Eq. 27.11.2**

$$KR = \frac{kD}{kL}$$ **Eq. 27.11.3**

The output high voltage **VOH** is calculated in terms of the drain supply voltage **VDD**, the threshold voltage at zero bias **VT0,** the fermi potential **ϕF** and the body coefficient **γ** in the fourth equation. The fifth equation defines the input voltage **Vin** in terms of the ratio **KR** between the load **kL** and drive **kD** MOS constants, **VDD**, the threshold of the load and drive transistors **VTL** and **VTD**. The sixth equation defines the threshold voltage of the load transistor, **VTL**.

$$VOH = VDD - \left(VT0 + \gamma \cdot \left(\sqrt{(VOH + 2 \cdot \phi F)} - \sqrt{2 \cdot \phi F}\right)\right)$$ **Eq. 27.11.4**

$$KR \cdot \left(2 \cdot (Vin - VTD) \cdot Vo - Vo^2\right) = (VDD - Vo - VTL)^2$$ **Eq. 27.11.5**

$$VTL = VT0 + \gamma \cdot \left(\sqrt{Vo + 2 \cdot \phi F} - \sqrt{2 \cdot \phi F}\right)$$ **Eq. 27.11.6**

The equation that follows computes the input high voltage **VIH** in terms of **VDD**, **VTL**, **KR** and **VT0**. The eighth equation computes the output voltage **Vo** in terms of **VDD**, **VTL**, **VT0** and **KR**. The last five equations show the performance parameters of the inverter circuit.

$$VIH = \frac{2 \cdot (VDD - VTL)}{\sqrt{3 \cdot KR + 1}} + VT0$$ **Eq. 27.11.7**

$$Vo = \frac{\left(VDD - VTL + VT0 + VT0 \cdot \sqrt{KR}\right)}{1 + \sqrt{KR}}$$ **Eq. 27.11.8**

The equation for **gmL** defines the transconductance of the load circuit while the equation for **τL** defines the characteristic time to charge the load capacitance **CL**.

$$gmL = kL \cdot (VDD - VTL)$$ **Eq. 27.11.9**

$$\tau L = \frac{CL}{gmL}$$ **Eq. 27.11.10**

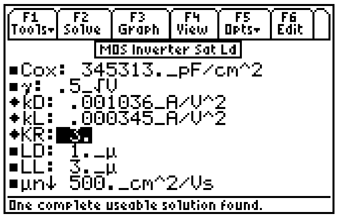
The charging time **tch** is the time required for the output rise to move from **Vo** to **V1**. The final two equations focus on the characteristic time **τD** and discharge time **tdis** for the circuit.

$$tch = \tau L \cdot \left(\frac{V1}{Vo} - 1\right)$$ **Eq. 27.11.11**

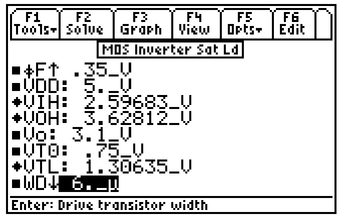
$$\tau D = \frac{CL}{kD \cdot (V1 - VT0)}$$ **Eq. 27.11.12**

$$tdis = \tau D \cdot \left(\frac{2 \cdot VTD}{V1 - VTD} + \ln\left(\frac{2 \cdot (V1 - VTD)}{Vo} - 1\right)\right)$$ **Eq. 27.11.13**

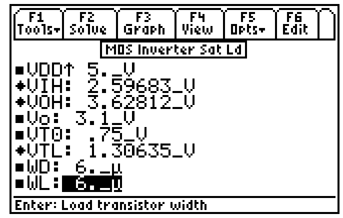
Example 27.11 - A MOS Inverter with a saturated MOS transistor as its load. The driver has a length of 1_μ and a width of 6μ while the load has a length of 3_μ and a width of 6_μ. The Fermi level for the substrate material is 0.35_V, a zero-bias threshold of 1.00 V. Assume a drain supply voltage of 5_V, and an output voltage of 3.0_ V find the output high voltage, the input high voltage, and the threshold of the load device. Assume a input voltage of 2.5_V.



Upper Display



Middle Display



Lower Display

Solution - Use Equations 27.11.1-27.11.4 and 27.11.6-17.11.7 to get a complete solution to the problem on hand. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above. It takes time to solve this problem.

Known Variables: Cox = 345313_pF/cm^2, **μn =** 500_cm^2/(V*s)**, LL =** 3_μ, **LD =** 1_μ, **WL =** 6_μ, **WD =** 6_μ, **γ**=.5_√V, **ϕF**=.35_V, **VDD**=5._V, **Vo**=3.1_V, **VT0**=.75_V

Computed Results: **kL**=0.000345_A/V^2, **kD** = .001036_A/V^2, **KR** = 3
VIH=2.59683_V, **VOH**=3.62812_V, **VTL**=1.30635_V.

27.12 MOS Inverter (Depletion Load)

This section lists the design equations for a MOS inverter with a depletion load.

The first two equations compute device constants **kL** and **kD** for the load and the driver transistors in terms of their geometries **WD**, **WL**, **LD**, and **LL**.

$$kL = \frac{\mu n \cdot Cox \cdot WL}{LL} \qquad \textbf{Eq. 27.12.1}$$

$$kD = \frac{\mu n \cdot Cox \cdot WD}{LD} \qquad \textbf{Eq. 27.12.2}$$

At the output low and output high, **VOL** and **VOH**, the driver is in the linear region while the load device is saturated. The next equation finds the threshold voltage **VTL** for the load device in terms of its zero bias threshold **VTL0**, Fermi potential **ϕF**, and body coefficient **γ**.

$$\frac{kD}{2} \cdot \left(2(VOH - VT0) \cdot VOL - VOL^2\right) = \frac{kL}{2} \cdot VTL^2 \qquad \textbf{Eq. 27.12.3}$$

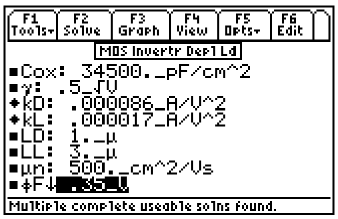
$$VTL = VTL0 + \gamma \cdot \left(\sqrt{Vo + 2 \cdot \phi F} - \sqrt{2 \cdot \phi F}\right) \qquad \textbf{Eq. 27.12.4}$$

The charging time **tch** for the **CL** is defined next. The current in the depletion load **I0** is given by the last equation.

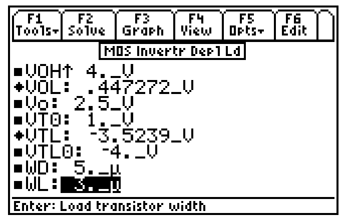
$$tch = \frac{CL \cdot VL}{I0} \qquad \textbf{Eq. 27.12.5}$$

$$I0 = kL \cdot VTL^2 \qquad \textbf{Eq. 27.12.6}$$

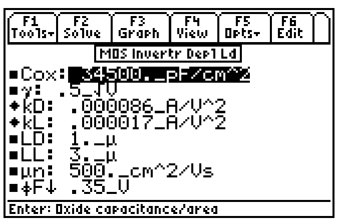
Example 27.12 - A MOS inverter with a depletion mode transistor as the load has a driver transistor 5_μ wide and 1_μ long while the load is a depletion mode device with a 0 bias threshold of -4_V, 3_μ long and 3_μ wide. Given an electron mobility of 500_cm^2/(V*s) and a depletion threshold of -4_V; for the load device, compute VOH and VTL when the output voltage is 2.5_V. Assume VOL to be .4_V and .5 for γ.



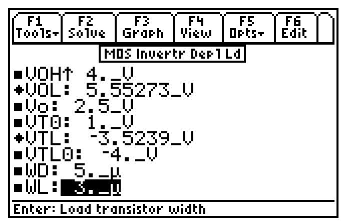
Solution 1: Upper Display



Solution 1: Lower Display



Solution 2: Upper Display



Solution 2: Lower Display

Solution - The problem can be solved when equations 27.12.1 - 27.12.4 are selected. Highlight each of these and press [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations.

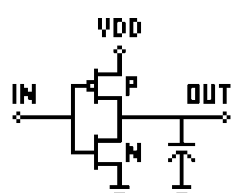
Two complete solutions are computed for this case and are shown in the screen displays above.

Known Variables: **Cox** = 34500_pF/cm^2, **γ** = .5_V^.5, **LD** = 1_μ, **LL** = 3_μ,
μn = 500_cm^2/(V*s), ϕ**F** = .35_V, **VOH** = 4._V, **Vo** = 2.5_V, **VT0** = 1_V,
VTL0 = -4._V, **WD** = 5_μ, **WL** = 3_μ

Computed Results:
Solution 1: **kD** = .000086_A/V^2, **kL** = .000017_A/V^2, **VOL** = .447272_V, **VTL** = -3.5239_V
Solution 2: **kD** = .000086_A/V^2, **kL** = .000017_A/V^2, **VOL** = 5.55273_V, **VTL** = -3.5239_V

27.13 CMOS Transistor Pair

These five equations describe the properties of a CMOS inverter. The first two equations compute device parameters for n and p channel devices. The second pair of equations compute input voltages **VIH** and **VIL**. The last equation computes **Vin** when the n-channel driver is in saturation and the p-channel device is in the linear region.



$$kP = \frac{\mu p \cdot Cox \cdot WP}{lP} \qquad \textbf{Eq. 27.13.1}$$

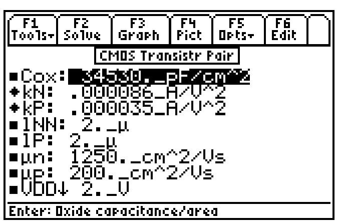
$$kN = \frac{\mu n \cdot Cox \cdot WN}{lNN} \qquad \textbf{Eq. 27.13.2}$$

$$VIH = 2 \cdot Vo + VTN + \frac{\frac{kP}{kN} \cdot \left(VDD - |VTP|\right)}{1 + \frac{kP}{kN}} \quad \{VDD > |VTP|\} \qquad \textbf{Eq. 27.13.3}$$

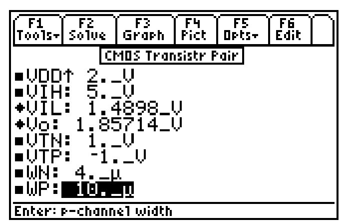
$$VIL = \frac{\left(2 \cdot Vo - VDD - VTP + \frac{kN}{kP} \cdot VTN\right)}{1 + \frac{kN}{kP}} \quad \{VDD \le |VTP|\} \qquad \textbf{Eq. 27.13.4}$$

$$\frac{kN}{2} \cdot (Vin - VTN)^2 = \frac{kP}{2} \cdot \left(VDD - Vin - |VTP|\right)^2 \qquad \textbf{Eq. 27.13.5}$$

Example 27.13 - Find the transistor constants for an N and P MOS transistor pair given:
N transistor: **WN**=4 µm, **lNN**=2. µm, **µn**=1250 cm^2/V/s, **Cox**=34530 pF/cm^2, **VTN**=1 V
P transistor: **VTP**= -1V, **Wp**=10 µm, **µp**=200 cm^2/V/s, **lP**=2µm



Upper Display



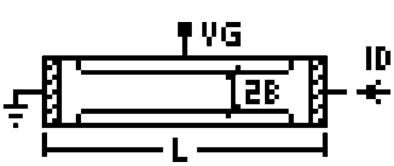
Lower Display

Solution - The solution can be calculated by selecting the first four equations. Select these equations by highlighting and pressing [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen display above.

Known Variables: WN = 4_µ, **lNN** = 2._µ, **µn** = 1250_cm^2/Vs, **Cox** = 34530_pF/cm^2,
VTN = 1._V, **VTP** = -1._V, **lP** = 2._µ, **VDD** = 2._V, **µp** = 200._cm^2/Vs, **WP** = 10._µ

Computed Results: **kN =** .000086_A/V^2, **kP** = .000035_A/V^2, , **VIL** = 1.4898_V, **Vo** = 1.85714_V

27.14 Junction FET



These five equations describe the characteristics of a symmetrical junction field effect transistor. The first equation stipulates the drain current **ID** in terms of the electron mobility **µn**, doping density **Nd**, channel width **b**, channel length **L**, channel depth **Z**, supply voltage **VDD**, pinch-off voltage **Vp**, gate voltage **VG**, and built-in voltage **Vbi**. In the next equation, the channel height **b** is related to the dielectric constant **εs**, **Nd**, **Vbi**, and the drain saturation voltage **VDsat**. The last two equations display the relationship for drain voltage and drain current upon saturation.

$$ID = \frac{2 \cdot q \cdot Z \cdot \mu n \cdot Nd \cdot b}{L} \cdot \left(VDD - \frac{2}{3} \cdot (Vbi - Vp) \cdot \left(\left(\frac{VDD + Vbi - VG}{Vbi - Vp} \right)^{1.5} - \left(\frac{Vbi - VG}{Vbi - Vp} \right)^{1.5} \right) \right) \qquad \textbf{Eq. 27.14.1}$$

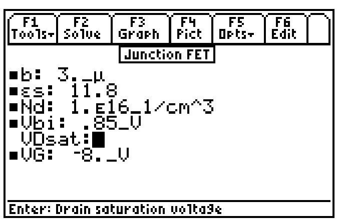
$$IDsat = \frac{2 \cdot q \cdot Z \cdot \mu n \cdot Nd \cdot b}{L} \cdot \left(VDsat - \frac{2}{3} \cdot (Vbi - Vp) \cdot \left(\left(\frac{VDD + Vbi - VG}{Vbi - Vp} \right)^{1.5} - \left(\frac{Vbi - VG}{Vbi - Vp} \right)^{1.5} \right) \right) \qquad \textbf{Eq. 27.14.2}$$

$$b = \sqrt{\frac{2\varepsilon 0 \cdot \varepsilon s}{q \cdot Nd} \cdot (Vbi + VDsat - VG)} \qquad when\{VG < Vp\} and \left\{ VDsat < \frac{2}{3}(Vbi - Vp) \right\} \qquad \textbf{Eq. 27.14.3}$$

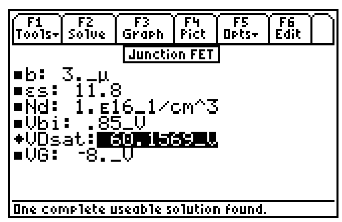
$$VDsat = VG - Vp \qquad when\{VG > Vp\} and \left\{ VDsat > \frac{2}{3}(Vbi - Vp) \right\} \qquad \textbf{Eq. 27.14.4}$$

$$IDsat = ID0 \cdot \left(1 - \frac{VG}{Vp} \right)^2 \qquad \textbf{Eq. 27.14.5}$$

Example 27.14 - Find the saturation current when the drain current at zero bias is 12.5 μA, the gate voltage is 5 V, and the Pinchoff voltage is 12 V.



Entered Values



Calculated Results

Solution - Use the third equation to solve this problem. Select the equation by highlighting and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed result is shown in the screen display above.

Known Variables: **b** = 3._μ, **εs** = 11.8, **Nd** = 1.E16_1/cm^3, **Vbi** = .85_V, **VG** = -8._V
Computed Results: **VDsat** = 60.1569_V

Chapter 28 Linear Amplifiers

This section covers linear circuit models (i.e., small signal models) used in making first order calculations using bipolar or junction transistors in amplifier circuits. These circuit models are referred to by many different names such as small signal circuit model, AC circuit model, linear circuit model. In addition, popular device configurations such as the Darlington pair, emitter-coupled pair, differential amplifier, and a source-coupled pair topics have been included.

- BJT (Common Base)
- BJT (Common Emitter)
- BJT (Common Collector)
- FET (Common Gate)
- FET (Common Source)
- FET (Common Drain)
- Darlington (CC-CC)
- Darlington (CC-CE)
- Emitter-Coupled Amplifier
- Differential Amplifier
- Source-Coupled JFET Pair

Variables

The table lists all variables used in this section along with a description and appropriate units.

Variable	Description	Unit
α0	Current gain, CE	unitless
Ac	Common mode gain	unitless
Ad	Differential mode gain	unitless
Ai	Current gain, CB	unitless
Aov	Overall voltage gain	unitless
Av	Voltage gain, CC/CD	unitless
β0	Current gain, CB	unitless
CMRR	Common mode reject ratio	unitless
gm	Transconductance	S
μ	Amplification factor	unitless
rb	Base resistance	Ω
rrc	Collector resistance	Ω
rd	Drain resistance	Ω
re	Emitter resistance	Ω
RBA	External base resistance	Ω
RCA	External collector resistance	Ω
RDA	External drain resistance	Ω
REA	External emitter resistance	Ω
RG	External gate resistance	Ω
Ric	Common mode input resistance	Ω
Rid	Differential input resistance	Ω

Rin	Input resistance	Ω
Rl	Load resistance	Ω
Ro	Output resistance	Ω
Rs	Source resistance	Ω

28.1 BJT (Common Base)

These six equations represent properties of a transistor amplifier connected in the common base configuration at mid frequencies. The first equation relates the common base current gain **α0** with the common emitter current gain **β0**. The second equation computes the input impedance **Rin** at the input terminals of the amplifier from the emitter and base resistances, **re** and **rb**. The third equation equates the output resistance **Ro** to the collector resistance **rrc**. The fourth equation represents the current gain **Ai**. The fifth equation calculates the voltage gain **Av** from **re**, **rb**, **α0**, **β0**, and the load resistance, **Rl**. The last equation computes the overall voltage gain for the amplifier system **Aov** from **Rin**, **rrc**, **re, α0, β0**, and the source impedance **Rs**.

$$\beta 0 = \frac{\alpha 0}{1 - \alpha 0}$$ **Eq. 28.1.1**

$$Rin = re + \frac{rb}{\beta 0}$$ **Eq. 28.1.2**

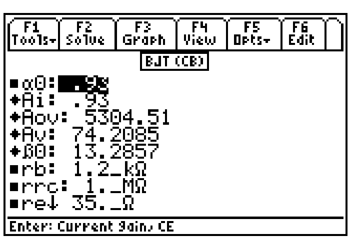
$$Ro = rrc$$ **Eq. 28.1.3**

$$Ai = \alpha 0$$ **Eq. 28.1.4**

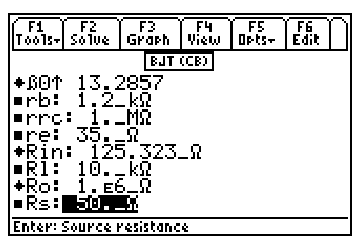
$$Av = \frac{\alpha 0 \cdot Rl}{re + \dfrac{rb}{\beta 0}}$$ **Eq. 28.1.5**

$$Aov = \frac{\alpha 0 \cdot rrc \cdot \left(\dfrac{Rin}{Rin + Rs}\right)}{re + \dfrac{rb}{\beta 0}}$$ **Eq. 28.1.6**

Example 28.1 - A common base configuration of a linear amplifier has an emitter resistance of 35Ω, collector and base resistances of 1 MΩ and 1.2 kΩ resistances, respectively. The load resistor is 10 kΩ. If the source resistance is 50 Ω and **α0** is 0.93, find **β0** and the gains for this amplifier.



Upper Screen Display



Lower Screen Display

Solution - All of the equations are needed to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: **α0** = .93, **rb** = 1.2_kΩ, **rrc** = 1._MΩ, **re** = 35._ Ω, **Rl** = 10._kΩ, **Rs** = 50._ Ω

Computed Results: **Ai =** .93, **Aov** = 5304.51, **Av** = 74.2085, **β0** = 13.2857, **Rin** = 125.323_Ω, **Ro** = 1.E6_Ω

28.2 BJT (Common Emitter)

This section contains the equations for an amplifier, at mid frequencies, connected in the common emitter configuration. The first equation displays the current gain **α0** in relation to the common current gain **β0**. The second equation computes the input **Rin**, in terms of base resistance **rb**, emitter resistance **re**, and the current gain **β0**. The output resistance **Ro** is defined in terms of collector resistance, **rrc** in the third equation. The next equation defines current gain **Ai** in terms of **β0**. The fifth equation computes the voltage gain **Av** from **β0**, the load, source and input resistances **Rl, Rs,** and **Rin.** The last equation calculates the overall voltage gain **Aov** from the source impedance **Rs**, **Rl, Rin** and **β0**.

$$\beta 0 = \frac{\alpha 0}{1-\alpha 0}$$ **Eq. 28.2.1**

$$Rin = rb + \beta 0 \cdot re$$ **Eq. 28.2.2**

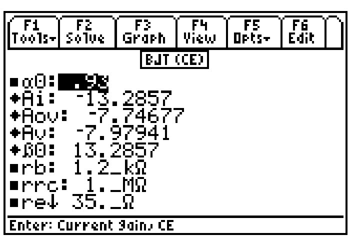
$$Ro = rrc$$ **Eq. 28.2.3**

$$Ai = -\beta 0$$ **Eq. 28.2.4**

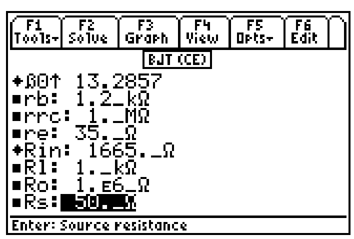
$$Av = \frac{-\beta 0 \cdot Rl}{\beta 0 \cdot re + rb}$$ **Eq. 28.2.5**

$$Aov = \frac{-\beta 0 \cdot Rl}{Rs + Rin}$$ **Eq. 28.2.6**

Example 28.2 - Using the same inputs as in the previous problem, with the exceptions that the load is a 1 KΩ resistor and the output resistance is 1 MΩ, find the gain parameters.



Upper Screen Display



Lower Screen Display

Solution - All of the equations are needed to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: **α0** = .93, **rb** = 1.2_kΩ, **rrc** = 1._MΩ, **re** = 35._ Ω, **Rl** = 1._kΩ, **Ro** = 1.E6_Ω, **Rs** = 50._ Ω

Computed Results: **Ai =** -13.2857, **Aov** = -7.74677, **Av** = -7.97941, **β0** = 13.2857, **Rin** = 1665._Ω

28.3 BJT (Common Collector)

These six equations describe the properties of a transistor amplifier connected in a common collector configuration at mid frequencies. The first equation couples the common emitter current gain **α0** with the common base current gain **β0**. The second equation computes the input impedance **Rin** in terms of base resistance **rb**, emitter resistance **re**, **β0**, and load resistance **Rl**. **Ro** represents the output resistance in terms of the source resistance, common base current gain **β0** and the load resistance **Rl**. The current gain **Ai** is shown in the fourth equation in terms of the collector resistance **rrc**, **α0**, **re**, and **Rl**. The final two equations cover the voltage gain **Av** and overall voltage gain **Aov** for the amplifier system. **Aov** includes the effect of source impedance **Rs**.

$$\beta 0 = \frac{\alpha 0}{1-\alpha 0}$$ **Eq. 28.3.1**

$$Rin = rb + \beta 0 \cdot re + (\beta 0 + 1) \cdot Rl$$ **Eq. 28.3.2**

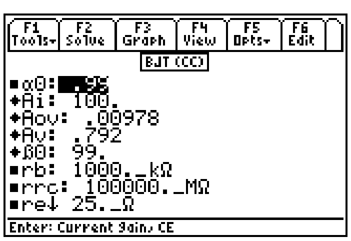
$$Ro = re + \frac{(Rs + rb)}{\beta 0}$$ **Eq. 28.3.3**

$$Ai = \frac{rrc}{rrc \cdot (1-\alpha 0) + Rl + re}$$ **Eq. 28.3.4**

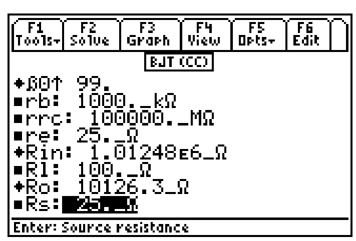
$$Av = \frac{\alpha 0 \cdot Rl}{re + Rl}$$ **Eq. 28.3.5**

$$Aov = \frac{(\beta 0 + 1) \cdot Rl}{Rs + Rin + (\beta 0 + 1) \cdot Rl}$$ **Eq. 28.3.6**

Example 28.3 - An amplifier in a common collector configuration has a gain **α0** of 0.99. The emitter, base and collector resistances are 25 Ω, 1000 kΩ, and 100,000 MΩ, respectively. If the source resistance is 25 Ω, find all the mid-band characteristics.



Upper Screen Display



Lower Screen Display

Solution - Use all of the equations to compute the solution for this problem. Press F2 to display the input screen, enter all the known variables and press F2 to solve the equations. The computed results are shown in the screen displays above.

Known Variables: **α0** = .99, **rb** = 1000._kΩ, **rrc** = 100000._MΩ, **re** = 25._ Ω, **Rl** = 100._ Ω, **Rs** = 25._ Ω

Computed Results: **Ai** = 100, **Aov** = .00978, **Av** = .792, **β0** = 99, **Rin** = 1.01248E6._Ω, **Ro** = 10126.3_Ω

28.4 FET (Common Gate)

The equations in this section focus on an FET amplifier in the common gate configuration. The amplification factor μ is described in the first equation in terms of the transconductance **gm** and the drain resistance **rd**. In the second equation the input resistance **Rin** is described as a function of load resistance **Rl**, **rd** and μ. The voltage gain **Av** is defined by the third equation in terms of **Rl**, **rd** and μ. The final equation computes the output resistance **Ro** in terms of **rd**, μ, and the external gate resistance **RG**.

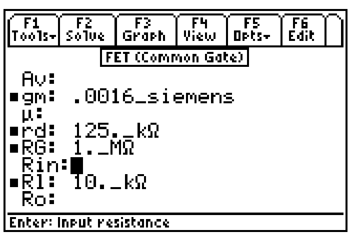
$$\mu = gm \cdot rd \qquad \textbf{Eq. 28.4.1}$$

$$Rin = \frac{(Rl + rd)}{\mu + 1} \qquad \textbf{Eq. 28.4.2}$$

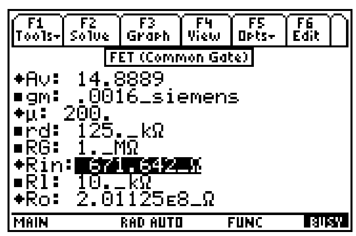
$$Av = \frac{(\mu + 1) \cdot Rl}{rd + Rl} \qquad \textbf{Eq. 28.4.3}$$

$$Ro = rd + (\mu + 1) \cdot RG \qquad \textbf{Eq. 28.4.4}$$

Example 28.4 - An FET amplifier connected in a common gate mode has a load of 10 kΩ. The external gate resistance is 1 MΩ, and the drain resistance is 125 kΩ. The transconductance is 1.6 x 10^{-3} siemens. Find the mid-band parameters.



Entered Values



Calculated Results

Solution - All of the equations need to be used to compute the solution for this problem. Press F2 to display the input screen, enter all the known variables and press F2 to solve the equations. The computed results are shown in the screen displays above.

Known Variables: **gm** = .0016_siemens, **rd** = 125._kΩ, **RG** = 1._ MΩ, **Rl** = 10._kΩ,

Computed Results: **Av** = 14.8889, **μ** = 200, **Rin** = 671.642_Ω, **Ro** = 2.01125E8_Ω

28.5 FET (Common Source)

These four equations represent the key properties of an FET amplifier in the mid frequency range. The first equation defines the amplification factor μ in terms of transconductance **gm** and drain resistance **rd**. The second equation computes input resistance **Rin** as a function of load resistance **Rl**, **rd** and μ. The voltage gain **Av** is defined in the third equation. The final equation computes the output resistance, **Ro**.

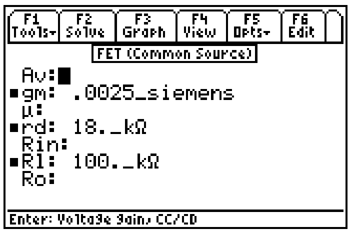
$$\mu = gm \cdot rd \qquad \textbf{Eq. 28.5.1}$$

$$Rin = \frac{(Rl + rd)}{\mu + 1}$$ **Eq. 28.5.2**

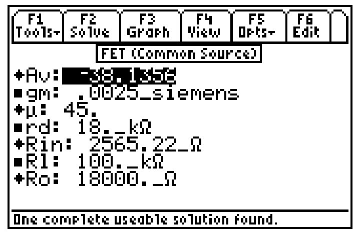
$$Av = -gm \cdot \left(\frac{rd \cdot Rl}{rd + Rl} \right)$$ **Eq. 28.5.3**

$$Ro = rd$$ **Eq. 28.5.4**

Example 28.5 - Find the voltage gain of an FET configured as a common-source based amplifier. The transconcductance is 2.5 x 10^{-3} siemens, a drain resistance of 18 kΩ and a load resistance of 100 kΩ. Find all the parameters for this amplifier circuit.



Entered Values



Calculated Results

Solution - Use all of the equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen display above.

Known Variables: **gm** = .0025_siemens, **rd** = 18._kΩ, **Rl** = 100._kΩ

Computed Results: **Av** = -38.1356, **μ** = 45, **Rin** = 2565.22_Ω, **Ro** = 18000._ Ω

28.6 FET (Common Drain)

The first equation defines the amplification factor μ in terms of transconductance **gm** and drain resistance **rd**. The second equation computes input resistance **Rin** as a function of load resistance **Rl**, **rd** and μ. Voltage gain **Av** is defined in the third equation. The final equation computes the output resistance, **Ro**.

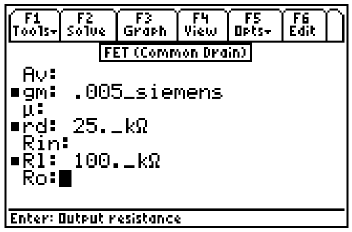
$$\mu = gm \cdot rd$$ **Eq. 28.6.1**

$$Rin = \frac{(Rl + rd)}{\mu + 1}$$ **Eq. 28.6.2**

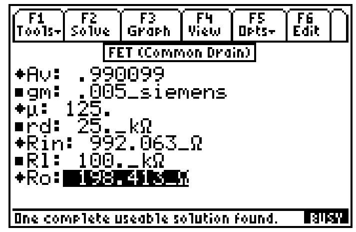
$$Av = \frac{\mu \cdot Rl}{(\mu + 1) \cdot Rl + rd}$$ **Eq. 28.6.3**

$$Ro = \frac{rd}{\mu + 1}$$ **Eq. 28.6.4**

Example 28.6 - Compute the voltage gain for a common-drain FET amplifier as configured in the previous example. The transconductance is 5 x 10^{-3} siemens, the drain resistance is 25 kΩ, and the load resistance is 100 kΩ.



Entered Values



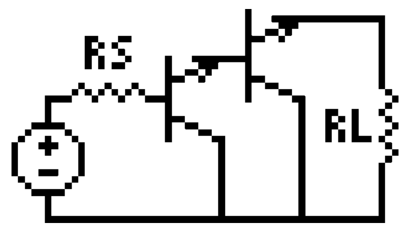
Calculated Results

Solution - Use all of the equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen display above.

Known Variables: **gm** = .005_siemens, **rd** = 25._kΩ, **Rl** = 100._kΩ

Computed Results: **Av** = .990099, **µ** = 125., **Rin** = 992.063_Ω, **Ro** = 198.413_ Ω

28.7 Darlington (CC-CC)



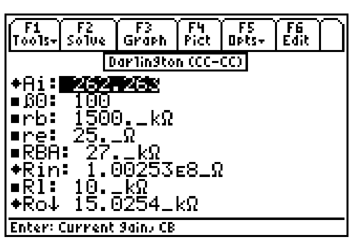
The first two equations yield the input and output resistances **Rin** and **Ro**, computed in terms of emitter resistance **re**, load resistance **Rl**, current gain **β0**, base resistance **rb**, and source resistance **Rs**. The final equation computes overall current gain **Ai** for the transistor pair in terms of **β0, re, Rl** and the external base resistance **RBA**.

$$Rin = \beta 0 \cdot \left(re + \beta 0 \cdot \left(re + Rl\right)\right)$$ **Eq. 28.7.1**

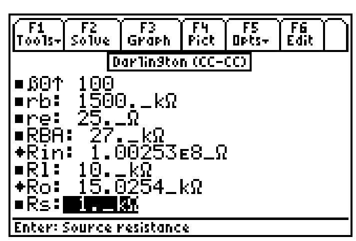
$$Ro = re + \frac{\left(\beta 0 \cdot \left(re + rb\right) + Rs\right)}{\beta 0^2}$$ **Eq. 28.7.2**

$$Ai = \frac{\beta 0^2 \cdot RBA}{RBA + \beta 0 \cdot \left(Rl + re\right)}$$ **Eq. 28.7.3**

Example 28.7 - Transistors in a Darlington pair having a **β0** value of 100 are connected to a load of 10 kΩ. The emitter, base and source resistances are 25 Ω, 1500 kΩ and 1kΩ, respectively. The external base resistance is 27 kΩ.



Upper Screen Display



Lower Screen Display

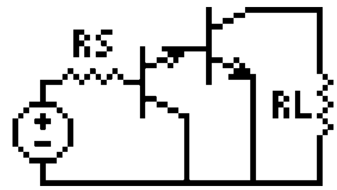
Solution - Use all of the equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: **β0 =** 100, **rb** = 1500._kΩ, **re** = 25._Ω, **RBA** = 27._kΩ, **Rl** = 10._kΩ, **Rs** = 1._kΩ

Computed Results: **Ai** = 262.263, **Rin** = 1.00253E8_Ω, **Ro** = 15.0254_kΩ

28.8 Darlington (CC-CE)

The Darlington configuration connected as a common collector-common emitter configuration is described in this section. The first two equations define the input resistance **Rin** and output resistance **Ro**, in terms of base resistance **rb**, emitter resistance **re**, collector resistance **rrc**, and current gain **β0**. The final equation calculates the voltage gain **Av**, in terms of the emitter and load resistances, the source impedance, and the current gain **β0**.

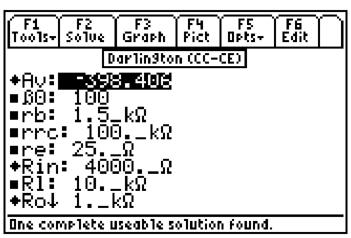


$$Rin = rb + \beta 0 \cdot re$$ **Eq. 28.8.1**

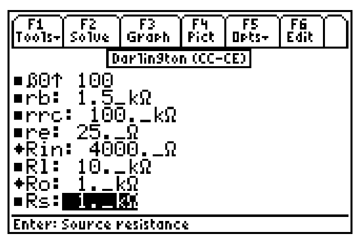
$$Ro = \frac{rrc}{\beta 0}$$ **Eq. 28.8.2**

$$Av = \frac{-Rl}{re + \frac{Rs}{\beta 0^2}}$$ **Eq. 28.8.3**

Example 28.8 - An amplifier circuit has a base, emitter, and load resistance of 1.5 kΩ, 25 Ω, and 10 kΩ, respectively. The configuration has a value of **β0** equal to 100. The source and collector resistances are 1 kΩ and 100 kΩ. Find the voltage gain, input and output resistances.



Upper Screen Display



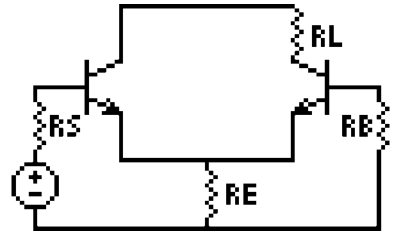
Lower Screen Display

Solution - Use all of the equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: **β0** = 100, **rb** = 1.5_kΩ, **rrc** = 100._kΩ, **re** = 25._ Ω, **Rl** = 10._kΩ, **Rs** = 1._kΩ

Computed Results: **Av** = -398.406, **Rin** = 4000._ Ω, **Ro** = 1._kΩ

28.9 Emitter-Coupled Amplifier



Two classes of emitter-coupled amplifiers are covered in this section. The first equation shows the general relationship between **β0** and **α0**; the current gains under common base and common emitter configurations. The next three equations show the input resistance **Rin**, output resistance **Ro**, and voltage gain **Av** for a common collector-common base method of connection. The last three equations correspond to cascade configuration of the transistors, which is a combination of common emitter-common base configuration resulting in a current gain **Ai** with corresponding input resistance **Rin** and output resistance **Ro**.

$$\beta 0 = \frac{\alpha 0}{1 - \alpha 0}$$ **Eq. 28.9.1**

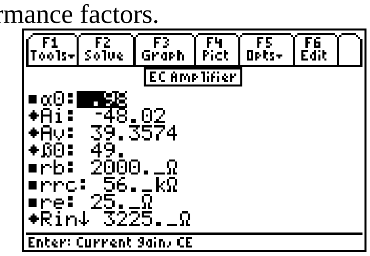
$$Av = Rl \cdot \left(\frac{\beta 0}{2 \cdot \beta 0 \cdot re + Rl} \right)$$ **Eq. 28.9.2**

$$Ai = -\alpha 0 \cdot \beta 0$$ **Eq. 28.9.3**

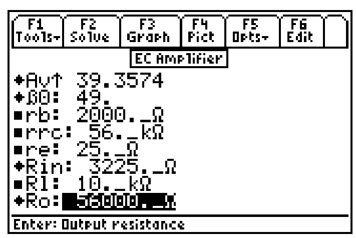
$$Rin = \beta 0 \cdot re + rb$$ **Eq. 28.9.4**

$$Ro = rrc$$ **Eq. 28.9.5**

Example 28.9 - An emitter coupled pair amplifier is constructed from transistors with α0=0.98. The emitter, base and collector resistances are 25 Ω, 2000 Ω, and 56 kΩ, respectively. If the load resistance is 10 kΩ, find the mid-band performance factors.



Upper Screen Display



Lower Screen Display

Solution - Use all of the equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: α0 = .98, **rb** = 2000._Ω, **rrc** = 56._kΩ, **re** = 25._ Ω, **Rl** = 10._kΩ

Computed Results: **Ai** = -48.02, **Av** = 39.3574, **β0** = 49, **Rin** = 3225._Ω, **Ro** = 56000._ Ω

28.10 Differential Amplifier

The gain **Ad** in the differential mode of operation is given by the first equation. The common mode gain, **Ac** is defined in terms of the external collector and emitter resistances **RCA** and **REA** and the emitter resistance **re**. The last two equations show input resistance for differential and common mode inputs **Rid** & **Ric**.

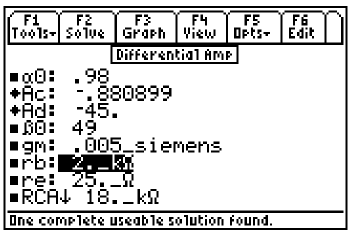
$$Ad = -\frac{1}{2} \cdot gm \cdot RCA \qquad \textbf{Eq. 28.10.1}$$

$$Ac = \frac{-\alpha 0 \cdot RCA}{2 \cdot REA + re} \qquad \textbf{Eq. 28.10.2}$$

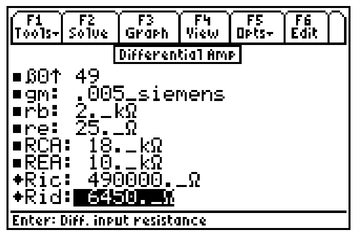
$$Rid = 2 \cdot \left(rb + \beta 0 \cdot re \right) \qquad \textbf{Eq. 28.10.3}$$

$$Ric = \beta 0 \cdot REA \qquad \textbf{Eq. 28.10.4}$$

Example 28.10 - A differential amplifier pair has a transconductance of 0.005 siemens, **α0**=0.98, **β0**=49. The external collector and external emitter resistances are 18 kΩ and 10 kΩ respectively. If the emitter resistance is 25 Ω and the base resistance is 2 kΩ, find the common mode, differential resistance and gains.



Upper Screen Display



Lower Screen Display

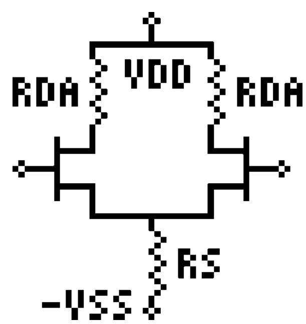
Solution - Use all of the equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: **α0** = 0.98, **β0** = 49, **gm** = .005_siemens, **rb** = 2._kΩ, **re** = 25._kΩ, **RCA** = 18._kΩ, **REA** = 10._kΩ

Computed Results: **Ac** = -.880899, **Ad** = -45, **Ric** = 490000._ Ω, **Rid** = 6450._ Ω

28.11 Source-Coupled JFET Pair

The first two equations describe the differential **Ad** and common mode **Ac** gains for a source-coupled JFET pair in terms of the external drain, drain and source resistances **RDA**, **rd** and **Rs**. The third equation shows the amplification factor **μ**, in terms of the transconductance **gm** and the drain resistance. The final equation calculates the common mode rejection ratio **CMRR**.



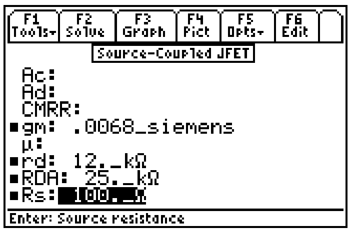
$$Ad = \frac{-\frac{1}{2} \cdot gm \cdot \left(rd \cdot RDA \right)}{rd + RDA} \qquad \textbf{Eq. 28.10.1}$$

$$Ac = \frac{-\mu \cdot RDA}{\left(\mu + 1 \right) \cdot 2 \cdot Rs + rd + RDA} \qquad \textbf{Eq. 28.10.2}$$

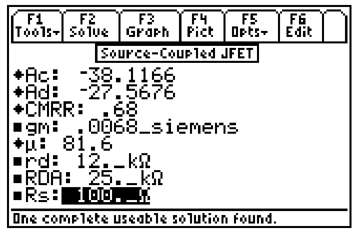
$\mu = gm \cdot rd$ **Eq. 28.10.3**

$CMRR = gm \cdot Rs$ **Eq. 28.10.4**

Example 28.11 - Find the gain parameters of a source-coupled JFET pair amplifier if the external drain resistance is 25 kΩ, and the source resistance is 100 Ω. The drain resistance is 12 kΩ and the transconductance is 6.8×10^{-3} siemens.



Entered Values



Calculated Results

Solution - Use all of the equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations. The computed results are shown in the screen displays above.

Known Variables: gm = .0068_siemens, **rd** = 12._kΩ, **RDA** = 25._kΩ, **Rs** = 100._Ω

Computed Results: **Ac** = -38.1166, **Ad** = -27.5676, **CMRR** = .68, **μ** = 81.6

Chapter 29 Class A, B and C Amplifiers

This chapter covers the section called Class A, B and C Amplifiers. These amplifier circuits forms the basis of a class of power amplifiers used in a variety of applications in the industry.

Read this!

Note: The equations in this section are grouped under topics which describe general properties of Class A, B, and C amplifiers. Equations for a variety of specific cases and are listed together under a sub-topic heading and are not necessarily a set of consistent equations which can be solved together. Choosing equations in a subtopic w/o regard as to whether the equations represent actual relationships could generate erroneous results or no solution at all. Read the description of each equation set to determine which equations in a sub-topic form a consistent subset before attempting to compute a solution.

- ❖ Class A Amplifier
- ❖ Power Transistor
- ❖ Push-Pull Principle
- ❖ Class B Amplifier
- ❖ Class C Amplifier

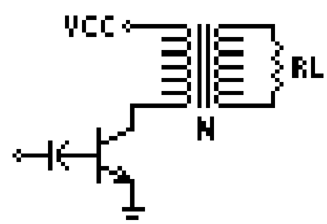
Variables

The variables used in this section are listed along with a brief description and units.

Variable	Description	Unit
gm	Transconductance	S
hFE	CE current gain	unitless
hOE	CE output conductance	S
I	Current	A
IB	Base current	A
IC	Collector Current	A
ΔIC	Current swing from operating pt.	A
ICBO	Collector current EB open	A
ICQ	Current at operating point	A
Idc	DC current	A
Imax	Maximum current	A
K	Constant	unitless
m	Constant	1/K
ς	Efficiency	unitless
n	Turns ratio	unitless
N1	# turns in primary	unitless
N2	# turns in secondary	unitless
Pd	Power dissipated	W
Pdc	DC power input to amp	W

Po	Power output	W
PP	Compliance	V
Q	Quality factor	unitless
θJA	Thermal resistance	W/K
R	Equivalent resistance	Ω
Rl	Load resistance	Ω
RR0	Internal circuit loss	Ω
RR2	Load resistance	Ω
RB	External base resistance	Ω
Rrc	Coupled load resistance	Ω
Rxt	External emitter resistance	Ω
S	Instability factor	unitless
TA	Ambient temperature	K
TJ	Junction temperature	K
ΔTj	Change in temperature	K
V0	Voltage across tank circuit	V
V1	Voltage across tuned circuit	V
VBE	Base emitter voltage	V
VCC	Collector supply voltage	V
ΔVCE	Voltage swing from operating pt.	V
VCEmx	Maximum transistor rating	V
VCEmn	Minimum transistor rating	V
Vm	Maximum amplitude	V
VPP	Peak-peak volts, secondary	V
XXC	Tuned circuit parameter	Ω
XC1	π equivalent circuit parameter	Ω
XC2	π equivalent circuit parameter	Ω
XL	π series reactance	Ω

29.1 Class A Amplifier



The eight equations in this section form the basis for analyzing a Class A amplifier with an ideal transformer coupled to a resistive load **Rl**.

The first equation specifies the equivalent load resistance **R** from the load resistance **Rl** in the secondary winding of the transformer with a turns ratio **n**. The second equation defines the AC current swing **ΔIC** in terms of the voltage swing **ΔVCE** and **R**. The third equation computes the maximum collector current **Imax** in terms of current at the operating point **ICQ** and **ΔIC**. These three equations are internally consistent and can be used as a set.

$$R = n^2 \cdot Rl \quad \textbf{Eq. 29.1.1}$$

$$\Delta IC = \frac{\Delta VCE}{R} \quad \textbf{Eq. 29.1.2}$$

$$\mathrm{Im}\,ax = ICQ + \Delta IC \quad \textbf{Eq. 29.1.3}$$

The DC power available **Pdc** is shown in the fourth equation. The DC power measurement is based on the supply voltage and quiscent operating current.

$$Pdc = VCC \cdot ICQ \quad \textbf{Eq. 29.1.4}$$

The compliance **PP** is defined as the full voltage swing across the emitter and collector and is expressed in terms of the minimum and maximum transformer ratings **VCEmx** and **VCEmn**. **VPP** represents the peak to peak voltage in the secondary transformer. The final two equations compute the output power **Po** and the conversion efficiency **ζ**.

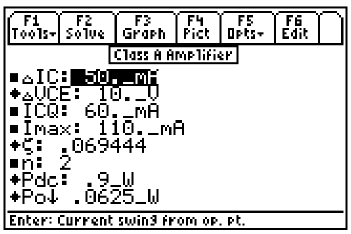
$$PP = VCEmx - VCEmn$$ **Eq. 29.1.5**

$$VPP = n \cdot PP$$ **Eq. 29.1.6**

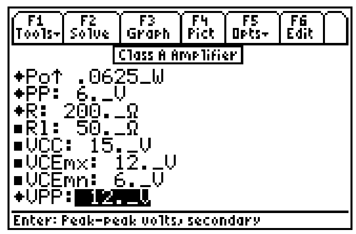
$$Po = \frac{\Delta IC^2 \cdot R}{8}$$ **Eq. 29.1.7**

$$\zeta = \frac{Po}{Pdc}$$ **Eq. 29.1.8**

Example 29.1 - A Class A power amplifier is coupled to a 50 Ω load through the output of a transformer with a turn ratio of 2. The quiescent operating current is 60 mA, and the incremental collector current is 50 mA. The collector-to-admitter voltage swings from 6 V to 12 V. The supply collector voltage is 15 V. Find the power delivered and the efficiency of power conversion. The maximum current is 110 mA.



Upper Display



Lower Display

Solution - Use all of the equations to solve this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: **ΔIC** = 50 mA, **ICQ** = 60._mA, **Imax** = 110._mA, **n** = 2, **Rl** = 50 Ω, **VCC** = 15._V, **VCEmx** = 12._V, **VCEmn** = 6._V,

Computed Results: **ΔVCE** = 10._V, **ζ** = .069444, **Pdc** = .9_W, **Po** = .0625_W, **PP** = 6._V, **R** = 200._Ω, **Rl** = 50._ Ω, **VPP** = 12._V

29.2 Power Transistor

Power amplifiers generate heat needing rapid transfer to ambient surroundings. The six equations in this section focus on thermal problems in terms of the junction temperature **TJ**, transistor currents **IB** and **IC**, and the instability factor **S**. The first equation defines the junction temperature **TJ** as linearly related to the power dissipation **Pd** and thermal resistance **θJA** and **TA**, the ambient temperature.

$$TJ = TA + \theta JA \cdot Pd$$ **Eq. 29.2.1**

The next two equations focus on the collector current **IC** and base current **IB** in terms of the current gain **hFE**, leakage current **ICBO**, external emitter resistance **Rxt** and external base resistance **RB**.

$$IC = hFE \cdot IB + (1 + hFE) \cdot ICBO$$ **Eq. 29.2.2**

$$IB = \frac{-(IC \cdot Rxt - VBE)}{Rxt + RB} \qquad \textbf{Eq. 29.2.3}$$

The fourth equation expresses a more exact form for the collector current **IC** in terms of **hFE**, **Rxt**, **RB**, **ICBO**, and **VBE**. In using this equation, care must be taken to ensure that Eq.29.2.3 and Eq. 29.2.4 are not selected at the same time. Such a choice will lead to the inability of the solver engine to perform the computation accurately.

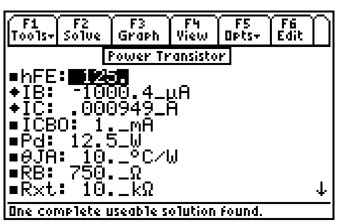
$$IC = \frac{-hFE \cdot VBE}{hFE \cdot Rxt \cdot RB} + \frac{hFE \cdot (Rxt + RB)}{hFE \cdot Rxt + RB} \cdot ICBO \qquad \textbf{Eq. 29.2.4}$$

The instability factor **S** is given by the fifth equation. Stability is a performance measure for the health of the amplifier. The final equation computes **IC** in terms of **hFE**, **ICBO**, a parameter **m**, **S**, and the change in junction temperature **ΔTj**.

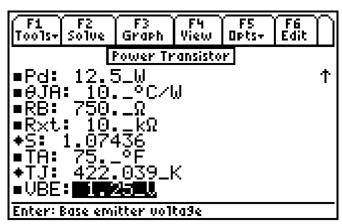
$$S = \frac{\left(1 + \frac{RB}{Rxt}\right) \cdot hFE}{hFE + \frac{RB}{Rxt}} \qquad \textbf{Eq. 29.2.5}$$

$$IC = -hFE \cdot IB + S \cdot ICBO \cdot (1 + m \cdot \Delta Tj) \qquad \textbf{Eq. 29.2.6}$$

Example 29.2 - A power transistor has a common emitter current gain of 125. A 750 Ω base resistance is coupled to an external emitter resistance of 10 kΩ. The ambient temperature is 75 °F and the thermal resistance of the unit is 10 °C/W. The power that needs to be dissipated is 12.5W. The base emitter voltage is 1.25V while ICBO is 1_ma. Find the junction temperature, collector current and the instability factor.



Input variables



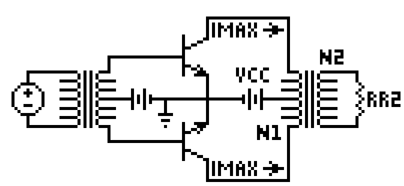
Computed results

Solution - We note from the equation set that IC is computed in three different ways. To make the calculations consistent given the data, we use Equations 1, 2, 4 and 5 to solve for this problem. Select these equations by highlighting the equation with the cursor bar and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen display above.

Known Variables: hFE = 125, **ICB0** = 1._mA, **Pd** = 12.5._W, **θJA** = 10._ºC/W, **RB** = 750._Ω, **Rxt** = 10._kΩ, **TA** = 75_ºF, **VBE** = 1.25_V

Computed Results: IB = -1004.4_µA, **IC** = .000949_A, **S** = 1.07436, **TJ** = 422.039_K

29.3 Push-Pull Principle



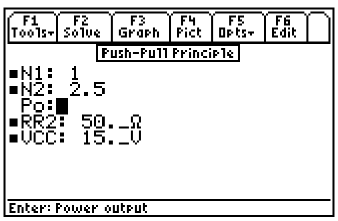
These equations introduce the push-pull principle. Two transistors have their collector outputs connected to the center-tapped primary winding of a transformer. The secondary winding is connected to a load **RR2**. The first equation computes an equivalent resistance **R** based on the maximum current supplied to the load **Imax** and the collector supply voltage **VCC**. The power output **Po** is computed by the second equation in terms of **VCC** and **R**. The final equation computes the power **Po** in terms of the load resistance **RR2** and the transformer windings **N1** and **N2**. Care must be exercised in selecting the equations. If you select to solve all the equations, ensure that appropriate inputs are selected.

$$R = \frac{VCC}{\mathrm{Im}ax} \qquad \textbf{Eq. 29.3.1}$$

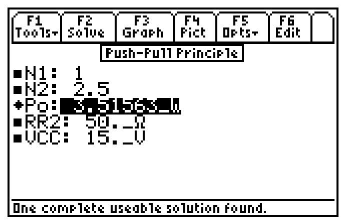
$$Po = \frac{VCC^2}{2 \cdot R} \qquad \textbf{Eq. 29.3.2}$$

$$Po = \frac{\left(\frac{N2}{2 \cdot N1}\right)^2 \cdot VCC^2}{2 \cdot RR2} \qquad \textbf{Eq. 29.3.3}$$

Example 29.3 - Find the output power for a push-pull circuit with a collector voltage of 15 V, a load resistance of 50 Ω. The push-pull transformer secondary winding amplifies voltage by a factor of 2.5.



Input variables



Computed results

Solution - Use the third equation to compute the solution for this problem. Select the equation using the highlight bar and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed result is shown in the screen display above.

Known Variables: **N1** = 1, **N2** = 2.5, **RR2** = 50._Ω, **VCC** = 15._V

Computed Results: **Po** = 3.51563_W

29.4 Class B Amplifier

Power transistors that are connected in a push-pull mode and biased to cutoff, operate under the Class B condition where alternate half-cycles of input are of forward polarity for each transistor. The nine equations in this section define the characteristic properties of this class of amplifiers.
The first equation represents the power output **Po** at any signal level in terms of the constant **K**, supply voltage **VCC**, and an equivalent resistance **R**. The second equation defines the DC current **Idc** as the average value of a sinusoidal half-wave adjusted by **K**.

$$Po = \frac{K^2 \cdot VCC^2}{2 \cdot R} \qquad \textbf{Eq. 29.4.1}$$

$$Idc = \frac{2 \cdot K \cdot \mathrm{Im}ax}{\pi} \qquad \textbf{Eq. 29.4.2}$$

The next two equations focus on the DC power **Pdc** in terms of **VCC**, **K**, **R**, and the maximum current **Imax**. The power calculations are possible in two ways as shown by these equations.

$$Pdc = \frac{2 \cdot K \cdot \mathrm{Im}ax \cdot VCC}{\pi} \qquad \textbf{Eq. 29.4.3}$$

$$Pdc = \frac{2 \cdot K \cdot VCC^2}{\pi \cdot R} \qquad \textbf{Eq. 29.4.4}$$

The efficiency of power conversion ζ is given by the fifth and sixth equations. The power dissipated by the circuit **Pd** is computed in the seventh equation. The eighth equation calculates the voltage **V1** across a tuned RLC circuit in terms of the transconductance **gm**, load resistance **Rl**, and output conductance **hOE**. The final equation calculates the average collector current **IC** for a half-sine wave from **gm, hOE, Rl** and the amplitude of the voltage **Vm**.

$$\zeta = \frac{Po}{Pdc} \qquad \textbf{Eq. 29.4.5}$$

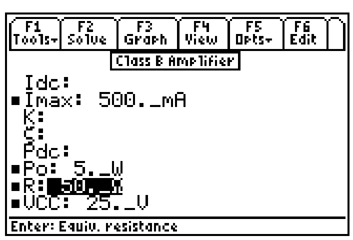
$$\zeta = \frac{\pi \cdot K}{4} \qquad \textbf{Eq. 29.4.6}$$

$$Pd = \frac{2 \cdot VCC^2}{\pi \cdot R} \cdot \left(K - \frac{K^2 \cdot \pi}{4} \right) \qquad \textbf{Eq. 29.4.7}$$

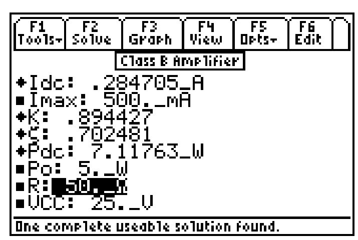
$$V1 = \frac{gm \cdot Rl \cdot Vm}{2 \cdot \sqrt{2}} \left(\frac{1}{1 + \frac{hOE \cdot Rl}{2}} \right) \qquad \textbf{Eq. 29.4.8}$$

$$IC = \frac{gm \cdot Vm}{\pi} \cdot \left(\frac{1}{1 + \frac{hOE \cdot Rl}{2}} \right) \qquad \textbf{Eq. 29.4.9}$$

Example 29.4 - A Class B amplifier provides 5 W to an effective load of 50 Ω. The collector voltage is 25 V. If the peak current is 500 mA, find the average DC current and the efficiency of power conversion.



Input variables



Computed results

Solution - Use the first, second, fourth and fifth equations to compute the solution for this problem. Select these by highlighting each equation and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed results are shown in the screen displays above.

Known Variables: Imax = 500._mA, **Po** = 5._W, **R** = 50._Ω, **VCC** = 25._V

Computed Results: Idc = .284705_A, **K** = .894427, **ζ** = .702481, **Pdc** = 7.11763_W

29.5 Class C Amplifier

These six equations outline the properties of a Class C amplifier. The first equation defines the efficiency of conversion ζ in terms of the current **I**, the coupled-in load **Rrc**, and the equivalent internal circuit loss resistance **RR0**. The next equation computes the tuned circuit parameters which have a capacitive reactance of **XXC**, which is given in terms of the load voltage **V0**, quality factor **Q**, and power **Po**. **XL** is expressed in terms of **XXC**,**Q,** load resistance **Rl**, and resistance **RR2** in the fourth and sixth equations. The remaining two equations calculate the load harmonic suppression resistance values in the output circuit **XC1** and **XC2**. Remember the equations to compute XL have two distinct forms. If this equation is part of your selection, be advised to ensure that the proper inputs are specified.

$$\zeta = \frac{I^2 \cdot Rrc}{I^2 \cdot (Rrc + RR0)}$$ **Eq. 29.5.1**

$$XXC = \frac{V0^2}{Q \cdot Po}$$ **Eq. 29.5.2**

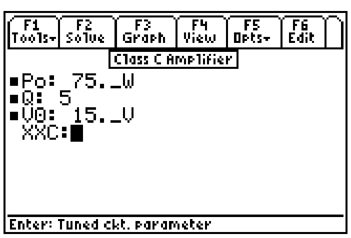
$$XL = \frac{XXC \cdot Q^2}{Q^2 + 1}$$ **Eq. 29.5.3**

$$XC1 = -\frac{Rl}{Q}$$ **Eq. 29.5.4**

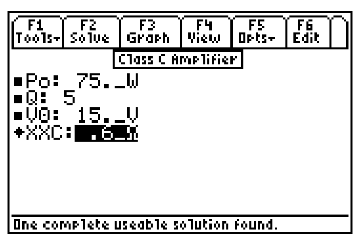
$$XL = \frac{1}{Q} \cdot \left(Rl + \sqrt{Rl + RR2} \right)$$ **Eq. 29.5.5**

$$XC2 = \frac{-RR2}{Q}$$ **Eq. 29.5.6**

Example 29.5 - A Class C amplifier is supplying a tuned circuit, with a quality factor of 5. If the output voltage is 15 V and the power delivered is 75_W, find the capacitive reactance of the circuit needed in the tank circuit.



Input variables



Computed results

Solution - Use the second equation to compute the solution for this problem. Select this by highlighting the equation with the cursor bar and pressing the [ENTER] key. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation. The computed result is shown in the screen displays above.

Known Variables: **Po** = 75._W, **Q** = 5, **V0** = 15._V

Computed Results: **XXC** = .6_Ω

Chapter 30 Transformers

The contents in this chapter is divided into two topics.

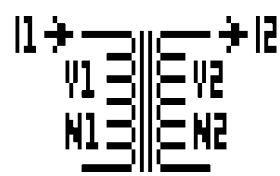
- ❖ Ideal Transformer
- ❖ Linear Equivalent Circuit

Variables

All variables used in this section are listed here with a brief description and units.

Variable	Description	Unit
I1	Primary current	A
I2	Secondary current	A
N1	# primary turns	unitless
N2	# secondary turns	unitless
RR1	Primary resistance	Ω
RR2	Secondary resistance	Ω
Rin	Equiv. primary resistance	Ω
Rl	Resistive part of load	Ω
V1	Primary voltage	V
V2	Secondary voltage	V
XX1	Primary reactance	Ω
XX2	Secondary reactance	Ω
Xin	Equivalent primary reactance	Ω
Xl	Reactive part of load	Ω
Zin	Primary impedance	Ω
ZL	Secondary load	Ω

30.1 Ideal Transformer



Four equations describe the properties of an ideal transformer. The first equation relates the primary and secondary voltages **V1** and **V2** in terms of the primary and secondary turns **N1** and **N2**. The second equation shows the corresponding relationship between the primary and secondary currents **I1** and **I2**. In the same fashion, the third equation relates primary and secondary power. The final equation calculates the effect of a load impedance **ZL** experienced at the primary winding terminal with a primary impedance **Zin**

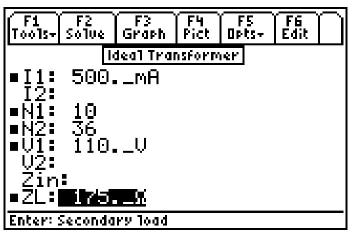
$$\frac{V1}{V2} = \frac{N1}{N2}$$ **Eq. 30.1.1**

$$I1 \cdot N1 = I2 \cdot N2$$ **Eq. 30.1.2**

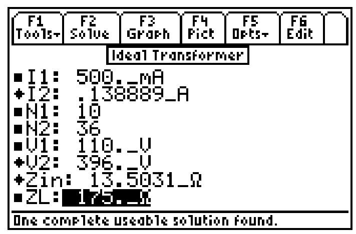
$$V1 \cdot I1 = V2 \cdot I2$$ **Eq. 30.1.3**

$$Zin = \left(\frac{N1}{N2}\right)^2 \cdot ZL$$ **Eq. 30.1.4**

Example 30.1 - An ideal transformer has 10 primary turns and 36 secondary turns. The primary side draws 500 mA when subjected to a 110 V input. If the load impedance is 175 Ω, find the input impedance at the primary side of the transformer in addition to the voltage and current on the secondary end.



Entered Values



Calculated Results

Solution - Use all of the equations to solve this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation set. The computed results are shown in the screen display above.

Known Variables: **I1** = 500._mA, **N1** = 10, **N2** = 36, **V1** = 110._V, **ZL** = 175._Ω

Computed Results: **I2** = .138889_A, **V2** = 396._V, **Zin** = 13.5031_Ω

30.2 Linear Equivalent Circuit

The first two equations define the primary voltage and current **V1** and **I1** in terms of **V2** and **I2**. The last two equations expand the equivalent resistance **Rin** and reactance **Xin** at the primary terminals in terms of the primary winding resistance **RR1**, secondary winding resistance **RR2**, load resistance **Rl**, reactances **XX1** and **XX2** and load reactance **Xl**.

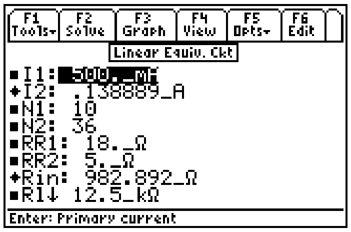
$$V1 = \left(\frac{N1}{N2}\right) \cdot V2$$ **Eq. 30.2.1**

$$I1 = \frac{I2 \cdot N2}{N1}$$ **Eq. 30.2.2**

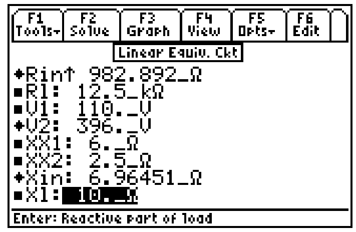
$$Rin = RR1 + \left(\frac{N1}{N2}\right)^2 \cdot \left(RR2 + Rl\right)$$ **Eq. 30.2.3**

$$Xin = XX1 + \left(\frac{N1}{N2}\right)^2 \cdot \left(XX2 + Xl\right)$$ **Eq. 30.2.4**

Example 30.2 - The transformer in the above problem has a primary and secondary resistance of 18 Ω and 5 Ω, respectively. The corresponding coils have a reactance of 6 and 2.5 Ω. The secondary side is loaded with an impedance of 12.5 kΩ. Find the voltage and current on the secondary side in addition to the equivalent impedance on the primary side.



Upper Screen Display



Lower Screen Display

Solution - All of the equations are used to solve this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation set. The computed results are shown in the screen displays above.

Known Variables: **I1** = 500._mA, **N1** = 10, **N2** = 36, **RR1** = 18._ Ω, **RR2** = 5._Ω, **Rl** = 12.5_kΩ, **V1** = 110._V, **XX1** = 6._Ω, **XX2** = 2.5_Ω, **Xl** = 10._Ω

Computed Results: **I2** = .138889_A, **Rin** = 982.892_Ω, **V2** = 396._V, **Xin** = 6.96451_Ω

Chapter 31 Motors and Generators

This section has thirteen topics covering various aspects of motors and generators. The topics are organized under these headings.

Read this!

Note: The equations in this section are grouped under topics which describe general properties of semiconductors or devices. Equations for a variety of specific cases and are listed together under a sub-topic heading and are not necessarily a set of consistent equations which can be solved together. Choosing equations in a subtopic w/o regard as to whether the equations represent actual relationships could generate erroneous results or no solution at all. Read the description of each equation set to determine which equations in a sub-topic form a consistent subset before attempting to compute a solution.

- Energy Conversion
- DC Generator
- Separately-Excited DC Generator
- DC Shunt Generator
- DC Series Generator
- Separately-Excited DC Motor
- DC Shunt Motor
- DC Series Motor
- Permanent Magnet Motor
- Induction Motor I
- Induction Motor II
- Single-Phase Induction Motor
- Synchronous Machines

Variables

All the variables used in this section are listed with a brief description and units.

Variable	Description	Unit
A	Area	m^2
ap	# parallel paths	unitless
B	Magnetic induction	T
Ea	Average emf induced in armature	V
Ef	Field voltage	V
Ema	Phase voltage	V
Es	Induced voltage	V
Eta	Average emf induced per turn	V
F	Magnetic pressure	Pa
H	Magnetic field intensity	A/m
Ia	Armature current	A
IIf	Field current	A
IL	Load current	A
Ir	Rotor current per phase	A

Isb	Backward stator current	A
Isf	Forward stator current	A
K	Machine constant	unitless
Kf	Field coefficient	A/Wb
KM	Induction motor constant	unitless
L	Length of each turn	m
θ	Phase delay	r
N	Total # armature coils	unitless
Ns	# stator coils	unitless
ρ	Resistivity	Ω/m
ϕ	Flux	Wb
p	# poles	unitless
P	Power	W
Pa	Mechanical power	W
Pma	Power in rotor per phase	W
Pme	Mechanical power	W
Pr	Rotor power per phase	W
RR1	Rotor resistance per phase	Ω
Ra	Armature resistance	Ω
Rd	Adjustable resistance	Ω
Re	Ext. shunt resistance	Ω
Rel	Magnetic reluctance	A/Wb
Rf	Field coil resistance	Ω
Rl	Load resistance	Ω
Rr	Equivalent rotor resistance	Ω
Rs	Series field resistance	Ω
Rst	Stator resistance	Ω
s	Slip	unitless
sf	Slip for forward flux	unitless
sm	Maximum slip	unitless
T	Internal torque	N*m
Tb	Backward torque	N*m
Tf	Forward torque	N*m
Tgmax	Breakdown torque	N*m
TL	Load torque	N*m
Tloss	Torque loss	N*m
Tmmax	Maximum positive torque	N*m
TTmax	Pullout torque	N*m
Ts	Shaft torque	N*m
Va	Applied voltage	V
Vf	Field voltage	V
Vfs	Field voltage	V
Vt	Terminal voltage	V
ωm	Mechanical radian frequency	r/s
ωme	Electrical radian frequency	r/s
ωr	Electrical rotor speed	r/s
ωs	Electrical stator speed	r/s
Wf	Magnetic energy	J
XL	Inductive reactance	Ω

31.1 Energy Conversion

The four equations in this section describe the fundamental relationship amongst electrical, magnetic and mechanical aspects of a system. For example, the first two equations show two ways of computing energy density **Wf** stored in a magnetic field. The first equation uses the field intensity **H** and flux density **B** in a magnetic region with length **L** and area **A**. The second an electric analogy to the magnetic circuit as it uses the magnetic reluctance **Rel** and flux **ϕ** to compute **Wf**.

$$Wf = \frac{1}{2} \cdot H \cdot B \cdot L \cdot A \qquad \textbf{Eq. 31.1.1}$$

$$Wf = \frac{1}{2} \cdot \mathrm{Rel} \cdot \phi^2 \qquad \textbf{Eq. 31.1.2}$$

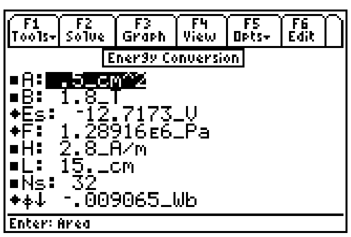
The third equation defines the mechanical pressure **F** due to the flux density **B.**

$$F = \frac{B^2}{2 \cdot \mu 0} \qquad \textbf{Eq. 31.1.3}$$

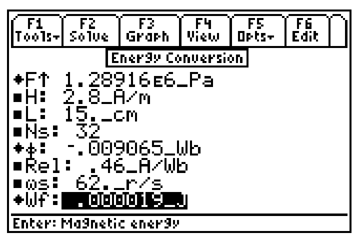
The last equation shows the r.m.s. value of the emf **Es** induced by **Ns** turns moving with an angular velocity **ωs** sweeping a magnetic flux of **ϕ**.

$$Es = \frac{Ns \cdot \omega s \cdot \phi}{\sqrt{2}} \qquad \textbf{Eq. 31.1.4}$$

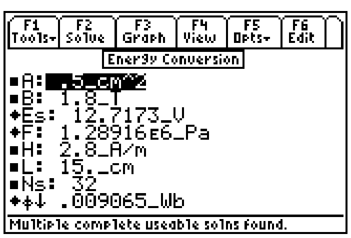
Example 31.1 - A conductor having a length of 15 cm and a cross sectional area of 0.5 cm^2 is subjected to a magnetic induction of 1.8 T and a field intensity of 2.8 A/m. The magnetic reluctance is 0.46 A/Wb. The conductor has 32 turns and is moving at a rotational speed of 62 rad/s. Find the magnetic flux, the magnetic energy, the induced electric field and the mechanical pressure on the coil.



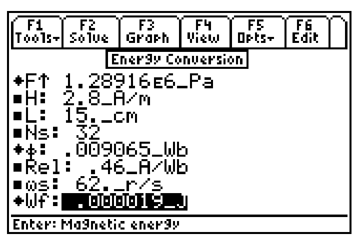
1st Solution: Upper Half



1st Solution: Lower Half



2nd Solution: Upper Half



2nd Solution: Lower Half

Solution - All of the equations are needed to solve this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to compute the solution. Since the flux is a squared term in the second equation, there are two equal and opposite results calculated for **ϕ** and **Es**.

Known Variables: **A** = .5_cm^2, **B** = 1.8_T, **H** = 2.8_A/m, **L** = 15._cm, **Rel** = .46_A/Wb, **Ns** = 32, **ωs** = 62._r/s

Computed Results: **Es** = 12.7173_V (or -12.7173_V), **F** = 1.28916E6_Pa, **ϕ** = .009065_Wb (or -.009065_Wb), **Wf** = .000019_J

31.2 DC Generator

The first equation describes the relation between electrical radian frequency **ωme**, the mechanical radian frequency **ωm**, and the number of poles in the generator **p**. The next equation expresses the emf generated per turn **Eta** with the relative motion of the coil with respect to the magnetic field ϕ.

$$\omega me = \frac{p}{2} \cdot \omega m$$ **Eq. 31.2.1**

$$Eta = \frac{p}{\pi} \cdot \omega m \cdot \phi$$ **Eq. 31.2.2**

The next two equations illustrate two ways to express the induced armature emf **Ea** as a function of number of armature coils **N**, the number of parallel paths **ap**, number of poles **p**, the mechanical radian frequency **ωm**, a machine constant **K**, and flux ϕ. The machine constant **K**, is seen to be dependent purely on the characteristics of the machine.

$$Ea = \frac{N}{ap} \cdot \frac{p}{\pi} \cdot \omega m \cdot \phi$$ **Eq. 31.2.3**

$$Ea = K \cdot \omega m \cdot \phi$$ **Eq. 31.2.4**

$$K = \frac{N \cdot p}{ap \cdot \pi}$$ **Eq. 31.2.5**

The sixth equation shows the conversion of mechanical energy available as torque **T** and mechanical angular velocity **ωm** to its electrical counterpart – namely, the emf and current in the armature **Ea**, and **Ia** and the voltage and current in the field windings **Ef** and **If**. The next equation for torque connects **T** with **K**, ϕ, and the current **Ia**.

$$T \cdot \omega m = Ea \cdot Ia + Ef \cdot IIf$$ **Eq. 31.2.6**

$$T = K \cdot \phi \cdot Ia$$ **Eq. 31.2.7**

The armature resistance is given by the equation for **Ra** in terms of **N**, **ap**, coil length **L**, area **A** and its resistivity ρ.

$$Ra = \frac{\rho \cdot N \cdot L}{ap^2 \cdot A}$$ **Eq. 31.2.8**

Vf represents the voltage across the field winding carrying a current **IIf** and a resistance **Rf**. The terminal voltage **Vt** represents the induced voltage minus the IR drop in the armature..

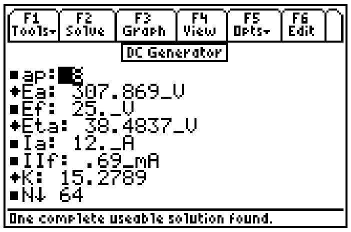
$$Vf = Rf \cdot IIf$$ **Eq. 31.2.9**

$$Vt = K \cdot \omega m \cdot \phi - Ra \cdot Ia$$ **Eq. 31.2.10**

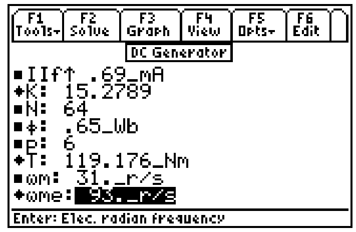
The final equation represents the shaft torque **Ts** needed to generate the induced emf, assuming a given value for equivalent loss of torque **Tloss**

$$Ts = K \cdot \phi \cdot Ia + Tloss$$ **Eq. 31.2.11**

Example 31.2 - A six-pole DC generator rotates at a mechanical speed of 31 rad/s. The armature sweeps across a flux of 0.65 Wb. There are eight parallel paths and 64 coils in the armature. The armature current is 12 A. The field is supplied by a 25 V source delivering a current of 0.69 A. Find the torque and the voltages generated in the armature.



Display: Upper Half



Display: Lower Half

Solution - Choose the first six equations. Select these by highlighting each equation and pressing [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation set. The computed results are shown in the screen displays above.

Known Variables: **ap** = 8, **Ef** = 25_V, **Ia** = 12._A, **IIf** = .69_mA, **N** = 64, **ϕ** = .65_Wb, **p** = 6, **ωm** = 31._r/s

Computed Results: **Ea** = 307.869_V, **Eta** = 38.4837_V, **K** = 15.2789, **T** = 119.176_Nm, **ωme** = 93._r/s

31.3 Separately-Excited DC Generator

The equations in this section describe the properties of a separately excited DC generator. The first equation computes the field current **IIf** in terms of field voltage **Vfs**, external shunt resistance **re**, and field coil resistance **Rf**. The next equation evaluates armature induced voltage **Ea** as a function of machine constant **K**, mechanical radian frequency **ωm**, and flux ϕ.

$$IIf = \frac{Vfs}{\mathrm{Re} + Rf} \qquad \textbf{Eq. 31.3.1}$$

$$Ea = K \cdot \omega m \cdot \phi \qquad \textbf{Eq. 31.3.2}$$

The third and fourth equations are alternate forms of expressing terminal voltage **Vt** in terms of load current **IL**, load resistance **Rl**, armature resistance **Ra**.

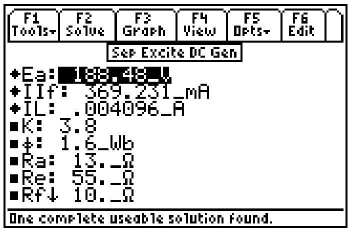
$$Vt = IL \cdot Rl \qquad \textbf{Eq. 31.3.3}$$

$$Vt = Ea - Ra \cdot IL \qquad \textbf{Eq. 31.3.4}$$

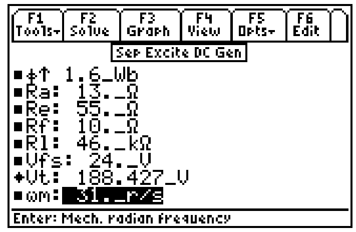
Finally the armature current **IL** in terms of **K**, ϕ, **ωm**, **Ra** and **Rl**.

$$IL = \frac{K \cdot \phi \cdot \omega m}{Ra + Rl} \qquad \textbf{Eq. 31.3.5}$$

Example 31.3 - A DC generator with a machine constant of 3.8 is driving a load of 46 kΩ and rotates at a speed of 31 rad/s. The magnetic flux is 1.6 Wb. The field is driven by a 24 V source. The field coil resistance is 10 Ω. The armature resistance is 13 Ω in series with an external resistance of 55 Ω. Find the field current, armature induced voltage and the terminal voltage.



Display: Upper Half



Display: Lower Half

Solution - Use all the equations to compute the solution for this problem. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation set. The computed results are shown in the screen displays above.

Known Variables: **K** = 3.8, **ϕ** = 1.6_Wb, **Ra** = 13._Ω, **Re** = 55._ Ω, **Rf** = 10._ Ω, **Rl** = 46._kΩ, **Vfs** = 24._V, **ωm** = 31._r/s

Computed Results: **Ea** = 188.48_V, **IIf** = 369.231_mA, **IL** = .004096_A, **Vt** = 188.427_V

31.4 DC Shunt Generator

The first equation in this section expresses the induced armature voltage **Ea** in terms of the machine constant **K**, the mechanical angular frequency **ωm**, and flux **ϕ**.

$$Ea = K \cdot \omega m \cdot \phi \qquad \textbf{Eq. 31.4.1}$$

The second equation defines terminal voltage **Vt** in terms of the field current **IIf**, external resistance **Re**, and field coil resistance **Rf**. The third equation computes **Vt** in terms of load current **IL** and load resistance **Rl**. The fourth equation expresses **Vt** as the induced emf **Ea** minus armature IR drop.

$$Vt = (\mathrm{Re} + Rf) \cdot IIf \qquad \textbf{Eq. 31.4.2}$$

$$Vt = IL \cdot Rl \qquad \textbf{Eq. 31.4.3}$$

$$Vt = Ea - Ra \cdot Ia \qquad \textbf{Eq. 31.4.4}$$

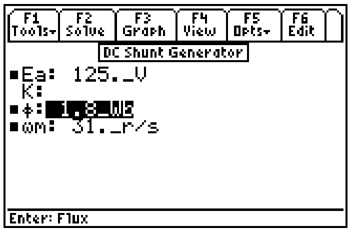
The armature current **Ia** is the sum of the load current **IL** and field current **IIf**.

$$Ia = IL + IIf \qquad \textbf{Eq. 31.4.5}$$

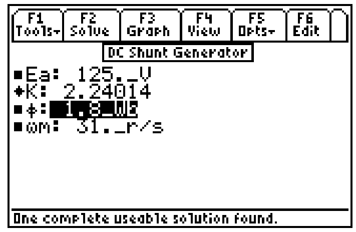
The final equation is an alternate form of expression for **Ea**.

$$Ea = Ra \cdot Ia + (\mathrm{Re} + Rf) \cdot IIf \qquad \textbf{Eq. 31.4.6}$$

Example 31.4 - Find the machine constant of a shunt generator running at 31 rad/s and producing 125 V with a 1.8 Wb flux.



Entered Values



Computed Results

Solution - Use the first equation to solve this problem. Select this by pressing [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation. The computed result is shown in the screen display above.

Known Variables: **Ea** = 125._V, **ϕ** = 1.8_Wb, **ωm** = 31._r/s

Computed Result: **K** = 2.24014

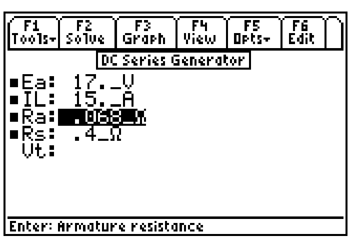
31.5 DC Series Generator

The two equations in this section describe the properties of a series DC generator. The first equation specifies the field current and the armature current to be the same. The second equation computes the terminal voltage **Vt** in terms of the induced emf **Ea**, load current **IL**, armature resistance **Ra**, and series field windings **Rs**.

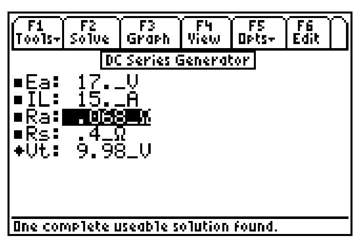
$$Ia = IIf \qquad \textbf{Eq. 31.5.1}$$

$$Vt = Ea - (Ra + Rs) \cdot IL \qquad \textbf{Eq. 31.5.2}$$

Example 31.5 - Find the terminal voltage of a series generator with an armature resistance of 0.068 Ω and a series resistance of 0.40 Ω. The generator delivers a 15 A load current from a generated voltage of 17 V.



Entered Values



Computed Results

Solution - Use the second equation to solve this problem. Select this with the highlight bar and press [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation. The computed result is shown in the screen display above.

Known Variables: **Ea** = 17._V, **IL** = 15._A, **Ra** = .068_Ω, **Rs** = .4_Ω

Computed Results: **Vt** = 9.98_V

31.6 Separately-Excited DC Motor

These equations form the working foundation for a separately excited motor. The first equation calculates the field voltage **Vf** in terms of the field current **IIf** and field coil resistance **Rf**.

$$Vf = Rf \cdot IIf \qquad \textbf{Eq. 31.6.1}$$

The second equation computes the terminal voltage **Vt** in terms of the machine constant **K**, magnetic flux **ϕ**, mechanical radian frequency **ωm**, armature current **Ia**, and armature resistance **Ra**.

$$Vt = K \cdot \phi \cdot \omega m + Ra \cdot Ia \qquad \textbf{Eq. 31.6.2}$$

The load torque **TL**, in the third equation is defined in terms of **K**, **ϕ**, **Ia** and **Tloss**.

$$TL = K \cdot \phi \cdot Ia - Tloss \qquad \textbf{Eq. 31.6.3}$$

Ea, the back emf induced in the rotor, is calculated by the next equation. Torque **T** links with **K**, **ϕ**, and **Ia**.

$$Ea = K \cdot \omega m \cdot \phi \qquad \textbf{Eq. 31.6.4}$$

$$T = K \cdot Ia \cdot \phi \qquad \textbf{Eq. 31.6.5}$$

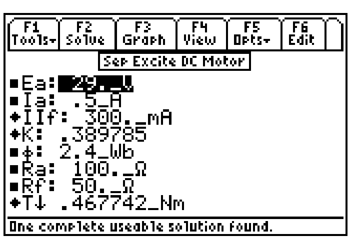
The reciprocal power relationship between **ωm** and **ϕ** by the inverse quadratic relationship. The next set of equations show the relationship between **T**, the torque lost due to friction **Tloss** and the torque load **TL**. The last equation in this set shows relationship of power with torque **T** and angular velocity **ωm**.

$$\omega m = \frac{Vt}{K \cdot \phi} - \frac{Ra \cdot T}{(K \cdot \phi)^2} \qquad \textbf{Eq. 31.6.6}$$

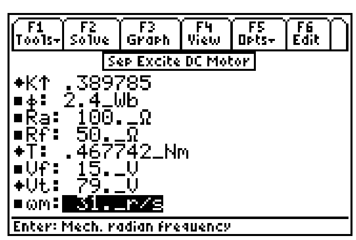
$$T = Tloss + TL \qquad \textbf{Eq. 31.6.7}$$

$$P = T \cdot \omega m \qquad \textbf{Eq. 31.6.8}$$

Example 31.6 - Find the terminal voltage, field current and machine constant for a motor with an armature current 0.5 A and resistance of 100 Ω rotating at an angular velocity of 31 r/s. The back emf is 29 V. The field is driven by a 15 V source driving a 50 Ω load. The flux available in the armature is 2.4 Wb.



Display: Upper Half



Display: Lower Half

Solution - Solve the first, second, fourth and fifth equations. Select these by highlighting and pressing ENTER. Press F2 to display the input screen, enter all the known variables and press F2 to solve the selected equation set. The computed results are shown in the screen display above.

Known Variables: **Ea** = 29._V, **Ia** = .5_A, **ϕ** = 2.4_Wb, **Ra** = 100._ Ω **Rf** = 50._ Ω , **Vf** = 15._V, **ωm** = 31._r/s

Computed Results: **IIf** = 300._mA, **K** = .389785, **T** = .467742_Nm, **Vt** = 79._V

31.7 DC Shunt Motor

These seven equations describe the principal characteristics of a DC shunt motor. The first equation expresses the terminal voltage **Vt** in terms of the field current **IIf** and field resistance **Rf** along with the external field resistance **Re**. The second equation defines the terminal voltage **Vt** in terms of the back emf (expressed in terms of the machine constant **K**, flux swept ϕ, and angular velocity **ωm**) and the IR drop in the armature circuit.

$$Vt = (\mathrm{Re} + Rf) \cdot IIf \qquad \textbf{Eq. 31.7.1}$$

$$Vt = K \cdot \phi \cdot \omega m + Ra \cdot Ia \qquad \textbf{Eq. 31.7.2}$$

The third equation refers to the torque available at the load **TL** due to the current **Ia** in the armature minus the loss of torque **Tloss** due to friction and other reasons.

$$TL = K \cdot \phi \cdot Ia - Tloss \qquad \textbf{Eq. 31.7.3}$$

The fourth equation gives the definitive relationship between the back emf **Ea**, **K**, ϕ and **ωm**.

$$Ea = K \cdot \omega m \cdot \phi \qquad \textbf{Eq. 31.7.4}$$

The next equation displays the reciprocal quadratic relationship between **ωm**, **Vt**, **K**, ϕ, armature resistance **Ra**, adjustable resistance **Rd** and **T**.

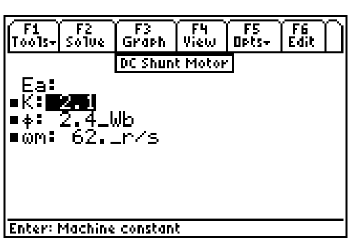
$$\omega m = \frac{Vt}{K \cdot \phi} - \frac{(Ra + Rd) \cdot T}{(K \cdot \phi)^2} \qquad \textbf{Eq. 31.7.5}$$

The last two equations compute torque **T** in terms of **Tloss**, load torque **TL**, flux ϕ, **Ia**, and **K**.

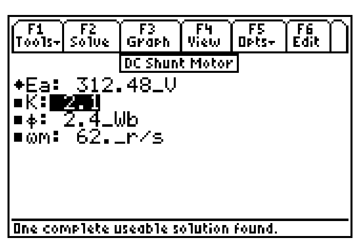
$$T = Tloss + TL \qquad \textbf{Eq. 31.7.6}$$

$$T = K \cdot \phi \cdot Ia \qquad \textbf{Eq. 31.7.7}$$

Example 31.7 - Find the back emf for a motor with a machine constant of 2.1, rotating at 62 rad/s in a flux of 2.4 Wb.



Entered Values



Calculated Results

Solution - Use the fourth equation to solve this problem. Select the equation with the cursor bar and press [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation. The computed result is shown in the screen display above.

Known Variables: **K** = 2.1, ϕ = 2.4_Wb, **ωm** = 62._r/s

Computed Result: **Ea** = 312.48_V

31.8 DC Series Motor

These eight equations describe the performance characteristics of a series DC motor. The first equation links the terminal voltage **Vt** to the back emf (**Ea** defined by the third equation) and the IR drop through the armature due to armature resistance **Ra**, adjustable resistance **Rd**, and series resistance **Rs**. The second equation calculates the load torque **TL** with the machine constant **K**, flux ϕ, load current **IL**, and the torque loss **Tloss**.

$$Vt = K \cdot \phi \cdot \omega m + \left(Ra + Rs + Rd\right) \cdot IL \qquad \textbf{Eq. 31.8.1}$$

$$TL = K \cdot \phi \cdot IL - Tloss \qquad \textbf{Eq. 31.8.2}$$

The third equation defines the back emf in the armature **Ea** in terms of **K**, ϕ, and mechanical frequency **ωm**. The fourth equation shows torque generated at the rotor due the magnetic flux ϕ and current **IL**.

$$Ea = K \cdot \omega m \cdot \phi \qquad \textbf{Eq. 31.8.3}$$

$$T = K \cdot \phi \cdot IL \qquad \textbf{Eq. 31.8.4}$$

The next equation shows a reciprocal quadratic link between **ωm**, **Vt**, **K**, ϕ, **Ra**, **Rs**, **Rd**, and torque **T**.

$$\omega m = \frac{Vt}{K \cdot \phi} - \frac{\left(Ra + Rs + Rd\right) \cdot T}{\left(K \cdot \phi\right)^2} \qquad \textbf{Eq. 31.8.5}$$

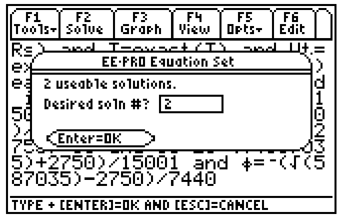
The sixth equation computes the torque generated **T** as the sum of load torque **TL** and lost torque **Tloss**. The last two equations show the connection between **K**, ϕ, a field constant **Kf**, load current **IL**, and torque **T**.

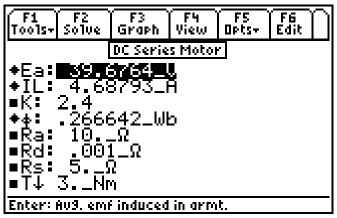
$$T = Tloss + TL \qquad \textbf{Eq. 31.8.6}$$

$$K \cdot \phi = Kf \cdot IL \qquad \textbf{Eq. 31.8.7}$$

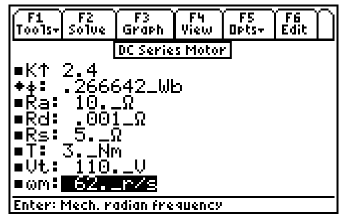
$$T = Kf \cdot IL^2 \qquad \textbf{Eq. 31.8.8}$$

Example 31.8 - A series motor, with a machine constant of 2.4, rotating at 62 rad/s, is supplied with a terminal voltage of 110 V and produces a torque of 3 Nm. The armature resistance is 10 Ω, the series resistance is 5 Ω, and the adjustable resistance is 0.001 Ω. Find the average voltage induced in the armature, the flux, and the load current.

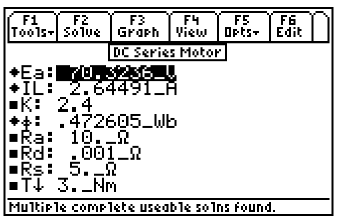




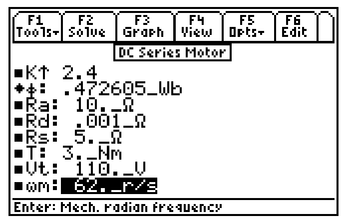
Solution 1: Upper Display



Solution 1: Lower Display



Solution 2: Upper Display



Solution 2: Lower Display

Solution - The first, third and fifth equations are needed to compute a solution. Select these by highlighting and pressing [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the selected equation set. There are two possible solutions for this example. Type the number of the solution set to be viewed and press [ENTER] twice. To view another solution set, press [F2] to and select another number. The computed results are shown in the screen displays above.

Known Variables: **K** = 2.4**,** **Ra** = 10Ω, **Rd** = .001_Ω, **Rs** = 5._ Ω, **T** = 3._Nm, **Vt** = 110._V, **ωm** = 62._r/s

Computed Results: **Ea** = 70.3236_V (39.6764_V), **IL** = 2.64491_A (4.68793_A), **ϕ** = .472605_Wb (.266642_Wb)

31.9 Permanent Magnet Motor

These five equations characterize the basic features of a permanent magnet motor. The first equation shows the back emf **Ea** in terms of machine constant **K**, flux **ϕ**, and radian velocity **ωm**. The second equation shows the connection between generated torque **T**, **K**, **ϕ** and armature current **Ia**. The terminal voltage **Vt** is the sum of back emf **Ea** and the inductive-resistance drop in the armature. The fourth equation shows conservation of various torques **T**, **TL** and **Tloss**. The final equation displays the quadratic relationship of **ωm** in terms of **K**, **Vt**, **ϕ**, **T** and **Ra**.

$$Ea = K \cdot \phi \cdot \omega m$$ **Eq. 31.9.1**

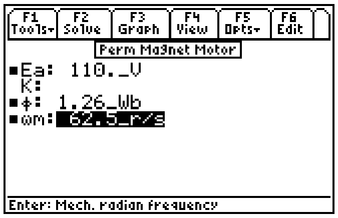
$$T = K \cdot \phi \cdot Ia$$ **Eq. 31.9.2**

$$Vt = Ea + Ra \cdot Ia$$ **Eq. 31.9.3**

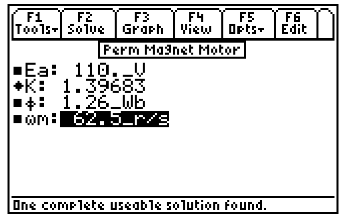
$$T = Tloss + TL$$ **Eq. 31.9.4**

$$\omega m = \frac{Vt}{K \cdot \phi} - \frac{Ra \cdot T}{(K \cdot \phi)^2}$$ **Eq. 31.9.5**

Example 31.9 – Find the machine constant for a permanent motor rotating at 62.5 rad/s in a magnetic flux field of 1.26 Wb. Assume a 110 V back emf.



Entered Values



Calculated Results

Solution - The first equation is needed to compute the solution. Select it by highlighting and pressing [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation.

Known Variables: **Ea** = 110._V, **ϕ** = 1.26_Wb, **ωm** = 62.5_r/s

Computed Result: **K** = 1.39683

31.10 Induction Motor I

These eleven equations define the relationships amongst key variables used in evaluating the performance of an induction motor.

The first equation expresses the relationship between the radian frequency induced in the rotor **ωr**, the angular speed of the rotating magnetic field of the stator **ωs**, the number of poles **p**, and the mechanical angular speed **ωm**.

$$\omega r = \omega s - \frac{p}{2} \cdot \omega m$$ **Eq. 31.10.1**

The second, third and fourth equations describe the slip **s** using **ωr** and **ωs**, **ωm**, **p**, the induced rotor power per phase **Pr**, and the power transferred to the rotor per phase **Pma**.

$$s = 1 - \frac{p}{2} \cdot \frac{\omega m}{\omega s}$$ **Eq. 31.10.2**

$$\frac{\mathrm{Pr}}{Pma} = s$$ **Eq. 31.10.3**

$$\omega r = s \cdot \omega s$$ **Eq. 31.10.4**

Pma is defined in the fifth equation in terms of the rotor current **Ir** and the rotor phase voltage **Ema**.

$$Pma = 3 \cdot Ir \cdot Ema$$ **Eq. 31.10.5**

The sixth and seventh equations account for the mechanical power **Pme** in terms of **p**, **ωm**, **ωs**, **Pma**, and torque **T**.

$$Pme = 3 \cdot \frac{p}{2} \cdot \frac{\omega m}{\omega s} \cdot Pma$$ **Eq. 31.10.6**

$$Pme = T \cdot \omega m$$ **Eq. 31.10.7**

The eighth equation expresses torque in terms of **p**, **Pma**, and **ωs**.

$$T = 3 \cdot \frac{p}{2} \cdot \frac{Pma}{\omega s}$$ **Eq. 31.10.8**

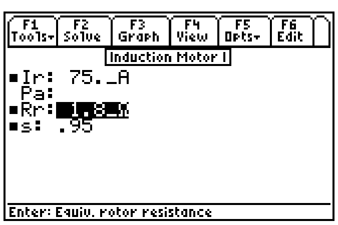
The last three equations show an equivalent circuit representation of induction motor action and links the power **Pa** with rotor resistance **Rr**, rotor current **Ir**, slip **s**, rotor resistance per phase **RR1** and the machine constant **KM**.

$$Pma = Rr \cdot Ir^2 + \frac{1-s}{s} \cdot Rr \cdot Ir^2$$ **Eq. 31.10.9**

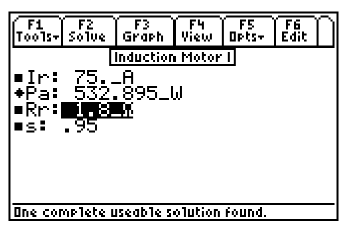
$$Pa = \frac{1-s}{s} \cdot Rr \cdot Ir^2$$ **Eq. 31.10.10**

$$Rr = \frac{RR1}{KM^2}$$ **Eq. 31.10.11**

Example 31.10 – Find the mechanical power for an induction motor with a slip of 0.95, a rotor current of 75 A , and a resistance of 1.8 Ω.



Entered Values



Calculated Results

Solution - Choose the next to last equation to compute the solution. Select by highlighting and pressing ENTER. Press F2 to display the input screen, enter all the known variables and press F2 to solve the equation.

Known Variables: **Ir** = 75._A, Rr = 1.8_Ω, s = .95

Computed Result: **Pa** = 532.895_W

31.11 Induction Motor II

These equations are used to perform equivalent circuit analysis of an induction motor. The first equation shows the power in the rotor per phase **Pma**, defined in terms of the rotor current **Ir**, rotor resistance **Rr**, and slip **s**.

$$Pma = \frac{Rr}{s} \cdot Ir^2 \qquad \textbf{Eq. 31.11.1}$$

The second equation shows the expression for torque **T** in terms of poles **p**, **Pma** and radian frequency of the induced voltage in the stator **ωs**. The third equation is an alternate representation of torque in terms of the applied voltage **Va**, stator resistance **Rst**, **Rr**, inductive reactance **XL**, and **ωs**.

$$T = \frac{3}{2} \cdot p \cdot \frac{Pma}{\omega s} \qquad \textbf{Eq. 31.11.2}$$

$$T = \frac{3}{2} \cdot \frac{p}{\omega s} \cdot \frac{Rr}{s} \cdot \frac{Va^2}{\left(Rst + \frac{Rr}{s}\right)^2 + XL^2} \qquad \textbf{Eq. 31.11.3}$$

The equation for **Tmmax** represents the maximum positive torque available at the rotor, given the parameters of the induction motor stator resistance **Rst**, **XL**, **Va**, **p**, and **ωs**.

$$Tm\max = \frac{3}{4} \cdot \frac{p}{\omega s} \cdot \frac{Va^2}{\sqrt{Rst^2 + XL^2} + Rst} \qquad \textbf{Eq. 31.11.4}$$

The maximum slip **sm** in the fifth equation represents the condition when dT/ds=0.

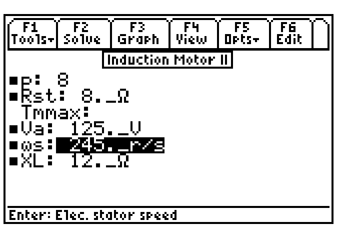
$$sm = \frac{Rr}{\sqrt{Rs^2 + XL^2}} \qquad \textbf{Eq. 31.11.5}$$

The sixth equation defines the so-called breakdown torque **Tgmax** of the motor. The final equation relates **Rr** with machine constant **KM** and the rotor resistance per phase **RR1**.

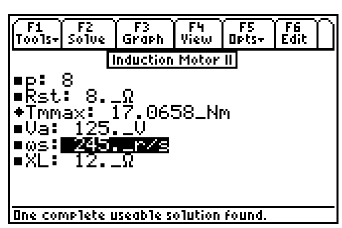
$$Tg\max = -\frac{3}{4} \cdot \frac{p}{\omega s} \cdot \frac{Va^2}{\sqrt{Rs^2 + XL^2} - Rst} \qquad \textbf{Eq. 31.11.6}$$

$$Rr = \frac{RR1}{KM^2} \qquad \textbf{Eq. 31.11.7}$$

Example 31.11 – An applied voltage of 125 V is applied to an eight pole motor rotating at 245 rad/s . The stator resistance and reactance is 8 and 12 Ω respectively. Find the maximum torque.



Entered Values



Calculated Results

Solution - Use the fourth equation to compute the solution. Select by moving the cursor bar, highlighting, and pressing [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation.

Known Variables: **p** = 8, **Rst** = 8._Ω, **Va** = 125._V, **ωs** = 245._r/s, **XL** = 12._ Ω

Computed Result: **Tmmax:** = 17.0658_Nm

31.12 Single-Phase Induction Motor

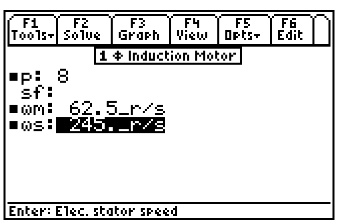
These three equations describe the properties of a single-phase induction motor. The first equation defines the slip for forward flux **sf** with respect to the forward rotating flux ϕ, the radian frequency of induced current in the stator **ωs**, the number of poles **p**, and the angular mechanical speed of the rotor **ωm**. The final two equations represent the forward and backward torques **Tf** and **Tb** for the system with respect to **sf,** the number of poles **p**, the electrical stator speed **ωs**, the equivalent rotor resistance **Rr** and the currents **Isf** and **Isb**. The forward torque is given by the power dissipated in the fictitious rotor resistor.

$$sf = 1 - \frac{p}{2} \cdot \frac{\omega m}{\omega s}$$ **Eq. 31.12.1**

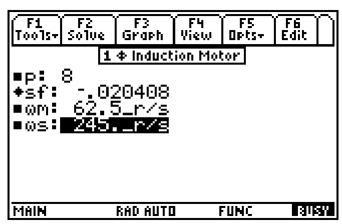
$$Tf = \frac{p}{2} \cdot \frac{1}{\omega s} \cdot \frac{Isf^{2} \cdot Rr}{2 \cdot sf}$$ **Eq. 31.12.2**

$$Tb = -\frac{p}{2} \cdot \frac{1}{\omega s} \cdot \frac{Isb^{2} \cdot Rr}{2 \cdot (2 - sf)}$$ **Eq. 31.12.3**

Example 31.12 – Find the forward slip for an eight pole induction motor with a stator frequency of 245 rad/s, and a mechanical radian frequency of 62.5 rad/s.



Entered Values



Calculated Results

Solution - The first equation is needed to compute the solution. Select by highlighting and pressing [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equation.

Known Variables: **p** = 8, **ωm** = 62.5_r/s **ωs** = 245._r/s

Computed Results: **sf** = -.020408

31.13 Synchronous Machines

These five equations focus on the basic properties of a synchronous machine. The first equation relates the radian mechanical and electrical speeds **ωm** and **ωs** with the number of poles **p**. The second equation shows maximum torque **TTmax** (sometimes referred to as pull out torque) in terms of current **IIf**, applied voltage **Va**, **p**, and **ωs**. **Pma** represents the power produced in the load with a phase delay of θ. The last two equations show torque relationships with mechanical power **Pme**, **ωm**, **Pma**, and **ωs**.

$$\omega m = \frac{2}{p} \cdot \omega s \qquad \textbf{Eq. 31.13.1}$$

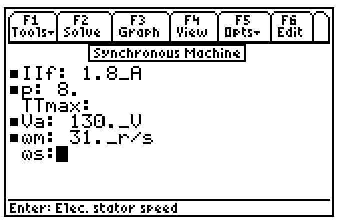
$$TT\max = 3 \cdot \frac{p}{2} \cdot \frac{IIf \cdot Va}{\omega s} \qquad \textbf{Eq. 31.13.2}$$

$$Pma = Va \cdot Ia \cdot \cos(\theta) \qquad \textbf{Eq. 31.13.3}$$

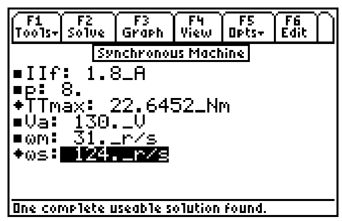
$$T = \frac{Pme}{\omega m} \qquad \textbf{Eq. 31.13.4}$$

$$T = 3 \cdot \frac{p}{2} \frac{Pma}{\omega s} \qquad \textbf{Eq. 31.13.5}$$

Example 31.13 – Find the stator radian frequency and the maximum torque for a synchronous machine with a mechanical rotational velocity of 31 rad/s. The motor has eight poles, a field current of 1.8 A, and experiences an applied voltage of 130 V.



Entered Values



Calculated Results

Solution - The first and second equations are needed to compute the solution. Select these using the cursor bar and pressing [ENTER]. Press [F2] to display the input screen, enter all the known variables and press [F2] to solve the equations.

Known Variables: **IIf** = 1.8_A, **p** = 8, **Va** = 130._V, **ωm** = 31._r/s

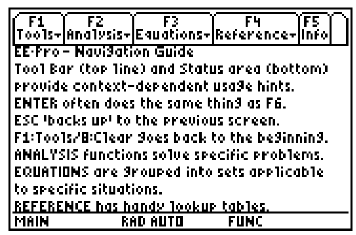
Computed Results: **TTmax** = 22.6452_Nm, **ωs** = 124._r/s

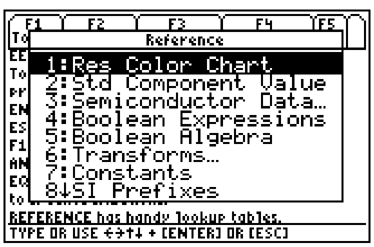
Chapter 32 Introduction to Reference

This chapter guides the user through the *Reference* Part of EE•*Pro*. The information in the *Reference* section of the software is organized in a similar fashion as *Analysis* and *Equations*, except the information is generally non-interactive.

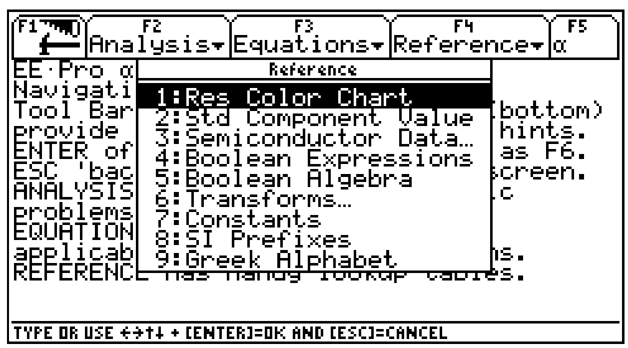
32.1 Introduction

The *Reference* Part is organized in nine sections that include topics the following topics: *Resistor Color Chart*, *Standard* (or preferred) *Component Values*, *Semiconductor Properties*, *Boolean Expressions*, *Boolean Algebra Properties*, *Fourier*, *Laplace* and **z** *transforms properties*, commonly used *Fundamental Constants*, *SI prefixes*, and the *Greek Alphabet*.





Pull down menu on TI - 89 and TI - 92 Plus



Unlike *Analysis* and *Equations*, the screen formats for the topics in the *Reference* section can differ significantly, depending on the information presented. Some Reference tables, such as the *Resistor Color Chart* and *Standard Component Values*, are dynamically interactive and perform calculations. Many sections include pictures for more clarification.

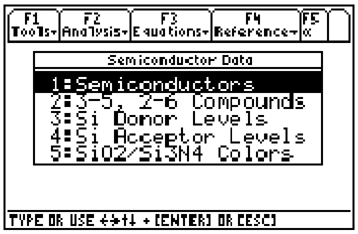
32.2 Finding Reference

The *Reference* Part is accessed by starting EE•*Pro.*

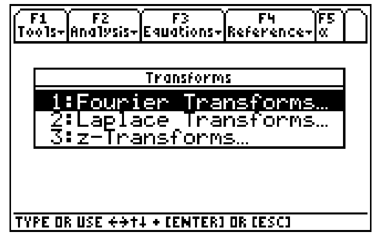
1. Start EE•*Pro*:
   - TI 89 and TI 92 Plus: Press [APPS] key to display the pull down menu. Use ⊖ key to move the high-light bar to EE•*Pro* and press [ENTER]. Alternatively, type in **[A]** when the pull down menu appears.

- Pressing [F4] accesses the menu for the *Reference* section listing the topics. EE•*Pro* is structured with a hierarchy of screens for choosing a specific topic.

2. Select a topic of *Reference* by moving the highlight bar to the desired section using the ▼ key and pressing [ENTER]. Alternatively, type in the number corresponding to the section desired. For example, press [3] to access *Semiconductor Data*, or press [6] to access the *Transforms* section.



Semiconductor Data Menu

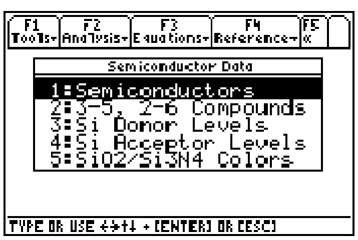


Transforms Menu

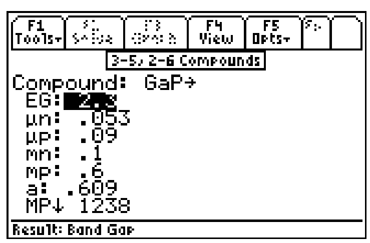
32.3 Reference Screens

The semiconductor data section has been chosen to illustrate how to navigate within a topic of the *Reference* section.

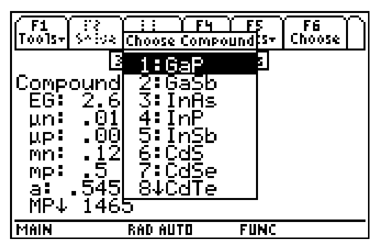
- When accessing the *Semiconductor Data* section, a dialog box appears listing the available topics. Use ▼ key to move the highlight bar to *3-5 and 2-6 Compounds* and press [ENTER]. This displays the electronic, and physical properties of the compound gallium phosphide, GaP.



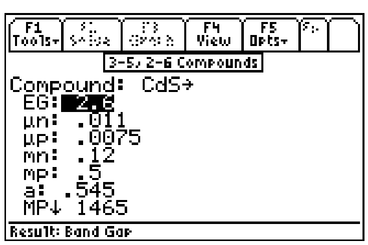
Sections in Semiconductor Data



Properties of GaP



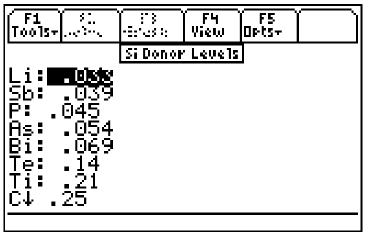
*Materials available in **3-5, 2-6 Compounds** section*



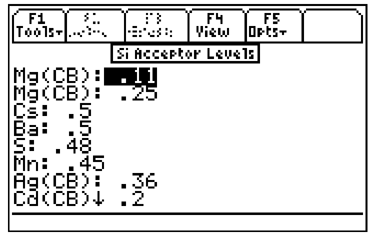
Properties of CdS

- Note that GaP has an arrow → to its right indicating that there are other materials whose properties are also listed. Move the highlight bar to GaP, press [ENTER] to view the other materials. The list of other materials includes GaSb, InAs, InP, InSb, CdS, CdSe, CdTe, ZnS, ZnSe, ZnTe. To display the properties of CdS, use the ▼ key to move the high light bar to CdS and press [ENTER]. Alternatively, type in [6] when the pull down menu appears.
- The data displayed automatically updates to list the properties of CdS as shown above.

- Other properties available in the section include *Donor and Acceptor levels* in Silicon shown in the screen displays below.



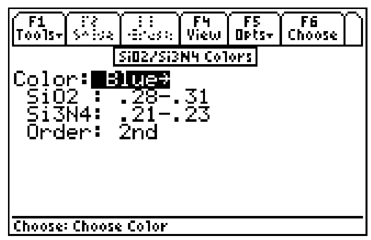
Silicon Donor Level



Silicon Acceptor Levels

The last topic in *Semiconductor Properties* includes the colors observed for Silicon dioxide and Silicon Nitride thickness. These colors are arranged in order of thickness (µm). Some colors appear multiple times due to multiple diffraction orders.

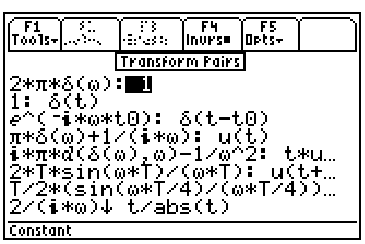
SiO2/Si3N4 Color Choices



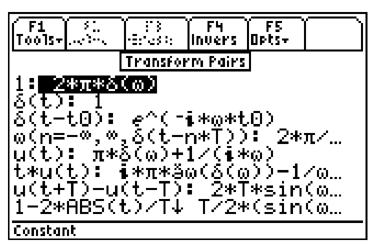
Properties of SiO2/Si3N4 (thickness in µm)

32.4 Using Reference Tables

The *Transform* section is used as an example of viewing reference tables. *Transforms* allows the user to inspect *Fourier*, *Laplace* or ***z**-transforms*. Each of these topics are divided into three sub-topics, *Definitions*, *Properties* and *Transform Pairs*. For example, navigate from *Transforms* → *Fourier Transforms* → *Transform Properties*. A screen display below shows the lists the equations displaying the fundamental properties of *Fourier* transform pairs. Note that the name of the selected transform equation appears in the status line. For example, if the highlight bar is moved to the sixth equation, the status line displays "Rectangular Pulse" as the description of the property.

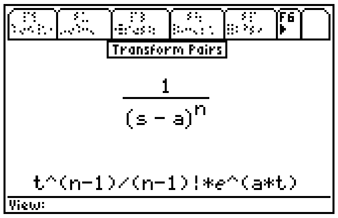


Normal View

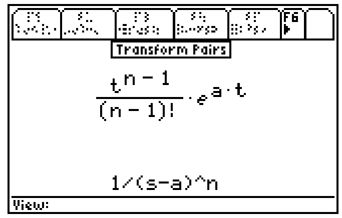


Inverse View (press [F4])

To view the equation in *Pretty Print* format, press ▶. The contents on the right side of the colon (:) are displayed in *Pretty Print*, while the contents to the left of the colon are displayed in regular type above the status line. To reverse this display (display the inverse of the property), press [ESC] to exit *Pretty Print* mode, press [F4] to display the *inverse* form of the transform property, and ▶ to view the inverse transform in *PrettyPrint.*



Regular View of Laplace Transform



Inverse View of Laplace Transform

Chapter 33 Resistor Color Chart

This section of EE•*Pro* allows the user to enter the color sequence of a physical resistor and compute its value and tolerance. Most physical resistors come with a band of colors to help identify its value. There are 3 variations of color bands used in practice: 3, 4 or 5 band of colors. The table below identifies the hierarchy used in practice. A picture of the color chart is included in the software and is displayed when the function key F4 is pressed.

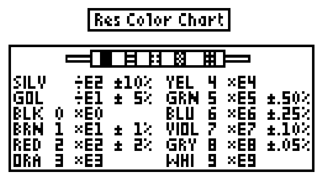


Table 33-1 Description of Colors in resistors

Band positions represent:

	3-Band	**4-Band**	**5-Band**
Band 1	digit	digit	digit
Band 2	digit	digit	digit
Band 3	multiplier	multiplier	digit
Band 4	N/A	tolerance	multiplier

Band positions represent:

	3-Band	**4-Band**	**5-Band**
Band 1	digit	digit	digit
Band 2	digit	digit	digit
Band 3	multiplier	multiplier	digit
Band 4	N/A	tolerance	multiplier
Band 5	N/A	N/A	tolerance

Colors represent:

	DIGIT	**MULTIPLIER**	**TOLERANCE**
SILVER	-	÷E2	10%
GOLD	-	÷E1	5%
BLACK	0	xE0	-
BROWN	1	xE1	1%
RED	2	xE2	2%
ORANGE	3	xE3	-
YELLOW	4	xE4	-
GREEN	5	xE5	0.5%

BLUE	6	xE6	0.25%
VIOLET	7	xE7	0.1%
GREY	8	xE8	0.05%
WHITE	9	xE9	-

Field Description

Input Fields

Num. of Bands: (*Number of Bands*) Pressing [ENTER] displays choice of 3, 4, or 5 bands.
Band 1: (see table above) Pressing [ENTER] displays choice of colors.
Band 2: (see table above) Pressing [ENTER] displays choice of colors.
Band 3: (see table above) Pressing [ENTER] displays choice of colors.
Band 4: (see table above) Pressing [ENTER] displays choice of colors.
Band 5: (see table above) Pressing [ENTER] displays choice of colors.

Output Fields

Value: (*Resistor Value*) Returns a Resistor Value.
Tolerance: (*Resistor Tolerance*) Returns a percent.

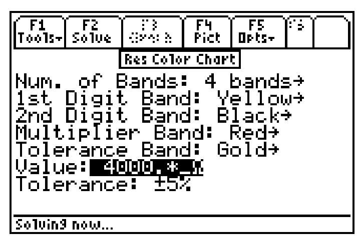
33.1 Using the Resistor Color Chart

Select this topic from the *Reference* section and press [ENTER].

1. Select the number of bands on the resistor (display automatically updates for the entry).
2. In each **Band field**, select a color using ▶ and pressing [ENTER].
3. The results are displayed in the **Value** and **Tolerance** lines of the display.

Example 33.1- Find the value and tolerance of a resistor with band colors yellow, black, red and gold. Using the steps outlined above.

1. Enter 4 for **Num. of Bands**.
2. For the **1st Digit Band**, select Yellow color.
3. For the **2nd Digit Band**, select Black color.
4. For the **Multiplier Band**, select Red color.
5. For **Tolerance Band**, select Gold.
6. The results show 4000_Ω in the **Value** field, and ± 5% in the **Tolerance** field as shown to the right.



Chapter 34 Standard Component Values

In this section, the software computes the inverse of the color chart computation described in the previous chapter (i.e.: given a value and a tolerance for a resistor, a color sequence is generated). As a side benefit the calculation algorithm also allows the user to estimate suitable “off-the-shelf” standard components for needed resistors, inductors and capacitors. These are also referred to as "Preferred Values" of components available from manufacturers.

Field Descriptions

Input Field

Value: (*Desired Value or Design Spec.*) — Enter a real number.

Tolerance: (*Tolerance of Component*) — Press [ENTER] to display selection. The values range from tolerance ±20% down to ±.0.05%.

Component: (*Type of Component*) — Press [ENTER] to display component choices: Resistor, Inductor, or Capacitor.

Output Field

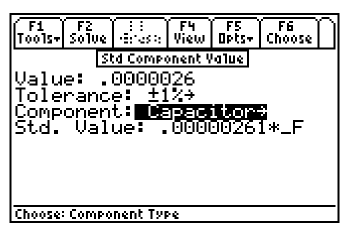
Value: (*Closest Standard Value to the Desired Value*) — Returns a "Preferred Value".

Bands: (*Resistor Color Bands - if the Component is a Resistor*) — Returns the color bands in a resistor.

Example 34.1 - A design calculation yields 2.6 microfarads for a capacitor. Find the closest preferred value with a tolerance of 1%.

Use the following directions:

1. Press the [MODE] setting and set **Display Digits** to **FLOAT 8,** press [ENTER].
2. In the **Value** field, enter **2.6E-6**.
3. In the **Tolerance** field, press [ENTER] to display choices; use ▼ key to move the highlight bar ±1 % and press [ENTER].
4. In the **Component** field, press [ENTER] to display; use ▼ key to move the highlight bar to "Capacitor" and press [ENTER] to select.
5. The Standard Component Value is displayed as **2.61E-6_F.**



Chapter 35 Semiconductor Data

Physical, chemical, electrical, electronic and mechanical properties of common semiconductors are presented in this section. The information is organized under five (5) topics listed in detail in Table 35-1. All properties are listed at 300 °K, unless otherwise specifically stated. Details of how to access the information is included in the table.

Table 35-1 Semiconductor Data

Section Label	*Data Fields*	*Description*
Semiconductors	**Input Field: Semiconductor:**	Press [ENTER] to display options (Si or GaAs), use ⊖ to move the highlighter to **Si** or **GaAs** and press [ENTER] to select
	Atoms: *(Atoms)*	**$1/cm^3$**
	At Wt: *(Atomic Weight)*	**g/mol**
	Br Fld: *(Breakdown Field)*	**V/cm**
	xtal: *(Crystal Structure)*	**structure name**
	ρ: *(Density)*	**g/cm^3**
	εr: *(Relative permittivity)*	**unitless**
	Nc: *(Density of states, CB)*	**$1/cm^3$**
	Nv: *(Density of states, VB)*	**$1/cm^3$**
	mle: *(Longitudinal e- mass)*	**unitless**
	mte: *(Transverse e-mass)*	**#**
	mlh: *(Light hole mass)*	**#**
	mhh: *(Heavy hole mass)*	**#**
	ϕ: *(Electron affinity)*	**V**
	EG: *(Band gap)*	**eV**
	ni: *(Intrinsic Density)*	**$1/cm^3$**
	a: *(Lattice constant)*	**nm**
	αth: *(Thermal expansion coefficient)*	**1/°K**
	MP: *(Melting Point)*	**°C**
	τ: *(Carrier lifetime)*	**s**
	µn: *(Electron mobility)*	**$cm^2/(V*s)$**
	µp: *(Hole Mobility)*	**$cm^2/(V*s)$**
	Raman E: *(Raman Photon Energy)*	**eV**
	Sp Ht: *(Specific heat)*	**J/g**
	Th. Cond: *(Thermal conductivity)*	**W/(cm*°K)**
	Diff Cons: *(Diffusion Constant)*	**cm^2/s**
	Vapor Pr: *(Vapor Pressure 1600°C)*	**torr**
	Vapor Pr: *(Vapor Pressure 930°C)*	**torr**
	Work Fn: *(Work Function)*	**V**

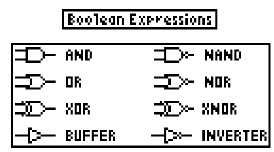
III-V, II-VI Compounds	**Input Field:** **Compound:** **EG:** *(Energy Gap)* **μn:** *(Electron mobility)* **μp:** *(Hole mobility)* **mn:** *(Electron Effective mass)* **mp:** *(Hole Effective mass)* **a:** *(Lattice constant)* **MP:** *(Melting point)* **εr:** *(Dielectric constant)* **ρ:** *(Density)*	**GaP →** Press ENTER to display pull down menu listing the III-V and II-VI semi-conducting compounds. They are: **1:GaP** **2:GaSb** **3:InAs** **4:InP** **5:InSb** **6:CdS** **7:CdSe** **8:CdTe** **9:ZnS** **A:ZnSe** **B:ZnTe** To select a compound, use the ▼ key to move to highlight bar to the item and press ENTER (or enter the item number). **eV** **m^2/(V*s)** **m^2/(V*s)** **unitless** **unitless** **nm** **°C** **unitless** **g/cm^3**
Si Donor Levels	**Output Field:** Silicon Donor levels are displayed relative to the conduction band. The donor list includes the following: **Li:** **Sb:** **P:** **As:** **Bi:** **Te:** **Ti:** **C:** **Se:** **Se:** **Cr:** **Ta:** **Ta:** **Cs:** **Ba:** **S:** **Mn:** **Mn(VB):**	All values are displayed in electron volts **(eV)** relative to the conduction band. In some cases there is a **(VB)** designation next to the element. In these cases, the location of the donor level is referenced *relative to the valence band.* For example, the donor level for **Te** is displayed as 0.14_eV indicating that the donor level is 0.14 eV *below the conduction band.* On the other hand **Gold** has **(VB)** appended. Thus the value 0.29_eV displayed reflects that the donor level of Gold (i.e., Au) is 0.29 eV *above the valence band.* Some elements have multiple energy levels and therefore appear more than once.

	Ag(VB): **Pt(VB):** **Si(VB):** **Si(VB):** **Na(VB):** **Au(VB):** **V:** **Mo:** **Mo(VB):** **Mo(VB):** **Hg(VB):** **Hg(VB):** **Sr:** **Sr(VB):** **Ge:** **Ge(VB):** **K:** **K(VB):** **Sn:** **W:** **W:** **W:** **W(VB):** **W(VB):** **Pb:** **O:** **O:** **Fe:** **Fe:** **Fe(VB):**	
Acceptor Levels	**Output Field:** Silicon Acceptor levels are displayed relative to the valence band. The acceptor list includes the following: **Mg(CB):** **Mg(CB):** **Cs:** **Ba:** **S:** **Mn:** **Ag(CB):** **Cd(CB):** **Cd(CB):** **Cd:** **Pt(CB):** **Pt:** **Si:** **B:** **Al:** **Ga:** **In:** **Tl:**	All values in are in electron volts **(eV)** relative to the valence band. For some elements, there is a **(CB)** appended to the element name. In these cases, the *location of the acceptor level is referenced relative to the conduction band.* For example, the acceptor level for Mg is displayed as 0.11_eV. **(CB)** follows the element name **Mg** indicating that the acceptor level is 0.11_eV *below the conduction band.* On the other hand, Platinum **(Pt)** has a value of 0.36 eV, with no additional information. This is an indicator that Pt produces an acceptor level 0.36 eV *above the valence band.* Some elements have multiple levels

	Pd: **Be:** **Be:** **Zn(CB):** **Zn:** **Au(CB):** **Co(CB):** **Co:** **Co:** **V:** **Ni(CB):** **Hg(CB):** **Hg(CB):** **Cu:** **Cu:** **Cu:** **Sn:** **Pb:** **O(CB):** **O:**	and appear more than once.
SiO2/Si3N4 Colors	**Input Field:** **Compound:** Once the specific color choice has been made, the display fields show the information for the following parameters: **SiO2:** Value in µm **Si3N4:** Value in µm **Order:** Value as a number	Silicon → Press [ENTER] to display the pull down menu listing the color of silicon with SiO2 or Si3N4 deposited on the surface. **1:Silicon** **2:Brown** **3:Golden brown** **4:Red** **5:Deep Blue** **6:Blue** **7:Pale Blue** **8:Very Pale Blue** **9:Silicon** **A: Light Yellow ZnSe** **B: Yellow** **C: Orange-Red** **D: Red** **E: Dark red** **F: Blue** **G: Blue Green** **H: Light Green** **I: Orange Yellow** **J: Red** To select a specific compound, enter the item number (or use ⊝ key) and press [ENTER]

Chapter 36 Boolean Expressions

This section covers the Boolean expressions reference table, which includes 16 commonly-used Boolean expressions. This section also contains a diagram of the most commonly-used logic components.



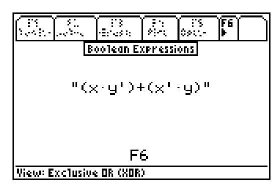
36.1 Using Boolean Expressions

This section displays a list of rules for Boolean algebra for two variables **x** and **y**:

"+" is used to indicate the OR function.
"**.**" is used to indicate AND function.
" **'** " represents a logical inversion.

The logic element symbols for AND, OR, NOR, BUFFER, NAND, INVERTER, XOR and XNOR, INVERTER are shown in this section and can be viewed by pressing the function key F4. The Boolean algebra rules are sixteen in number and are listed as functions ***F0-F15***. They are also identified by their name as shown in the Table 36-1.

Example 36.1 - Find the properties of an ***Exclusive OR (XOR)***.



1. Use the arrow key to move the highlight bar down the list. Continue scrolling until the status line reads "*Exclusive OR (XOR)*".
2. To view the expression in *Pretty Print*, press F5 to display the pull down menu and press either the ENTER key or 1. This will display the Boolean expression for XOR in *Pretty Print* form.
3. Press ESC to revert to the previous level.

Table 36-1 Boolean Expressions

Function Name	Boolean expression	Description of Function
F0	0	Null
F1	x.y	AND
F2	x.y'	Inhibition
F3	x	Transfer
F4	x'.y	Inhibition
F5	y	Transfer

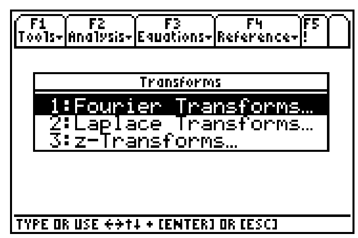
F6	(x.y')+(x'.y)	Exclusive OR (XOR)
F7	x+y	OR
F8	(x+y)'	NOT OR (NOR)
F9	(x.y)+(x'.y')	Equivalence (XNOR)
F10	y'	Complement NOT
F11	x+y'	Implication
F12	x'	Complement (NOT)
F13	x'+y	Implication
F14	(x.y)'	NOT AND (NAND)
F15	1	Identity

Chapter 38 Transforms

This section accesses a series of tables containing transforms of common interest to electrical engineers. The transforms are listed as three topics - *Fourier*, *Laplace* and *z-Transforms*. Each topic contains information categorized under three sub-topics - Definitions, Properties and Transform pairs. All formulae can be viewed in *Pretty Print* equation-display format. These sub-topics are not interactive, i.e., one cannot specify an arbitrary expression and expect to compute a transformed result.

38.1 Using Transforms

When the **Transform** section is selected, a dialog box is appears. To choose a topic, move the highlight bar using ⊽ or ⊼keys and press [ENTER] (alternatively, press the number associated with the topic).



1. Select **Fourier Transforms, Laplace Transforms**, or **z-Transforms**.
2. Select **Definitions, Properties** or **Transform Pairs**
3. Use the ⊽ or ⊼ keys to move to the transform line desired.
4. The forward transforms are displayed by default. Pressing [F4] toggles between the forward and inverse formats.
5. Press ▷ to view the transform property in *Pretty Print.*

- Information is presented on either side of the colon as shown below. The term on the left side of the colon, F(ω) represents the function in the frequency domain, while the right side of the colon represents the exact definition for F(ω) in terms of the time domain function f(t), integrated over all time modulated by e $^{-i\cdot\omega\cdot t}$.

Forward and Inverse Formats

- The information can be displaced in the inverse (as opposed to forward) form, meaning that the information on either side of the colon changes positions when the Inverse key [F4] is pressed. A '▪' symbol appears in the [F4] tool bar to indicate the inverse form of the transform function is being displayed.

$$F(\omega)\text{:} \int_{-\infty}^{+\infty} \left(f(t) \cdot e^{-i\cdot\omega\cdot t} \right) dt$$ ***Forward Fourier Transform***

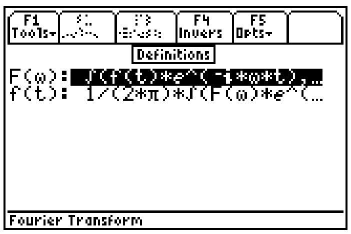
$$f\,(t):\frac{1}{2\pi}\int_{-\infty}^{+\infty}\left(F(w)\cdot e^{-i\cdot\omega\cdot t}\right)dw$$ ***Inverse Fourier Transform***

Status Line Message

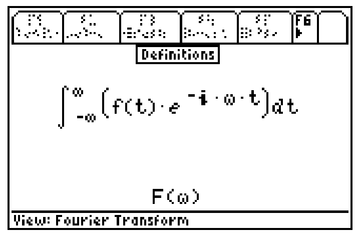
- The status line gives a description of the equation highlighted. The descriptions use standard mathematical terminology such as *Modulation, Convolution, Frequency Integration*, etc.

Example 38.1 -What is the definition of the *Inverse Fourier transform*?

1. In the main **Transforms** screen, move the highlight bar to **Fourier Transforms** and press [ENTER].
2. Press [ENTER] a second time to access **Definitions**.
3. Move the highlight bar to the second definition and press ▶ to display the equation in *Pretty Print* format.
4. Press ◀ or ▶ to scroll. Press any key to return to the previous screen.



Fourier Definitions

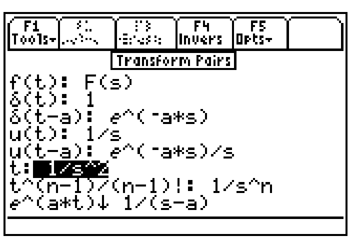


Pretty Print of Fourier (Time domain Transform)

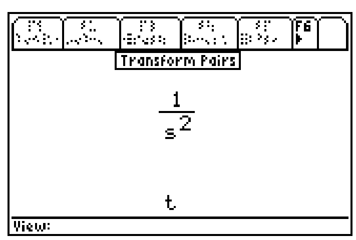
Example 38.2

View the **Laplace** transform of the time function **f(t)=t**.

1. In the initial **Transforms** screen, move the highlight bar to **Laplace Transforms** and press [ENTER].
2. Move the highlight bar to **Transform Pairs** and press [ENTER].
3. Scroll down to t: 1/s^2 and press ▶ to view the equation in *Pretty Print* format.



Laplace Transform Pairs



*Pretty Print of '**t**'*

Chapter 39 Constants

This *Constants Reference Table* section lists the values and units for 43 commonly-used universal constants. These constants are embedded in equations in the *Equations* section of EE•*Pro* and are automatically inserted during computations.

39.1 Using Constants

The *Constants* section in *Reference* is designed to give a quick glance for commonly used constants. It lists values of accuracy available by the standards of measurement established by appropriate international agencies. This section does not include any information of the uncertainty in measurement.

Table 39-1. Constants Reference Table

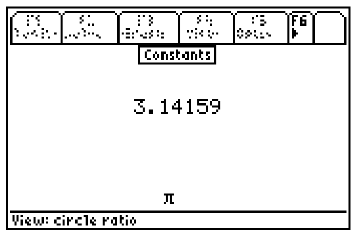
Const.	Description	Const.	Description
π	circle ratio	μq	mass μ / mass e-
e	Napier constant	ϕ0	magnetic flux quantum
γ	Euler constant	μB	Bohr magneton
ϕ	golden ratio	μe	e- magnetic moment
α	fine structure	μN	nuclear magneton
c	speed of light	μp	p+ magnetic moment
ε0	permittivity	μμ	μ magnetic moment
F	Faraday constant	a0	Bohr radius
G	Newton's Gravitational constant	R∞	Rydberg constant
g	acceleration due gravity	c1	1st radiation constant
h	Planck constant	c2	2nd radiation constant
hb	Dirac constant	b	Wien displacement
k	Boltzmann constant	σ	Stefan-Boltzmann constant
μ0	permeability	χc	e- Compton wavelength
q	e- charge	χn	n Compton wavelength
em	e- charge / mass	χp	p+ Compton wavelength
me	e- rest mass	SP	standard pressure
mn	n rest mass	ST	standard temperature
mp	p+ rest mass	Vm	molar volume at STP
mμ	μ rest mass	NA	Avogadro constant
pe	mass p+ / mass e-	R	molar gas constant
re	classical e- radius		

These constants were arranged in the following order: universal mathematical constants lead the list followed by universal physical constants, atomic and quantum mechanical constants, radiation constants, standard temperature and pressure, universal gas constant and molar constants. To view a constant, use the arrow key ⊖ key to move the highlight bar to the value and press the *View* key [F4]. The status line at the bottom of the screen gives a verbal description of the constant.

Example 39.1- Look up the value of π.

1. Pi is the first value to appear in the constant sections. Make sure it is selected by the highlight bar using the arrow keys.
2. Access the *View* function by pressing key [F4].
3. Press any key to return to the constants screen.

The number of significant digits displayed in *Pretty Print* can be changed in the [MODE] setting.



Chapter 40 SI Prefixes

The SI Prefixes section displays the prefixes used by the Systeme International [d'Unit[eacute]s] (SI).

40.1 Using SI Prefixes

The prefixes are listed in the order shown in Table 40-1. The ⊝ key is used to move the highlight bar to select a SI prefix multiplier. The name of the prefix is displayed in the status line. The prefix and multiplier can be viewed by pressing the F4 key.

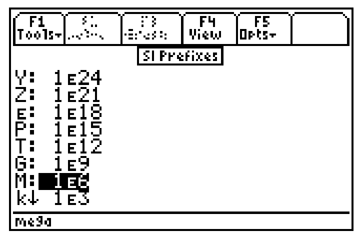
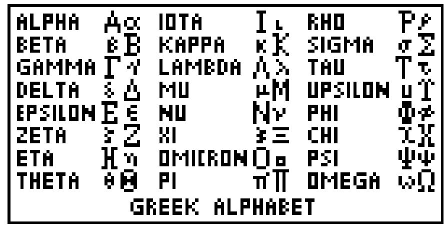


Table 40-1 SI Prefix Table

Prefix	Multiplier	Prefix	Multiplier
Y: (Yotta)	1E24	d: (deci)	1E-1
Z: (Zetta)	1E21	c: (Centi)	1E-2
E: (Exa)	1E18	m: (Milli)	1E-3
P: (Peta)	1E15	µ: (Micro)	1E-6
T: (Tera)	1E12	n: (Nano)	1E-9
G: (Giga)	1E9	p: (Pico)	1E-12
M: (Mega)	1E6	f: (Femto)	1E-15
k: (Kilo)	1E3	a: (Atto)	1E-18
h: (Hecto)	1E2	z: (Zepto)	1E-21
da: (Deka)	1E1	y: (Yocto)	1E-24

Chapter 41 Greek Alphabet



This section displays the Greek Alphabet and their names. There are several Greek letters supported by the TI - 89. To enter the Greek letters, the sequential keystrokes are listed in the TI-89 manual. They are repeated here for convenience of the user. Alternatively, 2nd + (or [CHAR]) followed by 1 will access an internal menu listing several Greek characters.

Table 40-1

Key stroke Sequence	Greek Letter	Key stroke Sequence	Greek Letter
◆ (alpha =	α		
◆ (alpha (	β		
◆ (alpha ,	δ	◆ (alpha ↑ ,	Δ
◆ (alpha ÷	ε		
◆ (alpha |	φ		
◆ (alpha 7	γ	◆ (alpha ↑ 7	Γ
◆ (alpha 4	λ		
◆ (alpha 5	μ		
◆ (alpha STO▸	π	◆ (alpha ↑ STO▸	Π
◆ (alpha 2	ρ		
◆ (alpha 3	σ	◆ (alpha ↑ 3	Σ
◆ (alpha T	τ		
◆ (alpha .	ω	◆ (alpha ↑ .	Ω
◆ (alpha X	ξ		
◆ (alpha Y	ψ		
◆ (alpha Z	ζ		

Appendix A Frequently Asked Questions

A complete list of commonly asked questions about the EE•*Pro* are listed here. Review this list for your questions prior to calling for Technical support. You might save yourself a phone call! The material is covered under four general headings.

A.1 Questions and Answers

- General Questions
- Analysis Questions
- Equations Questions
- Reference Questions

A.2 General Questions

The following is a list of questions about the general features of EE•*Pro*:

Q. Where can I find additional information about a variable?
A. A brief description of a highlighted variable appears in the status line at the bottom of the screen. More information, including its allowable entry parameters (i.e.: whether complex, symbolic or negative values can be entered, etc.) can be accessed by pressing [F5]**/Opts** and **2:Type**.

Q. What does the underscore "_" next to a variable mean?
A. This designates a variable which allows entry or expression of complex values.

Q . I am in the middle of a computation and nothing seems to be occurring. How can I halt this process?
A. Some computations can take a long time, particular if many equations and unknowns are being solved or a complex analysis function has been entered. Notice if the message in the status line at the bottom-right of the screen reads BUSY. This indicates that the TI math engine is attempting to solve the problem. Pressing the [ON] key usually halts a computation and allows the user to regain control of the software. If, for some reason, the calculator locks up and does not allow user intervention, a "cold start" will have to be performed. This can be done by holding down the three keys; [2nd], ◀, and ▶, and pressing [ON]. **WARNING:** This will delete folders containing any defined variables or stored programs. Use it as a last resort. A "cold start" will **not** delete EE•*Pro* from your calculator.

Q What do three dots (...) mean at the end of an item on the screen?
A. The three dots (an ellipsis) indicate the item is too wide to fit on the available screen area. To view an item in its entirety, select it by moving the highlight bar and press [F4] (or ▶, in some cases) to view the item in *Pretty Print*. Press ◀ or ▶ to scroll the item back and forth across the screen to view the entire object.

Q. How can I recall, or view values of a previously computed problem?

A. EE•*Pro* automatically stores its variables in the current folder specified by the user in [MODE] or the HOME screens. The current folder name is displayed in the lower left corner of the screen (default is "Main"). To create a new folder to store values for a particular session of EE•*Pro*, press [F1]**:/TOOLS,** [3]**:/NEW** and type the name of the new folder (see Chapter 5 of the TI-89 Guidebook for the complete details of creating and managing folders). There are several ways to display or recall a value:

- The contents of variables in any folder can be displayed using the [VAR-LINK], moving the cursor to the variable name and pressing [F6] to display the contents of a particular variable.
- Variables in a current folder can be recalled in the HOME screen by typing the variable name.
- Finally, values and units can be copied and recalled using the [F1]**/Tools 5:COPY** and **6:PASTE** feature.

All inputs and calculated results from *Analysis* and *Equations* section are saved as variable names. Previously calculated, or entered values for variables in a folder are replaced when equations are solved using new values for inputs.

Q. Why is it that some of the values of variables saved earlier are cleared when I graph an equation or analysis function which uses the variable name(s)?

A. When an equation or analysis function is graphed, EE•*Pro* creates a function for the TI grapher which expresses the dependent variable in terms of the independent variable. This function is stored under the variable name *pro(x)*. When the EE•*Pro*'s equation grapher is executed, values are inserted into the independent variable for *pro(x)* and values for the dependent value are calculated. Whatever values which previously existed in either of the dependent and independent variables in the current folder are cleared. To preserve data under variable names which may conflict with EE•*Pro*'s variables, run EE•*Pro* in a separate folder using the guidelines above.

Q. An item which is supposed to be displayed in a menu doesn't appear.
A. Some menus have more than eight items. If an arrow ↓ appears next to the digit 8, use the arrow key ⊖ to scroll the menu and view the remaining topics or press [2nd] ⊖ jump to the bottom of the menu.

Q. Is there a help section in the software?
A. There is a short series (slides) of general hints which can be accessed from the main screen of EE•*Pro* under [F5]**/Info**. A different message appears each time [F5] is pressed. We've attempted to keep most of the explanation of certain topics to the manual in an effort to keep the software compact. Consult the chapter corresponding to the appropriate section of the software. If your are still in need of clarification, contact Texas Instruments (contact information in the *Warranty and Technical Support* section of the manual) A compiled list of the received questions and answers will be posted periodically on the da Vinci website. *http://www.dvtg.com/faq/eepro*

A.3 Analysis Questions

These are some commonly asked questions about the *Analysis* section of EE•*Pro*.

Q. The screen display of computed results does not look identical to the example in the manual.
A. The [MODE] setting, which controls the number of floating point digits displayed in a value and whether an answer appears in exact or approximate form, may have been set differently on the calculator used to make the screen displays for the example problem. Press the [MODE] key to view or change the mode settings. The first page will display the number of floating point digits, whether the display is in NORMAL, SCIENTIFIC, OR ENGINEERING exponential formats. Pressing [F2]will display whether computed answers are displayed in APPROXIMATE or EXACT formats. The default mode setting for EE•*Pro* is *Float 6*, *Radian* and *Approximate* calculations.

Q. The calculated angle or radian frequency result isn't correct.
A. Check to be sure the MODE settings list **degrees** or **radians** for *angle* units and make sure it matches the units of your entered value or desired value. Secondly, if the result is greater than 2π or less than -2π ($|\text{result}| \geq 360^o$), the TI *solve(...)* function may be generating a non principal solution. A principal solution is defined as a value between 0 and 2π (or between 0 and 360^o). A non principal solution can be converted to a principal solution by adding or subtracting integer multiples of 2π (or 360^o) until the remainder is within the range of 0 and 2π (or 0 and 360^o). The remainder is the principal solution.

Example: Imagine solving the equation $\sin(x) = 0.5$. Non principle solutions include: 30°, 390°, -330°, 750°, etc., but the *principal* solution is 30°.

Q. The solution for an analysis function is expressed in symbolic terms or variables, whereas a numerical value was expected. Why?
A. If a variable name is entered as an input, EE•*Pro* will calculate a solution in symbolic form. In cases where a parameter entry is left blank, the variable's name will be used in a symbolic computation. A name cannot be entered which is identical to the variable name (i.e.: C for capacitance) instead, leave the entry blank.

Q. Units are not displayed in *Analysis* computations. Why?
A. The *Analysis* section incorporates methods for calculation which are unique to each topic in analysis (as opposed to *Equations* which uses similar methods of calculation in all of the sections). Unit management was omitted for simplicity. All entries and computed results in *Analysis* are assumed to be in common SI units (F, m, A, Ω, etc.) which are stated in the status line for each parameter. In some cases, variables will be expressed in units arbitrarily chosen by the user (example: The variable *len* in **Transmission Lines** can be entered in *km, m, miles* however the answers will be expressed in units of *len*).

If a value is entered that is inconsistent with the expected data type, an error dialog will appear which lists the entry name, the description, and the expected data type(s). See Appendix E for details on error messages.

Q. What is the multiple graph feature in Capital Budgeting and how do I get it to plot several projects simultaneously?
A. Activating the multiple graph feature allows successive graphs to be overlayed on the same. To do this, the graphing execution must be repeated each time a new project is plotted.
1. Make sure the cash flows for all the named projects have been entered.
2. Enable the **Multiple Graphs** feature by highlighting and pressing the ENTER key.
3. Select the name of a project you wish to graph and press F3.
4. To overlay a second project on the first, select a different project name and press F3 to graph.
5. Repeat step 4 each time a new project is to be graphed on top of previously plotted functions.

A.4 Equations Questions

These are some common questions about the Equations section of EE•*Pro*.

Q. There are already values stored in some of my variables. How do I clear or use those values?
A. These values remain from previous solving operations. It is okay to ignore the values. As long as they aren't selected '▪' they will be overwritten by new solutions. If you want to reset the values, clear one or all of the variables. A value can be re-used in a computation by highlighting the displayed value and pressing ENTER twice.

Q. Why do the values of the entered or calculated results change when the Units feature is deactivated in the F5 options menu?

A. When the Units feature is on, values can be entered and saved in any unit. When units are off, values can be entered in any unit, but the values will automatically be displayed on the screen in the default SI units. This is necessary so that when a series of equations are solved, all the values are consistent.

Q. When solving a set of equations "Too many unknowns to finish solving." is displayed. Why?
A. Sometimes the solver doesn't have enough to solve for all the remaining, unknown variables. In some cases, a *Partial Solution* set will be displayed. If the unknown value(s) is not calculated, more known values (or selected equations) will need to be selected to compute the solution.

Q. If I view the value of a variable in *Pretty Print*, I notice that the units contain an extra character (such as 'Δ').
A. In a few cases EE•*Pro* and the TI-89 and TI-92 operating systems use slightly different conventions for displaying units. The unit system in EE•*Pro* is designed to conform to the convention established by SI, however, in order to CUT and PASTE a value and units from EE•*Pro* to another area of the TI operating system, EE•*Pro* must insert extra characters in the units to match TI's syntax. This causes extra characters to appear or symbols to appear differently in *Pretty Print.*

Q. There are already values stored in some of my variables. How do I clear those values?
A. The values can be accessed via VAR-LINK menu. To delete variables in VAR-LINK, use the file management tool provided (use $\boxed{\text{F1}}$ key to access file management tools), check $\boxed{\text{F4}}$ the variables you want deleted and delete the variables.

Q. The solution to my problem is clearly wrong! An angle might be negative or unreasonably large. Why?
A. This is most likely to happen when angles are involved in the equation(s) you are solving. The TI 89 may have found a non-principal solution to your equation, or may have displayed the angle in radians (see the answer to the second question in the *Analysis* section).

If a non-principal solution is found, it may then be used to solve other equations, leading to strange results. Example: Imagine solving the equation $x + y = 90°$. If x is 30°, then y should be 60°. But if a non-principal solution for x was found, such as 750°, then the value of y will be -660°, which although technically correct, is also not a principal solution.

A.5 Reference

For more information, see Chapter 33, "Reference: Navigation Guide" and your TI 89 User's Guide.

Reference : Standard Component Values

- The message "Out of range" will occur if an entered component value is not in the range of $10^{\pm 23}$.

Appendix B Warranty, Technical Support

B.1 da Vinci License Agreement

By downloading/installing the software and/or documentation you agree to abide by the following provisions.

1. **License:** da Vinci Technologies Group, Inc. ("da Vinci") grants you a license to use and copy the software program(s) and documentation from the linked web/CD page ("Licensed Materials").

2. **Restrictions:** You may not reverse-assemble or reverse-compile the software program portion of the Licensed Materials that are provided in object code format. You may not sell, rent or lease copies that you make.

3. **Support:** Limited technical support is provided through Texas Instruments Incorporated. Details are listed below.

4. **Copyright:** The Licensed Materials are copyrighted. Do not delete the copyright notice, trademarks or protective notice from any copy you make.

5. **Warranty:** da Vinci does not warrant that the program or Licensed Materials will be free from errors or will meet your specific requirements. **The Licensed Materials are made available "AS IS" to you are any subsequent user.**

   Although no warranty is given for the License Material, the media (if any) will be replaced if found to be defective during the first three (3) months of use. For specific instructions, contact the TI webstore via www.ti.com. THIS PARAGRAPH EXPRESSES da Vinci's MAXIMUM LIABILITY AND YOUR SOLE AND EXCLUSIVE REMEDY.

6. **Limitations: da Vinci makes no warranty or condition, either express or implied, including but not limited to any implied warranties of merchantability and fitness for a particular purpose, regarding the Licensed Materials.**

7. **Restricted Rights:** The Licensed Materials are provided with Restricted Rights. Use, duplication or disclosure by the United States Government is subject to restrictions as set forth in subparagraph [c](1)(ii) of the Rights in Technical Data and Computer Software clause at DFARS 252.227-7013 or in subparagraph [c](1) and (2) of the Commercial Computer Software – Restricted Rights at 48 CFR 52.227-19, as applicable.

   In no event shall da Vinci or its suppliers, licensers, or sublicensees be liable for any indirect, incidental or consequential damages, lost of profits, loss of use or data, or interruption of business, whether the alleged damages are labeled in tort, contract or indemnity.

Some states do not allow the exclusion or limitation of incidental or consequential damages, so the above limitation may not apply.

B.2 How to Contact Customer Support

Customers in the U.S., Canada, Puerto Rico, and the Virgin Islands

For questions that are specific to the purchase, download and installation of EE•*Pro*, or questions regarding the operation of your TI calculator, contact Texas Instruments Customer Support:

phone: **1-800-TI-CARES (1-800-842-2737)**

e-mail: **ti-cares@ti.com**

For questions specific to the use and features of EE•*Pro,* contact da Vinci Technologies Group, Inc.

phone: **1-541-757-8416 Ext. 109, 9 AM-3 PM, P.S.T. (Pacific Standard Time), Monday thru Friday (except holidays).**

email: **support@dvtg.com**

Customers outside the U.S., Canada, Puerto Rico, and the Virgin Islands

For questions that are specific to the purchase, download and installation of EE•*Pro*, or questions regarding the operation of your TI calculator, contact Texas Instruments Customer Support:

e-mail: **ti-cares@ti.com**

Internet: **www.ti.com**

For questions specific to the use and features of EE•*Pro,* contact da Vinci Technologies Group, Inc.

e-mail: **support@dvtg.com**

Internet: **www.dvtg.com**

Appendix C Bibliography

In developing EE•*Pro* a number of resources were used. The primary sources we used are listed below. In addition, a large list of publications, too many to list here, were used as additional references.

1. Campsey, B. J., and Eugene F. Brigham, *Introduction to Financial Management*, Dryden Press, 1985, pp. 392-400
2. Van Horne, James C., *Financial management and Policy*, 8th Edition, Prentice-Hall, 1989, pp. 126-132
3. Edminister, Joseph A., *Electric Circuits, 2nd Edition, Schaum's Outline Series in Engineering*, McGraw-Hill Book Company, 1983
4. Nilsson, James W., Electric Circuits, 2nd Edition, Addison-Wesley Publishing Company, Reading MA 1987
5. Plonsey, Robert and Collins, Robert E., *Principles and Applications of Electromagnetic Fields*, McGraw-Hill Book Company, Inc. 1961.
6. Ryder, John D., *Electronic Fundamentals and Applications, 5th Edition*, Prentice-Hall Inc., Englewood Cliffs, NJ, 1980
7. Smith, Ralph J., *Electronic Circuits and Devices, 2nd Edition*, John Wiley and Sons, New York, NY 1980
8. Boylestad, Robert L., *Introduction to Circuit Analysis, 3rd Edition*, Charles E Merrill Publishing Company, Columbus, OH 1977
9. Jordan, Edward C., *Reference Data for Radio Engineers: Radio Electronics, Computers and Communications, 7th Edition*, Howard and Sams, Indianapolis IN 1985.
10. Coughlin, Robert F and Driscoll, Frederick F.., *Operational Amplifiers and Linear Integrated Circuits*, Prentice-Hall, Englewood Cliffs, NJ 1991.
11. Johnson, David E., and Jayakumar, V., *Operational Amplifier Circuits - Design and Applications*, Prentice-Hall, Englewood Cliffs, 1982
12. Stout, David F., *Handbook of Operational Amplifier Design*, McGraw-Hill Book Company, New York, 1976
13. Ghausi, Mohammed S., *Electronic Devices and Circuits: Discrete and Integrated*, Holt, Rienhard and Winston, New York, NY 1985
14. Slemon G. R., and Straughen, A., *Electric Machines*, Addison-Wesley, Reading, MA 1980
15. Mano, M.M., *Digital Logic and Computer Design*, Prentice-Hall Inc., Englewood Cliffs, NJ 1979
16. Cohen and Taylor, *Rev. Modern Physics, Vol. 59, No. 4, October 1987*, pp. 1139-1145
17. Sze, Simon, *Physics of Semiconductors*, John Wiley and Son, New Jersey, 1981
18. Mueller, Richard S., and Kamins, Theodore I., *Device Electronics for Integrated Circuits*, 2nd Edition, John Wiley and Son, New jersey, 1986
19. Hodges, David A., Jackson, Horace A., *Analysis of Digital Integrated Circuits*, McGraw-Hill, New York, 1988

20. Elmasry, Mohamed I., Editor, *Digital MOS Integrated Circuits*, IEEE Press, New York, 1981
21. Kuo, Benjamin C., *Automatic Control Systems*, Prentice Hall, New jersey, 1991
22. Stevenson Jr., William D., *Elements of Power Systems Analysis*, McGraw-Hill International, New York, 1982
23. Wildi, Theodore, *Electrical Power Technology*, John Wiley and Son, New Jersey, 1981
24. Yarborough, Raymond B., *Electrical Engineering Reference Manual*, Professional Publications, Belmont, CA 1990
25. Schroeder, Dieter K., *Advanced MOS Devices*, Addison Wesley, Reading MA 1987
26. Neudeck, Gerold W., *The PN Junction Diode*, Addison Wesley, Reading MA 1983
27. Pierret, Robert F., *Semiconductor Fundamentals*, Addison Wesley, Reading MA 1983
28. Pierret, Robert F., *Field Effect Devices*, Addison Wesley, Reading MA 1983
29. Neudeck, Gerold W., *The Bipolar Junction Transistor*, Addison Wesley, Reading MA 1983
30. Irwin, David J., *Engineering Circuit Analysis*, McGraw-Hill, New York, 1987

Appendix D: TI-89 & TI-92 Plus- Keystroke and Display Differences

D.1 Display Property Differences between the TI-89 and TI-92 Plus

The complete display specifications for both the TI-89 and TI-92 Plus calculators are displayed below.

Table D-1   TI-89 and TI-92 Plus display specifications.

Property	TI-89	TI-92 Plus
Display size Pixel Aspect ratio	 160 x 100 1.60	 240 x 128 1.88
Full Screen	26 characters/line 10 lines	40 characters/line 13 Lines
Horizontal Split Screen	156 x 39 pixels 25 characters 4 lines	236 x 51 pixels 39 characters, 6 lines
Vertical Split Screen	77 x 80 pixels 12 characters 10 lines	117 x 104 pixels 19 characters, 13 lines
Vertical Split Screen (1/3rd)	Not supported	236 x 33 pixels 39 characters, 4 lines
Vertical Split screen (2/3rd)	Not supported	236 x 69 pixels 39 characters, 8 lines
Horizontal Split Screen (1/3rd)	Not supported	77 x 104 pixels 12 characters, 13 lines
Horizontal Split Screen (2/3rd)	Not supported	157 x 104 pixels 26 characters, 13 lines
Key legends	16 pixel rows	20 pixel row

D.2 Keyboard Differences Between TI-89 and TI-92 Plus

The keystrokes in the manual for EE•*Pro* are written for the TI-89. The equivalent keystrokes for the TI-92 Plus are listed in the following tables.

Table D-2 Keyboard Differences, Representation in Manual

Function	Specific Key	TI-89 Key strokes	TI-92 Plus key strokes	Representation in the manual
Function Keys	F1	[F1]	[F1]	[F1]
	F2	[F2]	[F2]	[F2]
	F3	[F3]	[F3]	[F3]
	F4	[F4]	[F4]	[F4]
	F5	[F5]	[F5]	[F5]
	F6	[2nd] [F1]	[F6]	[F6]
	F7	[2nd] [F2]	[F7]	[F7]
	F8	[2nd] [F3]	[F8]	[F8]
Trig Functions	Sin	[2nd] [Y]	[SIN]	[SIN]
	Cos	[2nd] [Z]	[COS]	[COS]
	Tan	[2nd] [T]	[TAN]	[TAN]
	Sin^{-1}	[♦] [Y]	[2nd] [SIN]	**[SIN^{-1}]**
	Cos^{-1}	[♦] [Z]	[2nd] [COS]	**[COS^{-1}]**
	Tan^{-1}	[♦] [T]	[2nd] [TAN]	**[TAN^{-1}]**
Alphabet keys	A	[alpha] [=]	[A]	**A**
	B	[alpha] [(]	[B]	**B**
	C	[alpha] [)]	[C]	**C**
	D	[alpha] [,]		**D**
	E	[alpha] [÷]		**E**
	F	[alpha] [|]	[F]	**F**
	G	[alpha] [7]		**G**
	H	[alpha] [8]		**H**
	I	[alpha] [9]		**I**
	J	[alpha] [×]		**J**
	K	[alpha] [EE]		**K**
	L	[alpha] [4]		**L**
	M	[alpha] [5]		**M**
	N	[alpha] [6]	[N]	**N**
	O	[alpha] [−]	[O]	**O**
	P	[alpha] [STO▸]		**P**
	Q	[alpha] [1]		**Q**
	R	[alpha] [2]		**R**
	S	[alpha] [3]	[S]	**S**
	T	[T]		**T**
	U	[alpha] [+]		**U**

Function	Specific Key	TI-89 Key strokes	TI-92 Plus key strokes	Representation in the manual
	V	[alpha] [0]	[V]	**V**
	W	[alpha] [.]		**W**
	X	[X]	[X]	**X**
	Y	[Y]		**Y**
	Z	[Z]		**Z**
	Space	[alpha] [(-)]		[␣]
Log, EXP	LN	[2nd] [X]	[LN]	[LN]
	e^x	[◆] [X]	[2nd] [LN]	[e^x]
Special Characters	π	[2nd] [^]	[2nd] [^]	[π]
	θ	[◆] [^]	[θ]	[θ]
	Negation	[(-)]	[(-)]	[(-)]
	i	[2nd] [CATALOG]	[2nd] I	[*i*]
	∞	[◆] [CATALOG]	[2nd] J	[∞]
Graphing Functions	Y=	[◆] [F1]	[◆] W	[Y=]
	Window	[◆] [F2]	[◆] E	[WINDOW]
	Graph	[◆] [F3]	[◆] R	[GRAPH]
Editing Functions	Cut	[◆] [2nd]		[CUT]
	Copy	[◆] [↑]		[COPY]
	Paste	[◆] [ESC]		[PASTE]
	Delete	[◆] [←]	[◆] [←]	[DEL]
	Quit	[2nd] [ESC]		[QUIT]
	Insert	[2nd] [←]	[2nd] [←]	[INS]
	Recall	[2nd] [STO▸]	[2nd] [STO▸]	[RCL]
	Store	[STO▸]	[STO▸]	[STO▸]
	Backspace	[←]	[←]	[←]
Parenthesis, Brackets	(	[(]	[(]	[(]
	)	[)]	[)]	[)]
	{	[2nd] [(]	[2nd] [(]	[{]
	}	[2nd] [)]	[2nd] [)]	[}]
	[	[2nd] [,]	[2nd] [,]	[[]
	]	[2nd] [÷]	[2nd] [÷]	[]]
Math Operations	Addition	[+]	[+]	[+]
	Subtraction	[−]	[−]	[−]
	Multiplication	[×]	[×]	[×]
	Division	[÷]	[÷]	[÷]

	Raise to power	[^]	[^]	[^]
	Enter Exponent for power of 10	[EE]	[2nd] [1]	[EE]
	Equal	[=]	[=]	[=]
	Integrate	[2nd] [7]	[2nd] [7]	[∫]
	Differentiate	[2nd] [8]	[2nd] [8]	[*d*]

Function	**Specific Key**	**TI-89 Key strokes**	**TI-92 Plus key strokes**	**Representation in the manual**
Math Operations cont.	Less than	[2nd] [0]	[2nd] [0]	[<]
	Greater than	[2nd] [.]	[2nd] [.]	[>]
	Absolute value	[|]	[2nd] K	[|]
	Angle	[2nd] [EE]		[∠]
	Square root	[2nd] [×]	[2nd] [×]	[√]
	Approximate	[◆] [ENTER]	[◆] [ENTER]	[≈]
Tables	TblSet	[◆] [F4]	[◆] T	[TblSet]
	Table	[◆] [F5]	[◆] Y	[TABLE]
Modifier Keys	2nd	[2nd]	[2nd]	[2nd]
	Diamond	[◆]	[◆]	[◆]
	Shift	↑	[↑]	↑
	Alphabet	[alpha]		[alpha]
	Alphabet lock	[2nd] [alpha]		[a-lock]
Special Areas	Math	[2nd] [5]	[2nd] [5]	[MATH]
	Mem	[2nd] [6]	[2nd] [6]	[MEM]
	Var-Link	[2nd] [−]	[2nd] [−]	[VAR-LINK]
	Units	[2nd] [3]		[UNITS]
	Char	[2nd] [+]	[2nd] [+]	[CHAR]
	Ans	[2nd] [(-)]	[2nd] [(-)]	[ANS]
	Entry	[2nd] [ENTER]	[2nd] [ENTER]	[ENTRY]
Special Characters	Single Quote	[2nd] [=]		[′]
	Double Quote	[2nd] [1]	[2nd] L	["]
	Back slash	[2nd] [2]	[2nd] [=]	[\\]
	Underscore	[◆] [MODE]		[_]
	Colon	[2nd] [4]	[2nd] [θ]	[:]
	Semicolon	[2nd] [9]	[2nd] M	[;]
Number keys	One	[1]	[1]	**1**
	Two	[2]	[2]	**2**
	Three	[3]	[3]	**3**
	Four	[4]	[4]	**4**
	Five	[5]	[5]	**5**
	Six	[6]	[6]	**6**
	Seven	[7]	[7]	**7**
	Eight	[8]	[8]	**8**

Function	Specific Key	TI-89 Key strokes	TI-92 Plus key strokes	Representation in the manual
	Nine	[9]	[9]	**9**
	Zero	[0]	[0]	**0**
	Comma	[,]	[,]	**,**
	Decimal point	[.]	[.]	**.**
Main Functions	Home		[◆] Q	[HOME]
Main Functions cont.	Mode		[MODE]	[MODE]
	Catalog		[2nd] [2]	[CATALOG]
	Clear		[CLEAR]	[CLEAR]
	Custom		[2nd] [3]	[CUSTOM]
	Enter		[ENTER]	[ENTER]
	ON	[ON]	[ON]	[ON]
	OFF	[2nd] [ON]	[2nd] [ON]	[OFF]
	ESCAPE	[ESC]	[ESC]	[ESC]
	Application	[APPS]	[APPS]	[APPS]
Cursor Movement	Top	↑	↑	↑
	Right	→	→	→
	Left	←	←	←
	Bottom	↓	↓	↓

Appendix E Error Messages

- General Error Messages
- Analysis Error Messages
- Equations Error Messages
- Reference Error Messages

E.1 General Error Messages

1. **NOTE:** Make sure the settings in the [MODE] screen **do not** have the following configuration.

   Angle: DEGREE
   Complex Format: POLAR

   EE•*Pro* works best in the default mode settings of your calculator (ie. **Complex Format: REAL**, or **Angle: RADIAN**). If one of a set of error messages appears which includes **"An error has occurred while converting....", Data Error"**, **"Domain Error"**, and/or **"Internal Error"**, check to see if the above settings in the [MODE] screen exists. If it does, change the or reset your calculator to the default mode settings ([2nd] [MEM] [F1] [3] [ENTER]).

2. "**Syntax Error**" -- occurs if the entered information does not meet the syntax requirements of the expected entry. Check to make sure extra parenthesis are removed and the entered value meets the legal rules for number entry.

3. "**Insufficient Table Space**" or "**Insufficient Memory**" can occur when the system is low on available memory resources. Consult your TI-89 manual on methods of viewing memory status and procedures for deleting variables and folders to make more memory available.

4. The message "**Unable to save EE•Pro data**" will be displayed if EE•*Pro* is unable to save information of its last location in the program before exiting due to low memory availability. Consult your TI-89 manual under the index heading: *Memory-manage*.

5. "**The variable prodata1 was not created by EE•Pro...**" EE•*Pro* uses a variable called "prodata1" to recall its last location in the program when it is re-accessed. If this variable list is changed to a format which is non-recognizable to EE•*Pro*, it displays this message before overwriting.

6. "**Data length exceeds buffer size. The variable name will be displayed instead. The variable's value may be viewed with VAR-LINK using [F6] or recalled to the author line of the HOME screen."**

7. "**An error has occurred while converting this variable's data for display**. (The name of the variable is in the title of this dialog box.) **There may be something stored in the variable that EE•Pro can't make sense of. You may be able to correct the problem by deleting the variable**."

8. **“storage error...”** This message is set to occur if the user attempts to enter a value into a variable which is locked or archived, or a memory error has occured. Check the current status of the variable by pressing [VAR-LINK] and scrolling to the variable name, or check the memory parameters by pressing [MEM].

9. **“Invalid variable reference. Conflict with system variable or reserved name.”** This can occur if a variable name is entered which is reserved by the TI operating system. A list of reserved variable names is included in Appendix F.

E.2 Analysis Error Messages

AC Circuits Error Messages

1. **“No impedances/admittances defined”** This message is displayed if an entry for impedance **ZZ**_or **YY**_admittance is not a real, complex number or a defined variable in the **Voltage Divider** and **Current Divider** sections of **AC Circuits**.

Ladder Network Error Messages

1. When displaying a list of ladder network elements, an element may be named **"Unknown Element"** if it contains erroneous element-type information. This may occur if the variable "ladnet", which contains information of the components and arrangement of the ladder network, has been altered or corrupted. View "ladnet" in [VAR-LINK], and delete it if necessary. If deleted, the user will need to re-enter the ladder network information.
2. A dialog displaying **"LadNet invalid. Delete and try again."** may occur if a ladder network contains one or more elements with erroneous data. See above.
3. A dialog displaying **"No ladder elements exist."** will occur if an attempt is made to solve a ladder network that contains no defined elements. Add elements to the network by pressing [F7].
4. **“Invalid variable reference. Conflict with system variable or reserved name.”** This error is displayed if a variable name is entered as an input which is identical to a variable name used by EE•*Pro*. This message is also displayed if an entered variable name is a reserved system variable. A complete list of variables reserved by the TI operating system is listed in Appendix F.

Filter Design Error Messages

5. A dialog displaying "**Invalid freq. ratios.**" will occur if an attempt is made to design a passive filter using frequency data that does not apply to the particular filter topology. Check your entered values, you may need to try a different filter design.

Gain and Frequency: Transfer Function/Bode Diagrams

6. The computed transfer function H(s) may contain **“[Entry error]”** rather than an actual transfer function. This will occur when the number of zero (or numerator) terms greater than or equal to the number of pole (or denominator) terms.
7. An empty plot or the following dialogue may occur if an attempt is made to graph the transfer function before one has been defined: **"Undefined variable. Usually this error is caused by graphing the Bode diagram before the transfer function Hs has been defined. F2:Analysis 5:Gain and Frequency/1:Transfer Function calculates Hs."**

Computer Engineering:

7. An **"Invalid number format”** message will be displayed if an entered number does not follow the legal rules of the number base, or if a decimal term is entered. The format of numbers in *the Computer Engineering* section of EE•*Pro* is (p)nnnn…, where p is the letter prefix **b**, **o**, **d**, or **h** indicating binary, octal, decimal, and hexadecimal, number systems and n represents the legal digits

for the number base. If a number does not begin with a letter prefix in parenthesis, then it is assumed to be in the number base set in the [F4]/**Mode** dialog.

8. **"Entry truncated"** will appear if an entered value exceeds the binary word size allocated in the [F4]/**Mode** dialog. For example, the decimal number 100 is expressed as a 7 bit binary number:1100100. If a **word size** of 6 bits is designated in the [F4]/**Mode** dialog, the latter six digits of the number (100100) will be entered into the available word space.

Computer Engineering : Binary Arithmetic

9. The message **"Undefined Result"** will be displayed if an attempt is made to divide by zero.

Computer Engineering: Karnaugh Map

10. **"Two few unique letters in Vars."** This occurs when **n**, the number of unique, single-letter variables in **Vars** does not meet the criteria that 2^n must be greater than the largest number appearing in the **Minterms** or **Don't Care** series. Thus if the largest number is 15, there must be no less than four unique, single-letter variables since $2^4>15$.

Capital Budgeting

11. When changing the name of a project, the error **"Duplicate project variable name."** will occur if the entered name is already in use by an existing project.
12. The **"Too few cash flows"** message will be displayed if an attempt is made to solve a project which contains too few or no cash flow entries.
13. The message **"Data Error. Reinitializing project."** will occur if the project data has been altered or is inconsistent with current state. EE•*Pro* will restart.

E.3 Equation Messages

If a value is entered that is inconsistent with the expected data type, an error dialog will appear which lists the entry name, the description, and the expected data type(s), and the expected units.

If an error occurs during a computation that involves temperature, **"temp conversion err"** or **"deg/watt conversion err"** will be displayed.

When solving equation sets, several messages can be displayed. These messages include:

- **"One or more equations has no unknowns....."** This message occurs if one or more of the selected equations in a solution set has all of its variables defined by the user. This can be remedied by pressing [ESC], deselecting the equation(s) where all of the variables are defined and resolving the solution set by pressing [F2] twice. To determine which equation has all of its variables defined, press [ESC] to view the equations, select an equation in question by highlighting the equation and pressing [ENTER], and pressing [F2] to view the list of variables. A '▪' next to a variable indicates a value has been specified for that variable by the user. If all of the variables in an equation are marked with a '▪', no unknown variables exist for that equation. This equation should not be included in the solution set. Press [ESC] to view the list of equations. Select the equations to be solved, *excluding the equation with no unknowns*, and press [F2] twice to resolve the set of equations.

- **"Unable to find a solution in the time allowed. Examine variables eeinput and eeprob to see the exact statement of the problem. EE\xB7Pro sets Exact/Approx mode to AUTO during solve."**
- **"No equations have been selected. Please select either a single equation to solve by itself, or several equations to solve simultaneously."**
- **"Too many unknowns to finish solving"-**generally occurs if the number of equations is less than the number of unknowns

- **"It may take a long time to find a complete solution, if one can be found at all. You may abort the calculation at any time by pressing the ON key."** -this occurs if there are many unknowns or multiple solutions.
- **"No input values provided...."** occurs if none of the variables have values designated when solving an equation set.

- **"The nsolve command will be used. The existing value for the unknown, if any, will be used as an initial guess."** The *nsolve* function is used when a single unknown exists in the equation and the unknown variable is an input in a user defined function (an example is the error function *erf* in Semiconductor Basics of *Solid State* or the *eegalv* in Wheatstone Bridge in *Meters and Bridges*). The nsolve function will not generate multiple solutions and the solution which nsolve converges upon may not be unique. It may be possible to find a solution starting from a different initial guess. To specify an initial guess, enter a value for the unknown and then use F5:Opts/7:Want to designate it as the variable to solve for. More information on the differences between the *solve*, *nsolve* and *csolve* functions is listed in the TI-89 manual.
- **"One complete useable solution found."** All of the unknown variables were able to be solved in the selected equations.
- **"One partial useable solution found."** Only some of the variables in the selected equations were able to be solved.
- **"Multiple complete useable solns found."** One or more variables in the selected equations have two possible values
- **"Multiple partial useable solns found."** One or more variables in the selected equations have two possible values, however not all of the unknown variables were able to be solved.

The following messages can appear when attempting to graph equation set functions:

- **"Independent and dependent variables are the same."**
- **"Unable to define Pro(x)"-**cannot resolve the dependent and independent variables.
- **"Undefined variable"** too many dependent variables or dependent variable unable to be defined in terms of the independent variable.
- **"Error while graphing."**

E.4 Reference Error Messages

For more information, see Chapter 33, "Reference: Navigation Guide" and your TI 89 User's Guide.

Reference : Standard Component Values

- The message "Out of range" will occur if an entered component value is not in the range of $10^{\pm 23}$.

Appendix F: System Variables and reserved names

The TI-89 and TI-92 Plus has a number of variable names that are reserved for the Operating System. The table below lists all the reserved names that are not allowed for use as variables or algebraic names.

Graph	y1(x)-y99(x)* xt(t)-xt99(t)* ui1-ui99* tc xfact xmax ymax Δx zsc1 ncontour tmin tplot Estep nmax	y1'(t)-y99'(t)* yt(1)-y99(t)* xc rc yfact xsc1 ysc1 Δy eye0 θmin tmax ncurves fldpic plotStrt	Yi1-yi99* z1(x,y)-z99(x,y) yc θc zfact xrid ygrid zmin eyeϕ θmax tstep difto1 fldres plotStep	r1(θ)-r99(θ)* u1(n)-u99(n)* zc nc xmin ymin xres zmax eyeφ θstep t0 dtime nmin sysMath
Graph Zoom	Zxmin Zymin Zxres Ztmin Ztmaxde Zmax zeyeφ zpltstep	Zxmax Zymax zθmin ztmax ztstepde zzsc1 znmin	Zxscl Zyscl zθmax ztstep ztplotde zeyeθ znmax	Zxgrid Zygrid zθstep zt0de zzmin zeyeϕ zpltstrt
Statistics	$\bar{x}$ Σx^2 Σy^2 medStat medyl minY regCoef Sx	$\bar{y}$ Σxy corr medx1 medy2 nStat regEq(x)* Sy	Σx Σy maxX medx2 medy3 q1 seedl R^2	σx σy maxY medx3 minX q3 seed2
Table	tblStart	Δtbl	tblInput	
Data/Matrix	C1-c99	SysData		
Miscellaneous	Main	Ok	Errornum	
Solver	Eqn*	Exp*		