TRLINE User’s Guide

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TRLINE Version 1H(e)
User’s Guide Version 1B(g)
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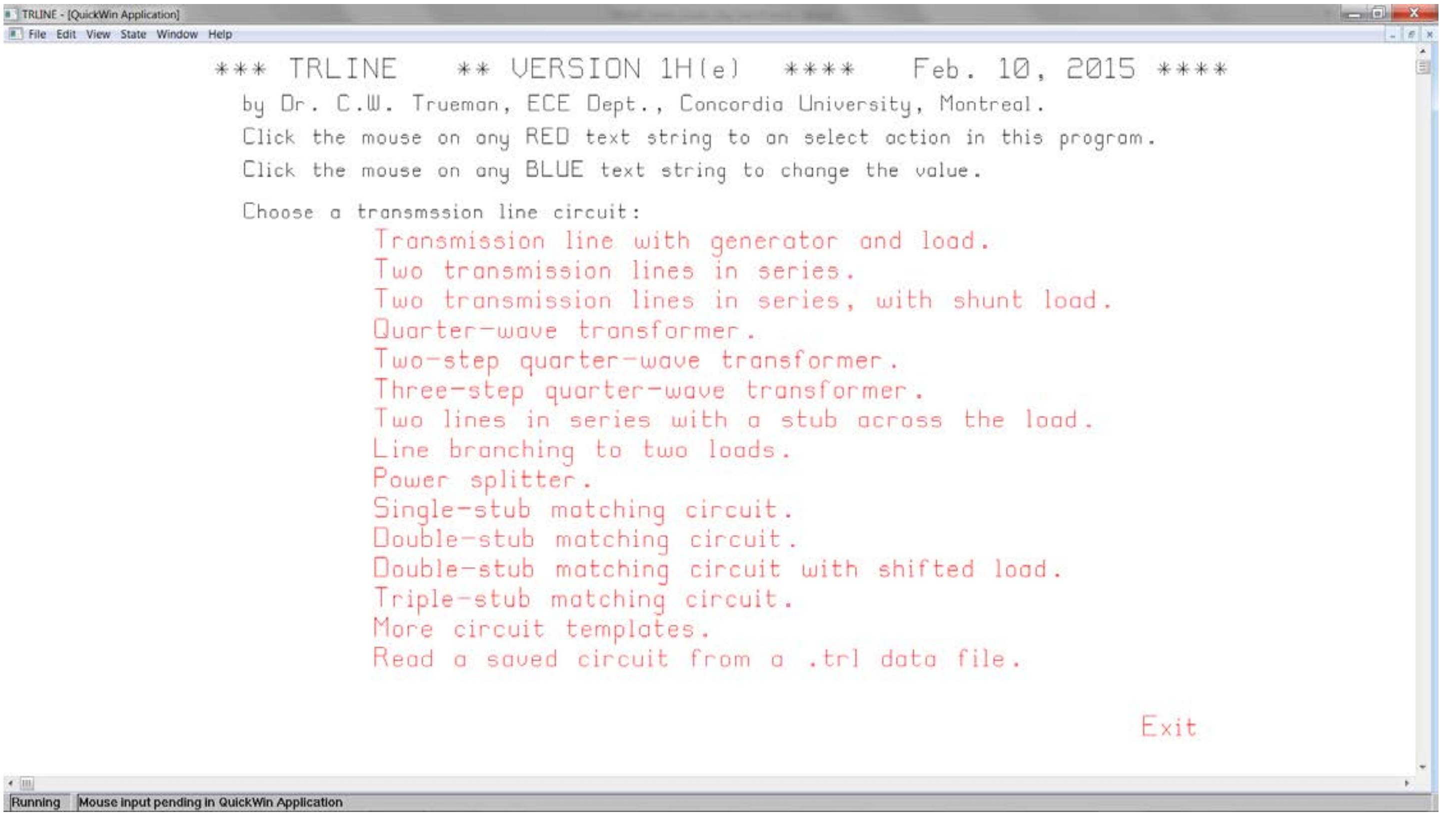
1. Introduction

Program TRLINE or “Transmission Line” solves transmission line circuits in the frequency domain. The program contains 15 circuit templates for circuits commonly solved in a “Fields and Waves” course and a course in passive microwave circuits: simple transmission line, transmission lines in series, quarter wave transformers, branching transmission lines, single, double and triple stub tuners, low pass filter, and band stop filter. TRLINE provides a “software laboratory” for testing pencil-and-paper solutions to homework problems in transmission line theory. The program emphasizes frequency response, which is difficult to evaluate with pencil-and-paper solutions. The program provides interactive design for single and double stub tuning circuits. TRLINE is useful for testing designs in a passive microwave engineering course.

This User’s Guide explains the features of the TRLINE program. It illustrates transmission line problems commonly encountered in the introductory “Fields and Waves” course and in the “Microwave Engineering” course. TRLINE was described in a paper published in the IEEE Transactions on Education [1].

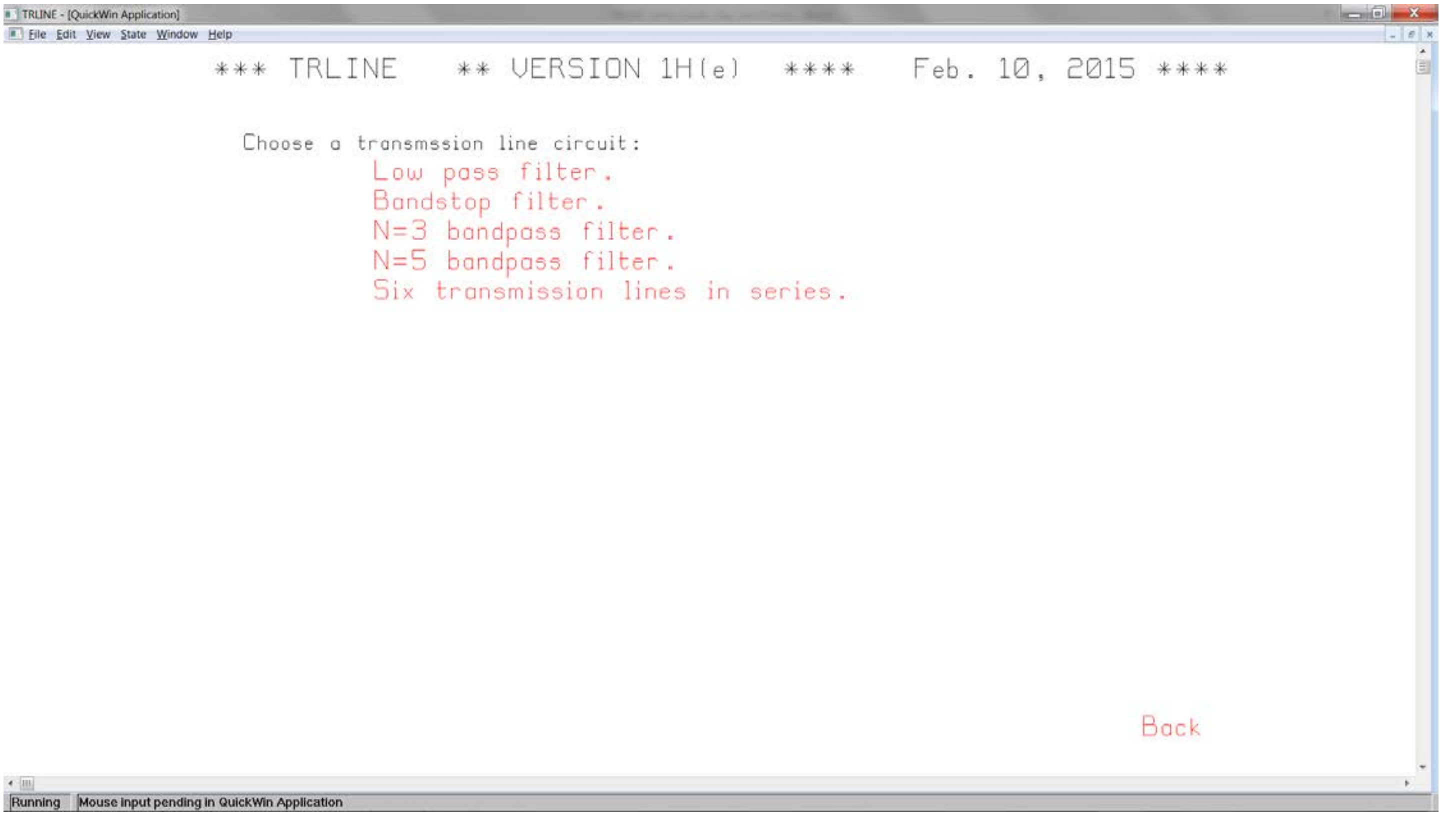


```
*** TRLINE    ** VERSION 1H(e)   ****    Feb. 10, 2015 ****
  by Dr. C.W. Trueman, ECE Dept., Concordia University, Montreal.
  Click the mouse on any RED text string to an select action in this program.
  Click the mouse on any BLUE text string to change the value.

  Choose a transmssion line circuit:
           Transmission line with generator and load.
           Two transmission lines in series.
           Two transmission lines in series, with shunt load.
           Quarter-wave transformer.
           Two-step quarter-wave transformer.
           Three-step quarter-wave transformer.
           Two lines in series with a stub across the load.
           Line branching to two loads.
           Power splitter.
           Single-stub matching circuit.
           Double-stub matching circuit.
           Double-stub matching circuit with shifted load.
           Triple-stub matching circuit.
           More circuit templates.
           Read a saved circuit from a .trl data file.

                                                         Exit
```

Fig. 2.1(a) TRLINE’s circuit template menu.



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*** TRLINE   ** VERSION 1H(e)   ****   Feb. 10, 2015 ****

        Choose a transmssion line circuit:
                Low pass filter.
                Bandstop filter.
                N=3 bandpass filter.
                N=5 bandpass filter.
                Six transmission lines in series.

                                                     Back
```

Fig. 2.1(b) The “more circuit templates” sub-menu.

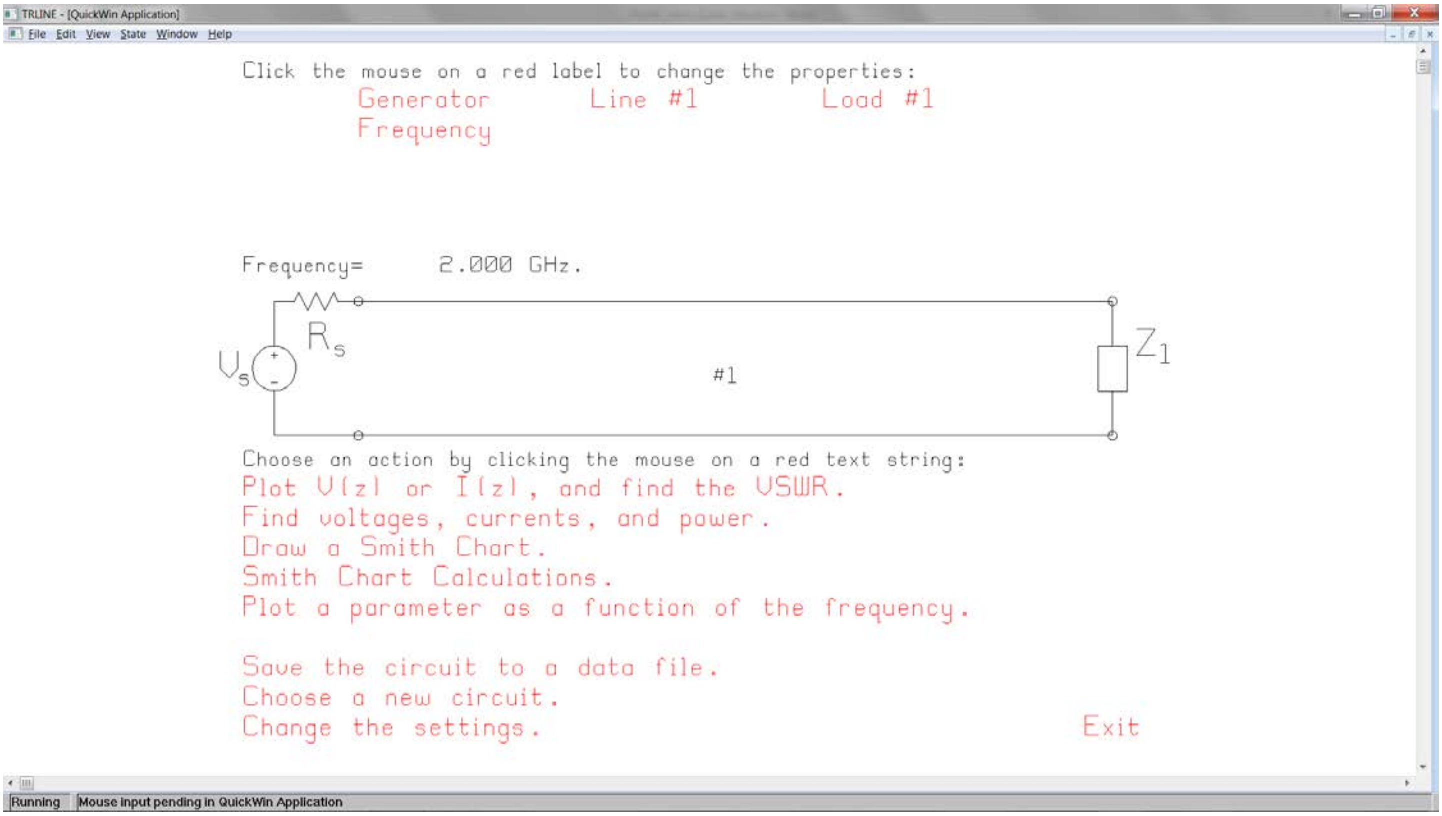
2. TRLINE Menus

TRLINE starts by showing the circuit template menu of Fig. 2.1(a). The menu reports the version number and date of the TRLINE “exe” file at the top of the screen. New versions that correct errors or add features are available from time to time.

It is often convenient to make a directory for your TRLINE project and to copy the “TRLINE.exe” file into the directory. To run TRLINE, open the directory as a window and double-click TRLINE.exe, or open a DOS window, change to the project directory, and type TRLINE.

The “circuit template” menu of Fig. 2.1(a) asks the user to choose a circuit for study from the list shown. In all the menus in TRLINE, menu choices are shown as red character strings and are called “buttons”. Click the mouse on any red text string in any menu in the program to get an “action”. In the circuit template menu, the names of the circuits are buttons and the user clicks the mouse on a circuit name to select that circuit. Also, a saved circuit can be recalled from the disc using the “Read a saved circuit” button. In the lower right-hand corner of the screen we see an “Exit” button. The exit button terminates execution of the TRLINE program.

There are more circuits in TRLINE than conveniently fit on one screen, so there is a “more circuit templates” button in the list. Click “more circuit templates” to get the sub-menu of Fig. 2.1(b). This offers five additional circuits. Section 5 of this manual describes the demonstration associated with each of the circuits.



Click the mouse on a red label to change the properties:

Generator Line #1 Load #1

Frequency

Frequency= 2.000 GHz.

Choose an action by clicking the mouse on a red text string:

Plot V(z) or I(z), and find the VSWR.

Find voltages, currents, and power.

Draw a Smith Chart.

Smith Chart Calculations.

Plot a parameter as a function of the frequency.

Save the circuit to a data file.

Choose a new circuit.

Change the settings. Exit

Fig. 2.2 The TRLINE main menu.

When a circuit has been chosen, the program goes to the “main menu” in Fig. 2.2, which gives access to a menu for each of the program’s functions. The main menu is organized with a schematic diagram for the circuit across the center of the menu, “properties buttons” at the top, and action items at the bottom. The “properties buttons” are used to tell the program about the properties of each part of the circuit. Click “frequency” to specify the operating frequency. Click “generator” to specify the voltage of the generator, and its internal resistance. Click “line #1” to specify the length, characteristic impedance, and wave speed for line #1. If the circuit has, say, five transmission lines, there will be five properties buttons, one for each transmission line. Click “Load #1” to specify the resistance and reactance of the load. The “properties buttons” appear on other menus, such as the transmission line menu and the Smith Chart menu.

The bottom of the main menu has buttons which give you access to the computations that the program can do for you. When you have set the lengths and characteristic impedances of the transmission lines, and the values of the loads, and so forth, you can save the values to a disk file by clicking “Save the circuit…”. The program asks you for a file name. The program uses the extension “trl” for its data files.

The TRLINE program has five principal functions. Clicking “Plot V(z)..” gets the transmission line menu. This is used to graph the amplitude and phase of the voltage or the current on the transmission lines. There are two kinds of graphs that the program creates. The first is a schematic of the transmission line circuit with V(z) or I(z) graphed above it. The second is a graph of the voltage amplitude on any one of the lines as a function of distance, including two “markers” which let you read back values from the graph. These are described further below.

The second function is “Find voltages, currents, and power”. This gets the “voltage and power menu”. This menu lets you ask for the voltage, current and power delivered by the generator, or for the voltage, current and power delivered to any load, or for the voltage, current and power flowing into and out of any transmission line.

The third function is obtained by clicking “Draw a Smith Chart” and is used to graph the load impedance and input impedance of any transmission line in the circuit. This button starts the “Smith Chart menu”, which can draw a Smith Chart for any transmission line in the circuit. The chart can be an impedance chart or an admittance chart. The Smith Chart display shows the Smith Chart, with the load impedance for that line being transformed back to an input impedance. The Smith Chart display reports the load and input impedance or admittance.

The fourth function is “Smith Chart Calculations”. The TRLINE program lets you design single and double stub matching interactively, as described below.

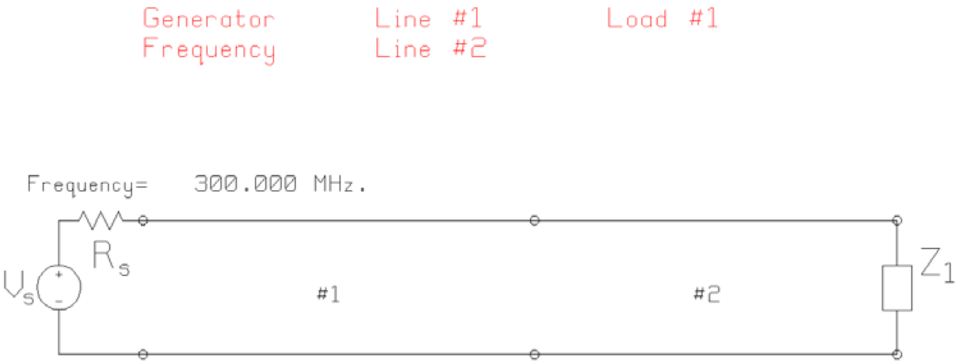
The fifth function of the program is obtained by clicking “Plot a parameter as a function of the frequency”. This menu lets you graph one of five parameters as a function of frequency. You can set the frequency range with a sub-menu. You can graph the input impedance as a function of frequency at any port, that is, looking into any transmission line in the circuit. You can graph the reflection coefficient or VSWR looking into any transmission line. You can plot the return loss. And you can graph the transmission loss between any two junctions in the circuit. These are usually chosen as the input terminals and the load terminals. The frequency-sweep graphs include two markers that can read back points from the graph. Also, there is a “snap” function which lets you snap the position of the markers to a desired level, say –20 dB return loss. Then the program reports the bandwidth between the markers.

There are three buttons at the bottom of the screen. “Save the circuit” lets you save all the parameter values to a “trl” file, so that you can recall the circuit later, with all the parameter values set correctly. “Choose a new circuit” takes you back to the circuit template menu. “Change the settings” lets you choose to work in MHz or GHz, with RMS values or amplitudes, with impedance or admittance, and whether to report complex numbers as magnitudes and angles, or as real part and imaginary part.

The following describes each of the program’s functions in more detail, with some examples.

Frequency= 2.000 GHz.

Fig. 2.3 (a) Simple transmission line



Frequency= 300.000 MHz.

Fig. 2.3 (b) Two transmission lines in series.

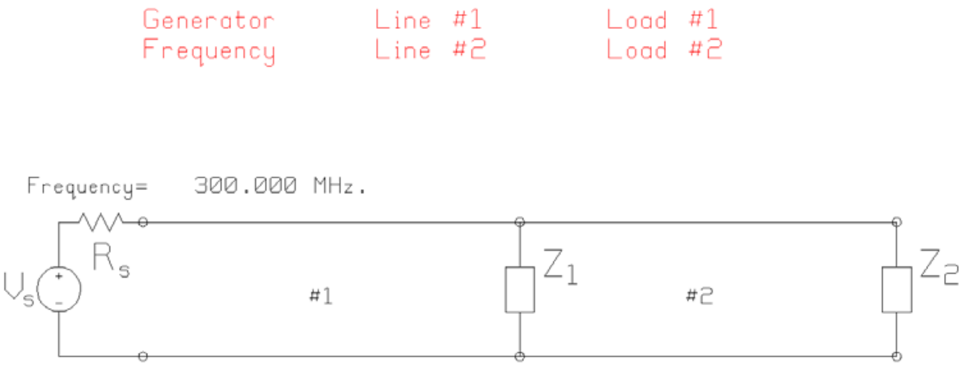


Fig. 2.3 (c) Two transmission lines in series, with shunt load.

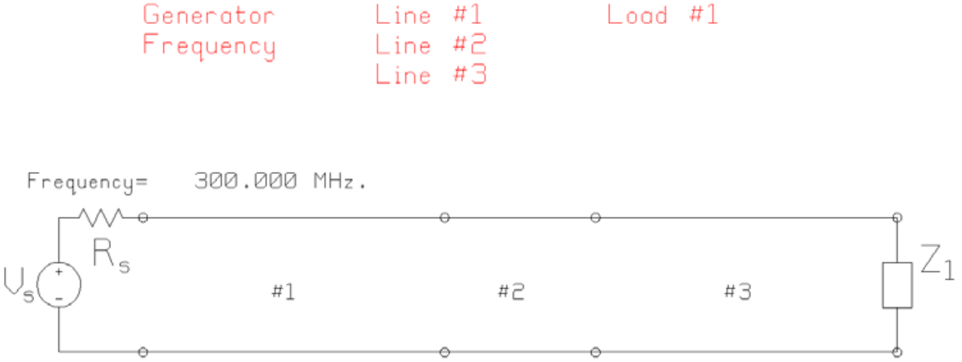


Fig. 2.3 (d) Quarter wave transformer.

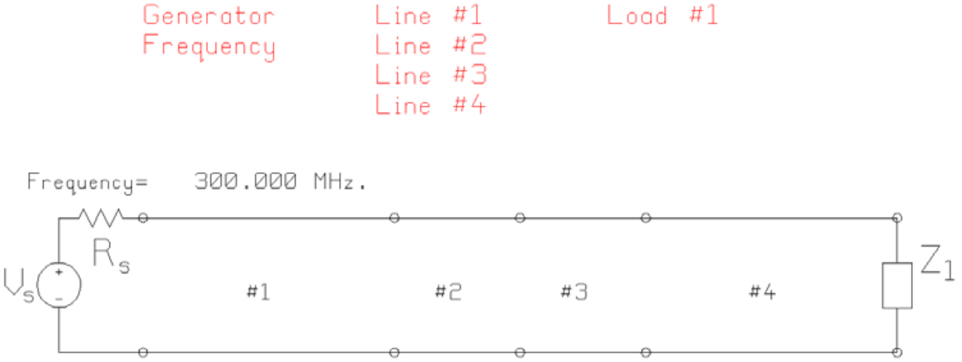


Fig. 2.3 (e) Two step quarter-wave transformer.

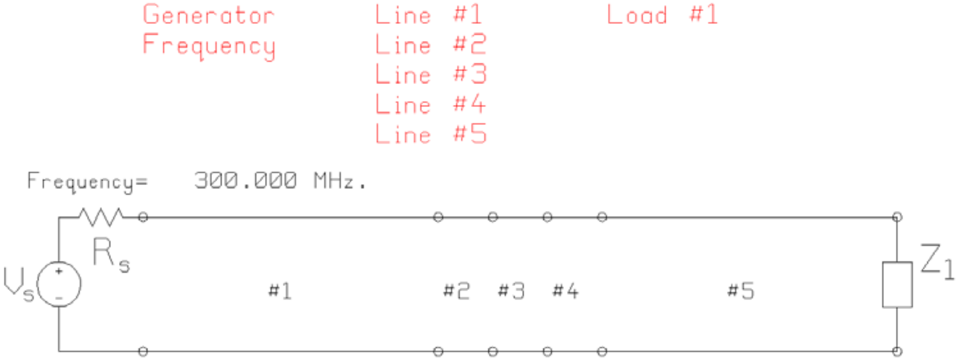


Fig. 2.3 (f) Three-step quarter wave transformer.

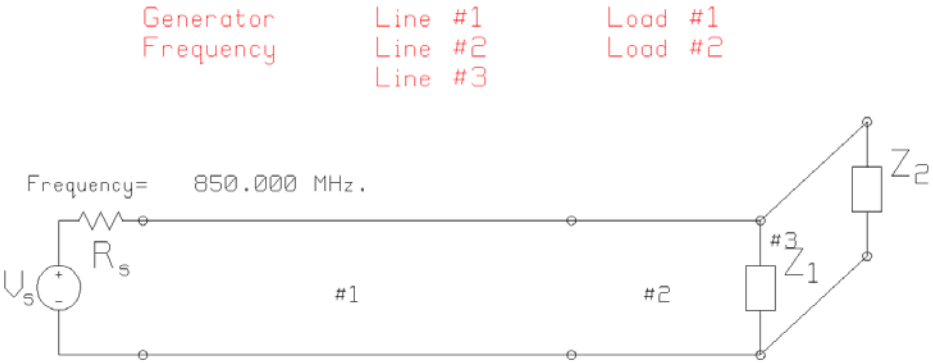


Fig. 2.3 (g) Two lines in series, with a stub at the load.

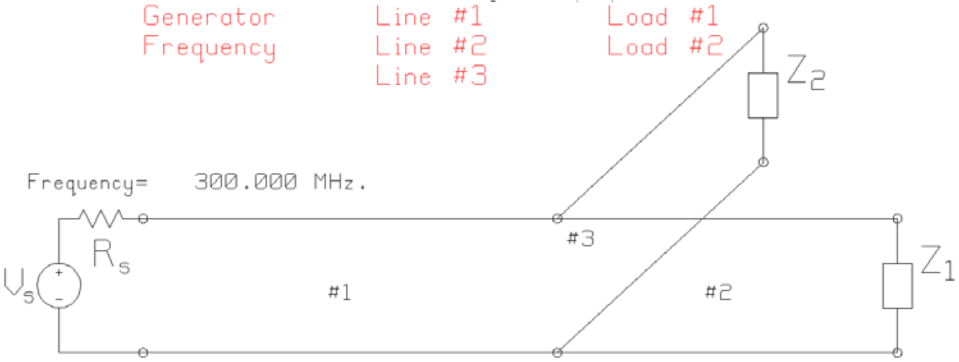


Fig. 2.3 (h) Line branching to two loads.

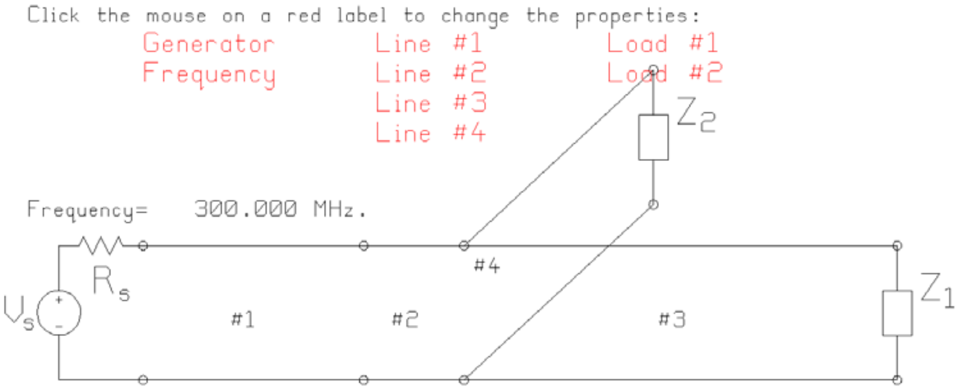


Fig. 2.3 (i) Power splitter.

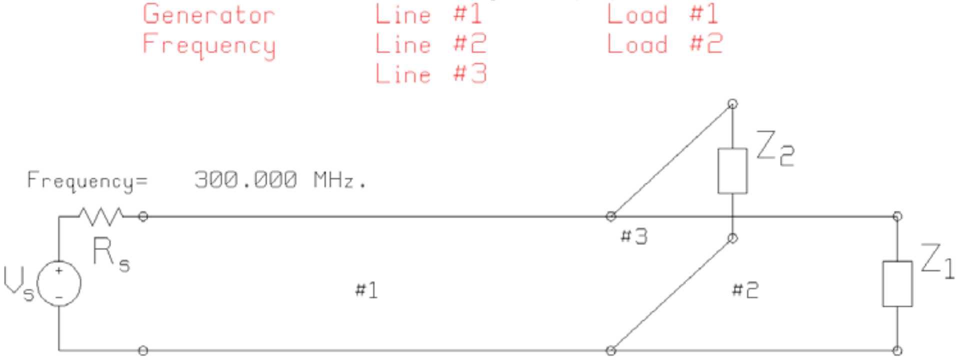


Fig. 2.3 (j) Single stub matching circuit.

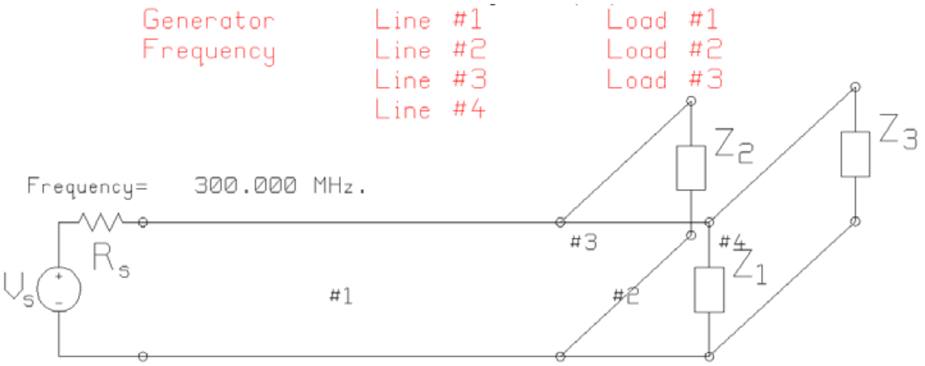


Fig. 2.3 (k) Double stub matching circuit.

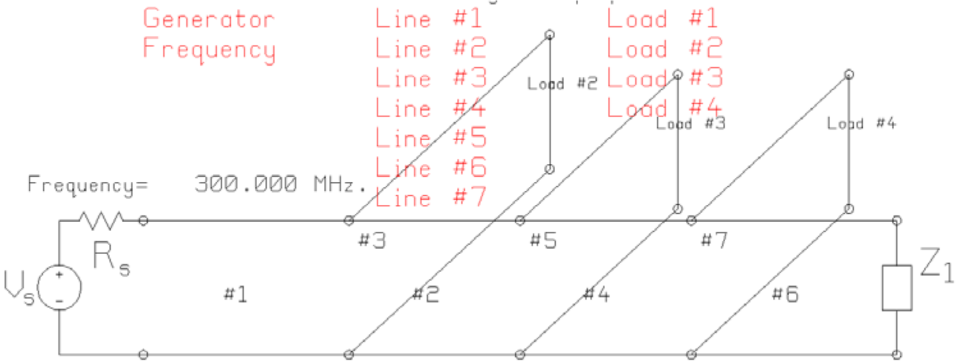


Fig. 2.3 (l) Triple stub matching circuit.

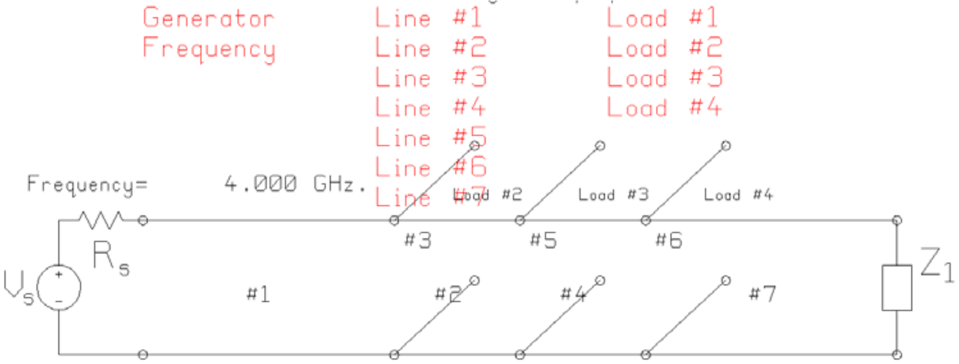


Fig. 2.3 (m) Low pass filter.

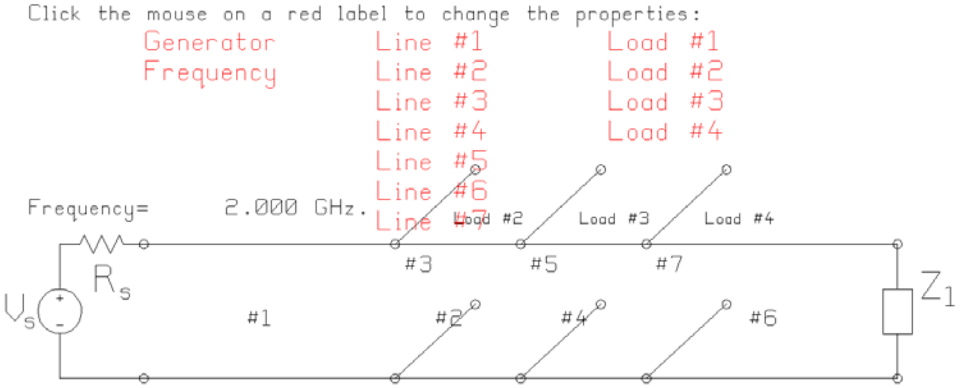
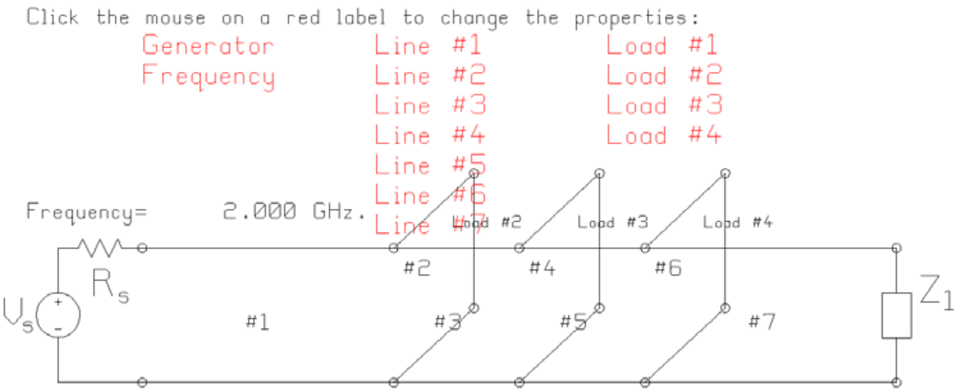
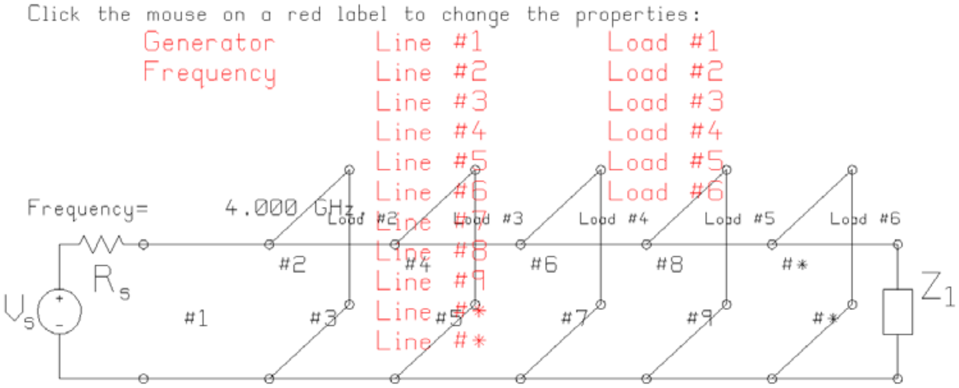

Click the mouse on a red label to change the properties:

Fig. 2.3 (n) Bandstop filter.



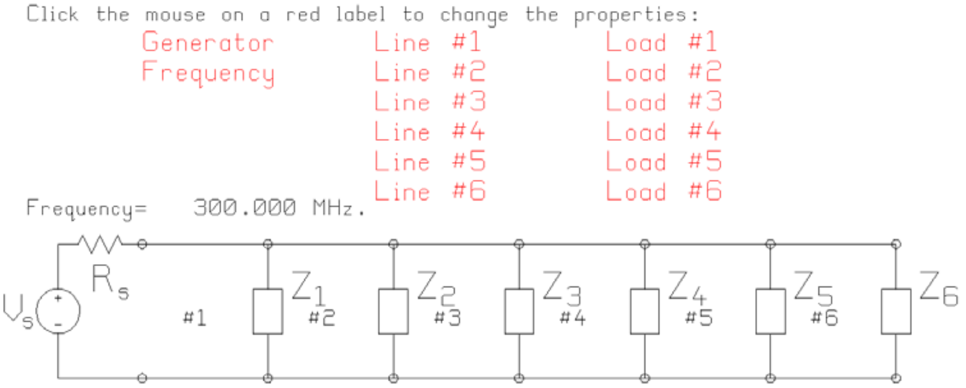
Click the mouse on a red label to change the properties:

Fig. 2.3 (o) N=3 Bandpass filter.



Click the mouse on a red label to change the properties:

Fig. 2.3 (p) N=5 Bandpass filter.



Click the mouse on a red label to change the properties:

Fig. 2.3 (1) Six transmission lines in series, with shunt loads.

Fig. 2.3 The circuit templates available in TRLINE.

2.1.Choosing a Circuit

The “circuit template” menu of Fig. 2.1 offers a variety of circuits that are useful in learning about transmission lines at the elementary and intermediate level. The simple circuit of Fig. 2.3(a) consists of a generator, one transmission line, and a load. It is used, as discussed below, to demonstrate travelling waves and standing waves, and explore mismatch. It is also used to demonstrate the operation of the Smith Chart. Two transmission lines in series, Fig. 2.3(b), is used to show transition from a line of say 50 ohms characteristic impedance to a line of a different characteristic impedance, say 25 ohms or 100 ohms. Fig. 2.3(c) puts a shunt load at the junction and provides an exercise in the use of the Smith Chart to find the input impedance. Also the length and characteristic impedance of the interconnecting line can be chosen to try to obtain a specified relationship of the voltage amplitude and phase across the two loads.

Fig. 2.3(d) provides a circuit template with three transmission lines in series, with the parameters chosen to demonstrate a quarter-wave transformer at 300 MHz. Figs. 2.3(e) and (f) provide templates for two-step and three-step quarter wave transformers for a microwave engineering course. The default values for the line lengths, characteristic impedances and the frequency achieve a good match in these circuits. This is convenient for classroom demonstration of the program, for the circuits can be invoked rapidly from the circuit template menu. The match can be demonstrated by graphing the amplitude of *V(z)* on each transmission line, and the frequency sweep feature used to demonstrate the bandwidth of each transformer.

Fig. 2.3(g) has two transmission lines in series, with a tuning stub across the load. The circuit can be used to introduce impedance matching for a complex-valued load. Use the stub to tune out the imaginary part of the load, and line #2 as a quarter-wave transformer to match the real part of the load.

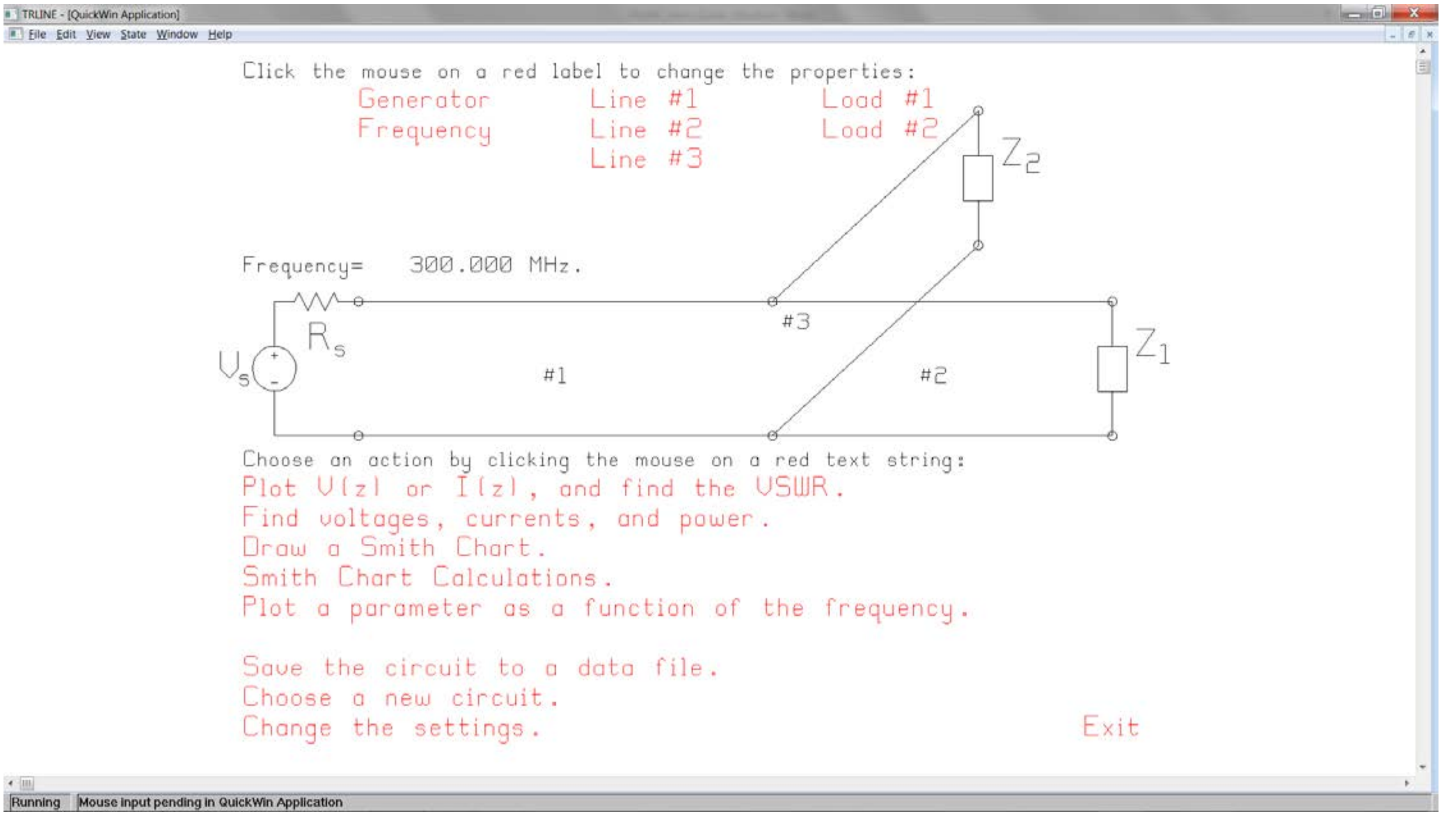
Fig. 2.3(h) is a problem commonly given as a homework exercise, consisting of a transmission line that branches to two loads of different, complex-valued characteristic impedance. The student must find the input impedance, then the power delivered to each load impedance. The problem of choosing the line lengths and characteristic impedances to better match the source can be considered.

Fig. 2.3(i) is the same circuit as (h), but is set up to be a power splitter. A transmission line branches to two lines of equal characteristic impedance, terminated with matched loads. A quarter-wave transformer is included to match the source to the branch. We can note in passing that the TRLINE program could solve this circuit with two- or three-step transformers, but the program does not provide a circuit template. The user could construct a “trl” data file to create such a circuit.

Fig. 2.3(j), (k) and (l) provide circuit templates for single, double, and triple stub matching. These circuits have default values that achieve a good match, again for classroom demonstration purposes.

Fig. 2.3(m) and (n) use open-circuited stubs to demonstrate a low-pass and a bandstop filter, respectively. These circuit templates are actually the same as the triple stub matching circuit, with the loads on the stubs set to high impedances rather than short circuits. The low-pass filter comes with default values that can be used in classroom demonstration to show the voltages on the lines and the transmission loss. Similarly, the bandstop filter is set with values useful for demonstrating the concept.

The following describes the features of the program that can be used to demonstrate the operation of these various circuits.



Click the mouse on a red label to change the properties:

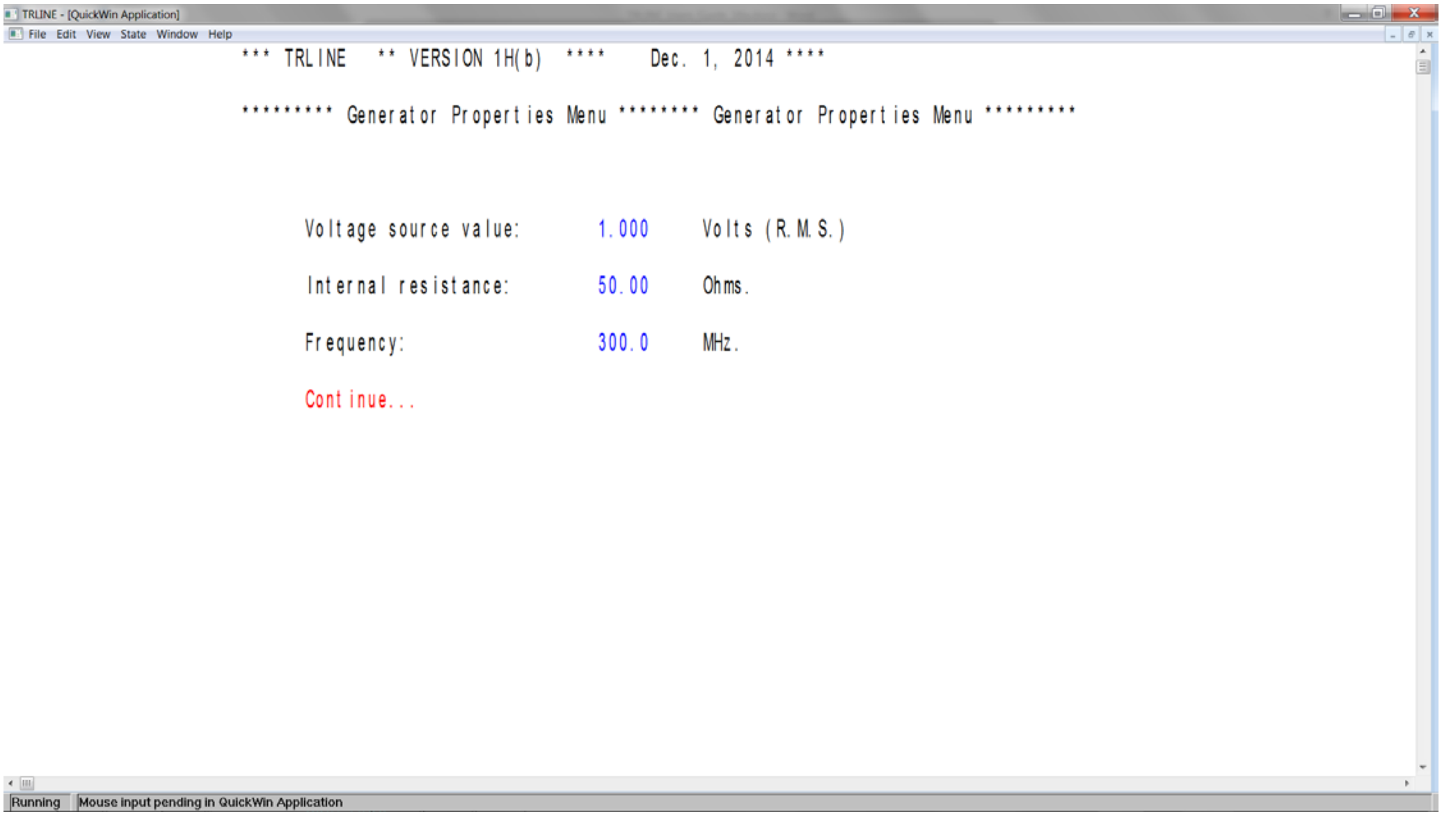
Frequency= 300.000 MHz.

Choose an action by clicking the mouse on a red text string:

Fig. 2.4 The main menu showing the “properties buttons” across the top of the screen.

2.2.Setting the Component Values: Properties Menus

Start the TRLINE program and choose a circuit, say the transmission line branching to two loads. This gets the main menu, shown in Fig. 2.4. To set the component values to correspond to those of the circuit we wish to solve, we use the “properties buttons” across the top of the screen. Recall that “buttons” in the program are red text strings, so you can click the mouse on any red text string to select a function in the program.



```
*** TRLINE   ** VERSION 1H(b)  ****    Dec. 1, 2014 ****

********* Generator Properties Menu ******* Generator Properties Menu *********


      Voltage source value:       1.000    Volts (R.M.S.)

      Internal resistance:        50.00    Ohms.

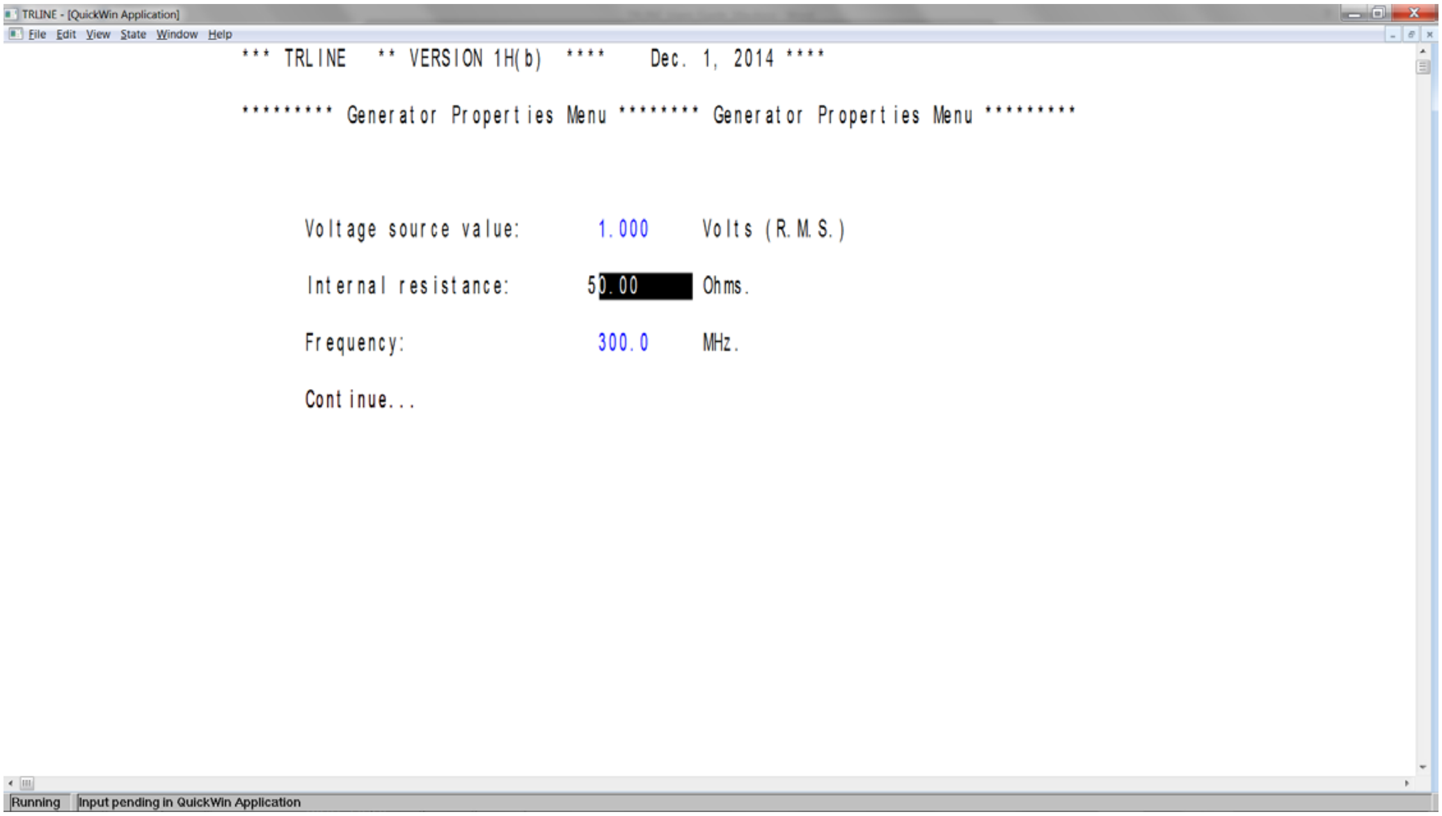
      Frequency:                  300.0    MHz.

      Continue...
```

```
Running    Mouse input pending in QuickWin Application
```

Fig. 2.5 The generator menu.

Click on “Generator” to get the generator menu of Fig. 2.5. This menu has fields to specify the R.M.S. value of the open-circuit voltage of the generator, and the generator’s internal resistance. Also, the frequency can be set. At the bottom of the list we have a red “Continue” button. Click “Continue” to return to the main menu.



```
*** TRLINE   ** VERSION 1H(b)  ****    Dec. 1, 2014 ****

********* Generator Properties Menu ******* Generator Properties Menu *********


      Voltage source value:       1.000    Volts (R.M.S.)

      Internal resistance:       50.00     Ohms.

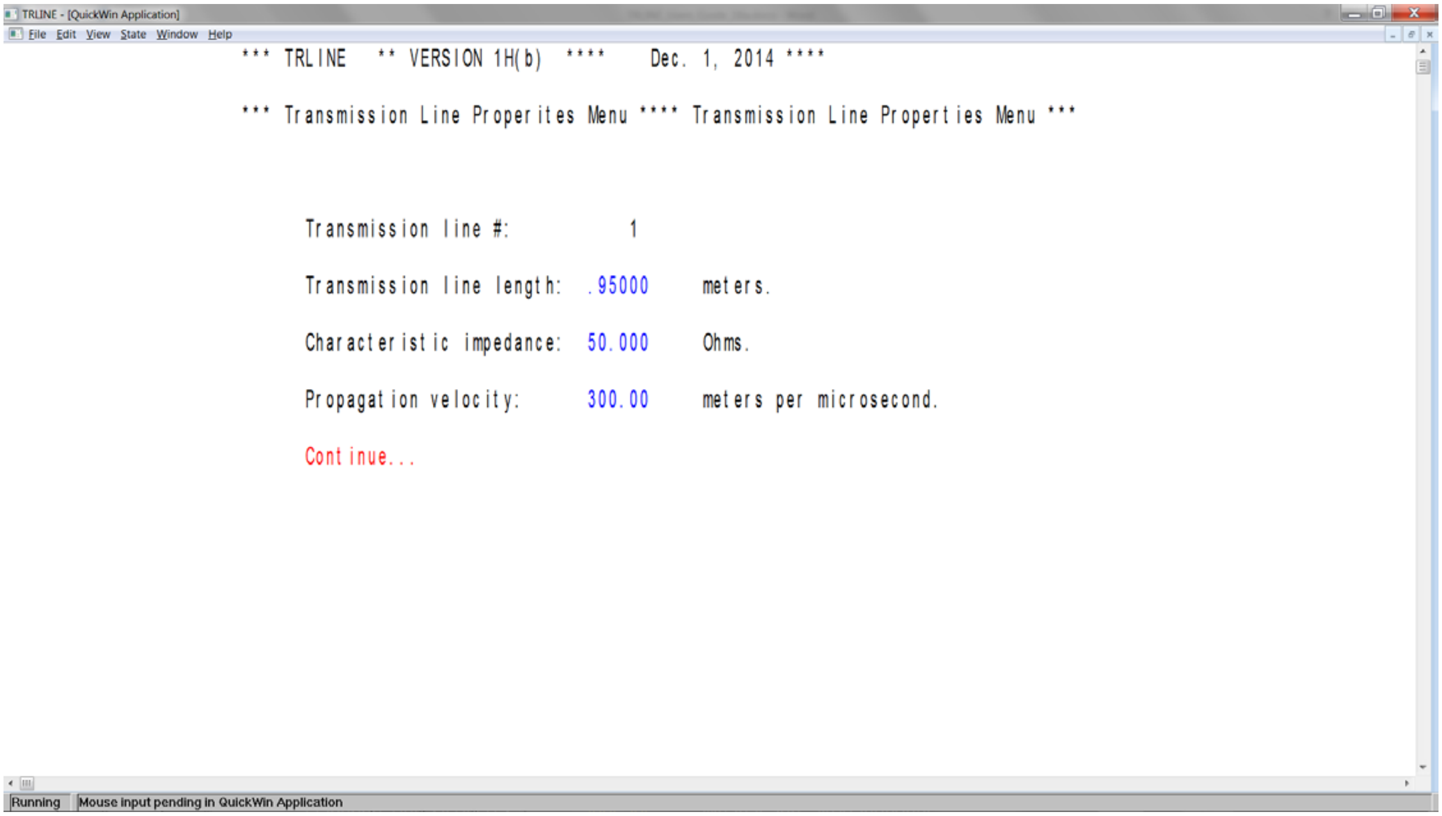
      Frequency:                  300.0    MHz.

      Continue...
```

```
Running    Input pending in QuickWin Application
```

Fig 2.6 Changing the value of a parameter in a field.

In TRLINE, any text string shown in blue is a “field” containing a value that the user can set. Click the mouse on the blue text string 50.00 in Fig. 2.5 to change the value of the source internal resistance, to obtain the screen shown in Fig. 2.6. The field changes to inverse video, and you can type the new value. Note that the “Continue” button is black, because it is not active when you are editing a field. Type the “Enter” key to finish and return to the menu of Fig. 2.5. The “Continue” button changes back to red. Also when you are editing a field you can use the “tab” key to change to the next field, or use the up or down arrow key to change fields. Again, type “Enter” to finish editing the numerical value fields.



```
*** TRLINE   ** VERSION 1H(b)  ****   Dec. 1, 2014 ****

*** Transmission Line Properites Menu **** Transmission Line Properties Menu ***


     Transmission line #:          1

     Transmission line length:  .95000    meters.

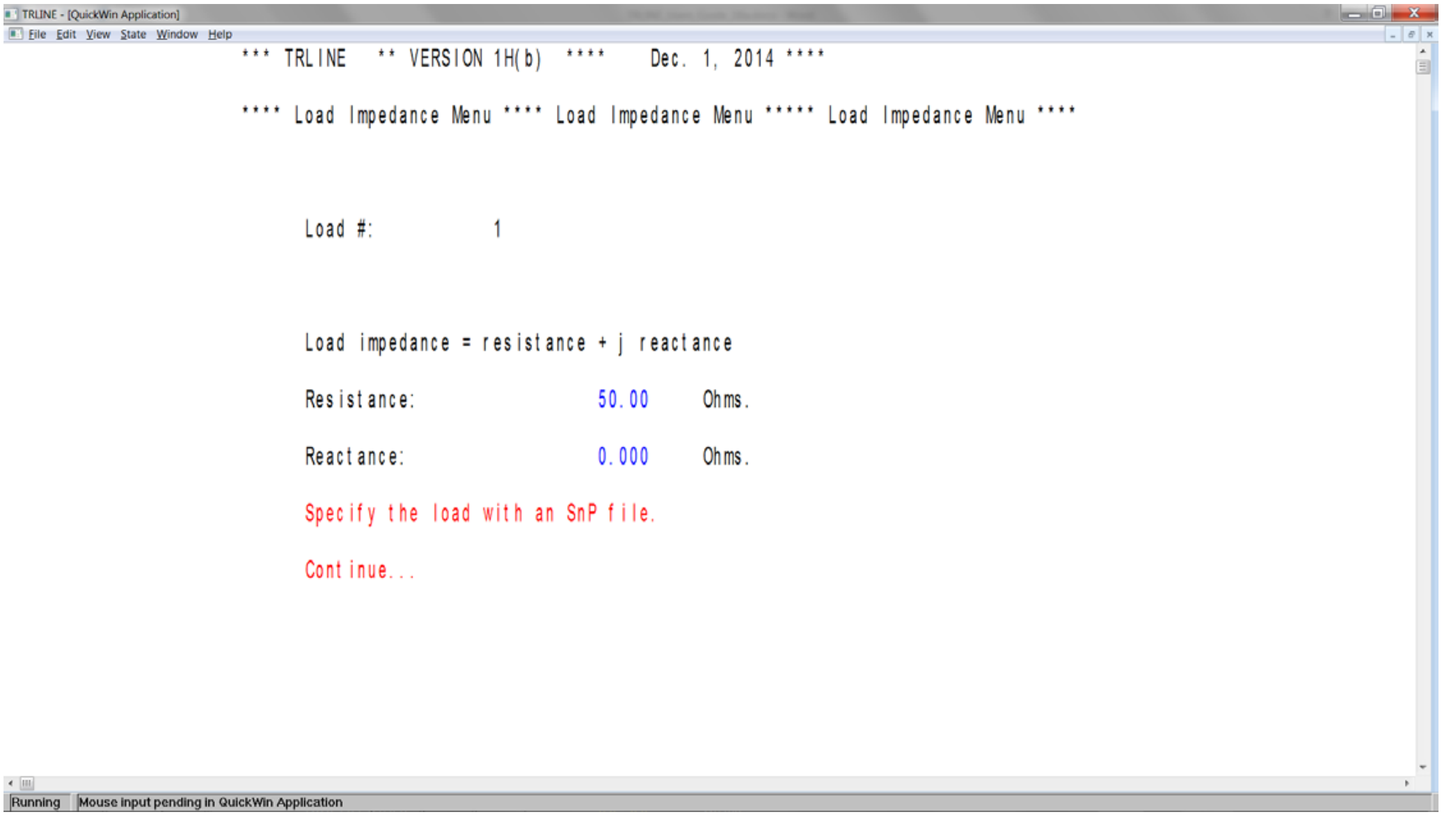
     Characteristic impedance:  50.000    Ohms.

     Propagation velocity:      300.00    meters per microsecond.

     Continue...
```

Fig. 2.7 The transmission line properties menu.

To set the properties of transmission line #1 in Fig. 2.4, click the mouse on “Line #1” at the top of the screen to get the transmission line properties menu of Fig. 2.7. This menu has fields for typing the characteristic impedance of the line, the length of the line and the phase velocity of waves on the line. Click the mouse on a blue “field” to change the value. Transmission lines in TRLINE are lossless, so there is no loss parameter. To return to the main menu, click “Continue”.



```
*** TRLINE   ** VERSION 1H(b)   ****    Dec. 1, 2014 ****

**** Load Impedance Menu **** Load Impedance Menu ***** Load Impedance Menu ****


     Load #:          1


     Load impedance = resistance + j reactance

     Resistance:                 50.00     Ohms.

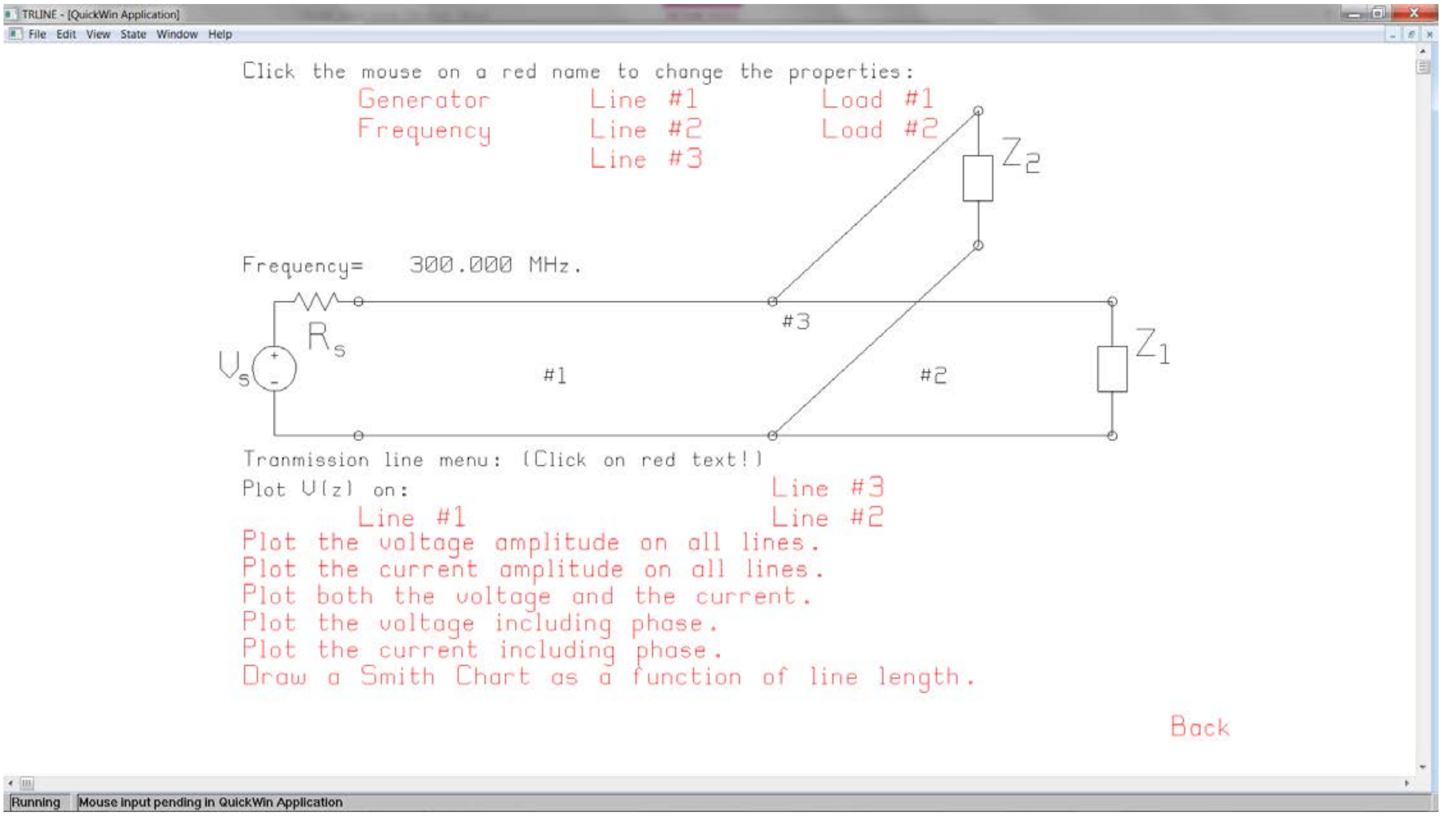
     Reactance:                  0.000     Ohms.

     Specify the load with an SnP file.

     Continue...
```

Fig. 2.8 The load properties menu.

Fig. 2.8 shows the properties menu for a load. Type the resistance and the reactance into the fields. Loads have a constant value as the frequency varies. If the load varies with frequency, the prepare an SnP file giving the value of the load at each frequency, and use the “Specify the load with an SnP file” button to give TRLINE the file name for the SnP file. TRLINE reads either the input impedance or the S_{11} scattering parameter from the SnP file. Some commercial electromagnetic solver programs prepare SnP files as output. Also, some network analyzers can write an SnP file of measured scattering parameters. This allows TRLINE to be used to work with load impedance as a function of frequency that has been measured as part of a lab experiment.



Click the mouse on a red name to change the properties:

Generator Line #1 Load #1

Frequency Line #2 Load #2

Line #3

Frequency= 300.000 MHz.

Tranmission line menu: (Click on red text!)

Plot V(z) on: Line #3

Line #1 Line #2

Plot the voltage amplitude on all lines.

Plot the current amplitude on all lines.

Plot both the voltage and the current.

Plot the voltage including phase.

Plot the current including phase.

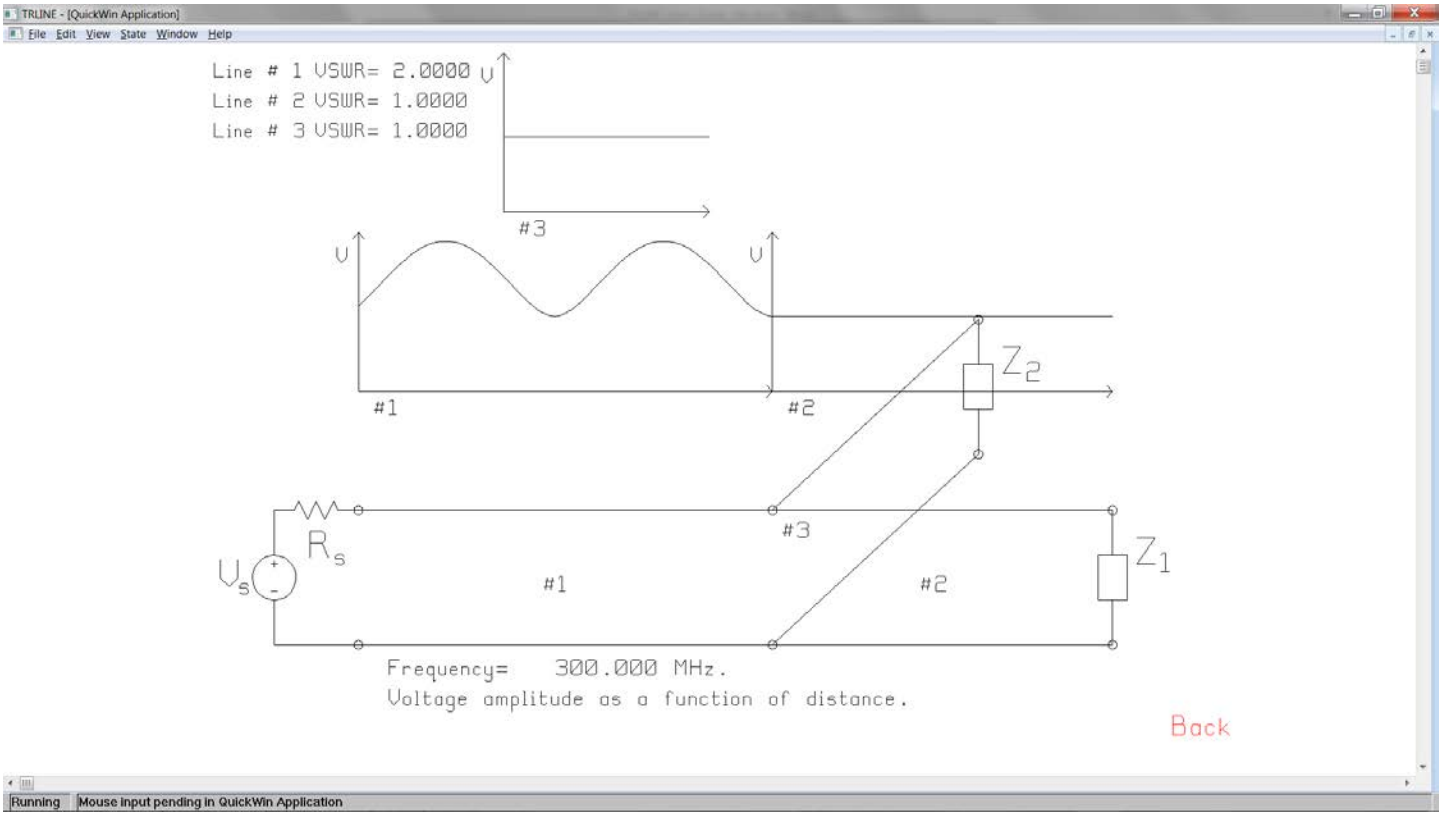
Draw a Smith Chart as a function of line length.

Back

Fig. 2.9 The “transmission line” menu offers various options for graphing the voltage.

2.3.Graphing the Voltage on the Transmission Lines

To solve the circuit and graph the voltages on the transmission lines, click “Plot V(z)…” in Fig. 2.4 to get the transmission line menu of Fig. 2.9. This menu lets the user graph voltage and current as a function of position on any of the transmission lines. Across the top of the menu we find the “properties buttons” used to change the parameters of the generator, lines and loads, as discussed above. At the bottom we find the menu’s action buttons. You can plot the voltage, the current, both the voltage and the current, and the voltage or current including the phase. You can also draw a Smith Chart.

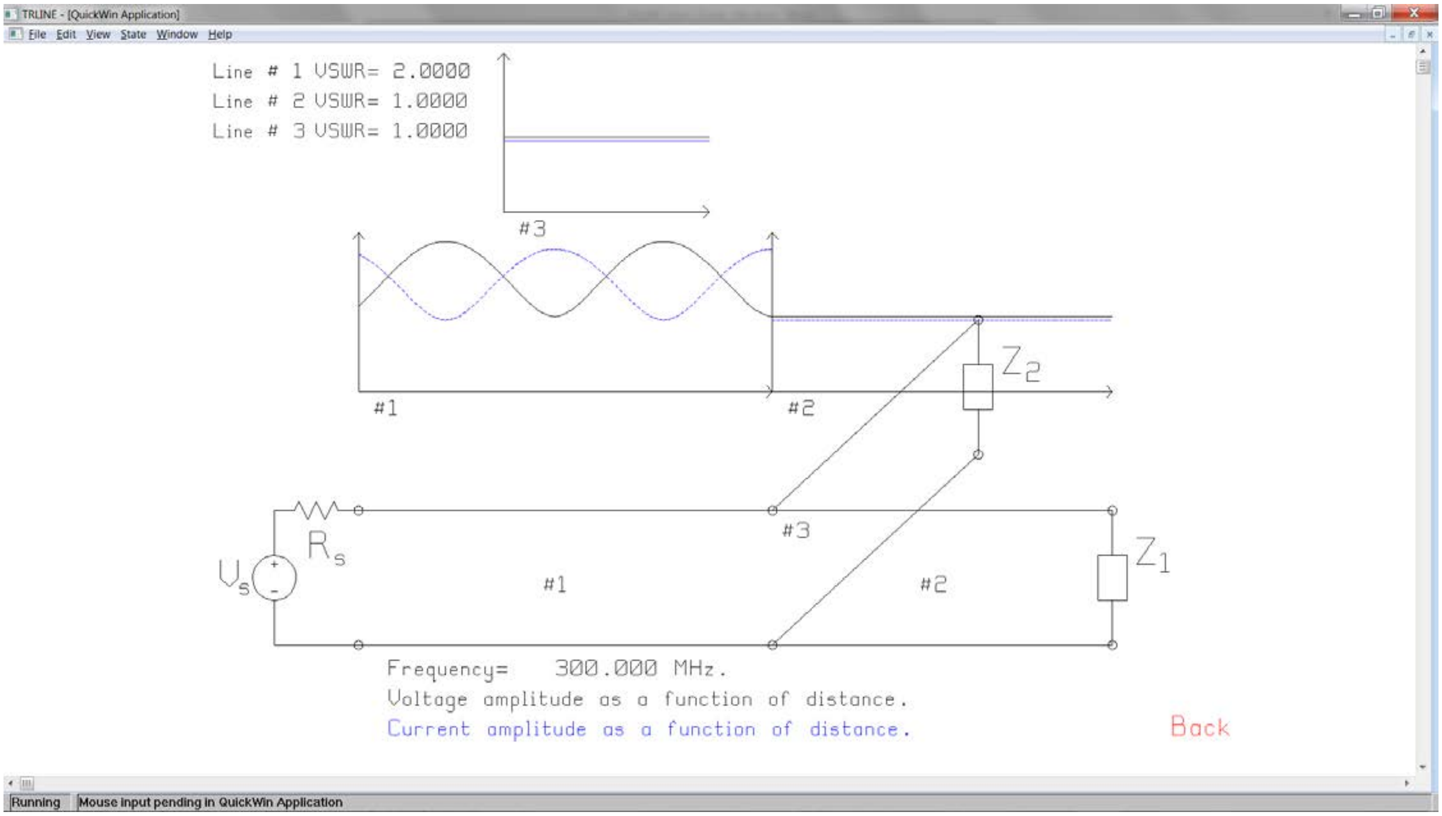


```
Line # 1 VSWR= 2.0000
Line # 2 VSWR= 1.0000
Line # 3 VSWR= 1.0000
```

```
Frequency=   300.000 MHz.
Voltage amplitude as a function of distance.
```

Fig. 2.10 The voltage on all the transmission lines.

Click “Plot the voltage amplitude on all lines” to get the schematic diagram of Fig. 2.10. We see the voltage standing wave on line #1. On line #2, we have a matched load and a constant voltage with position. Branching lines are shown across the top of the screen, and we see a constant voltage on line #3, which also has a matched load. The “Back” button at the lower right returns to the transmission line menu.

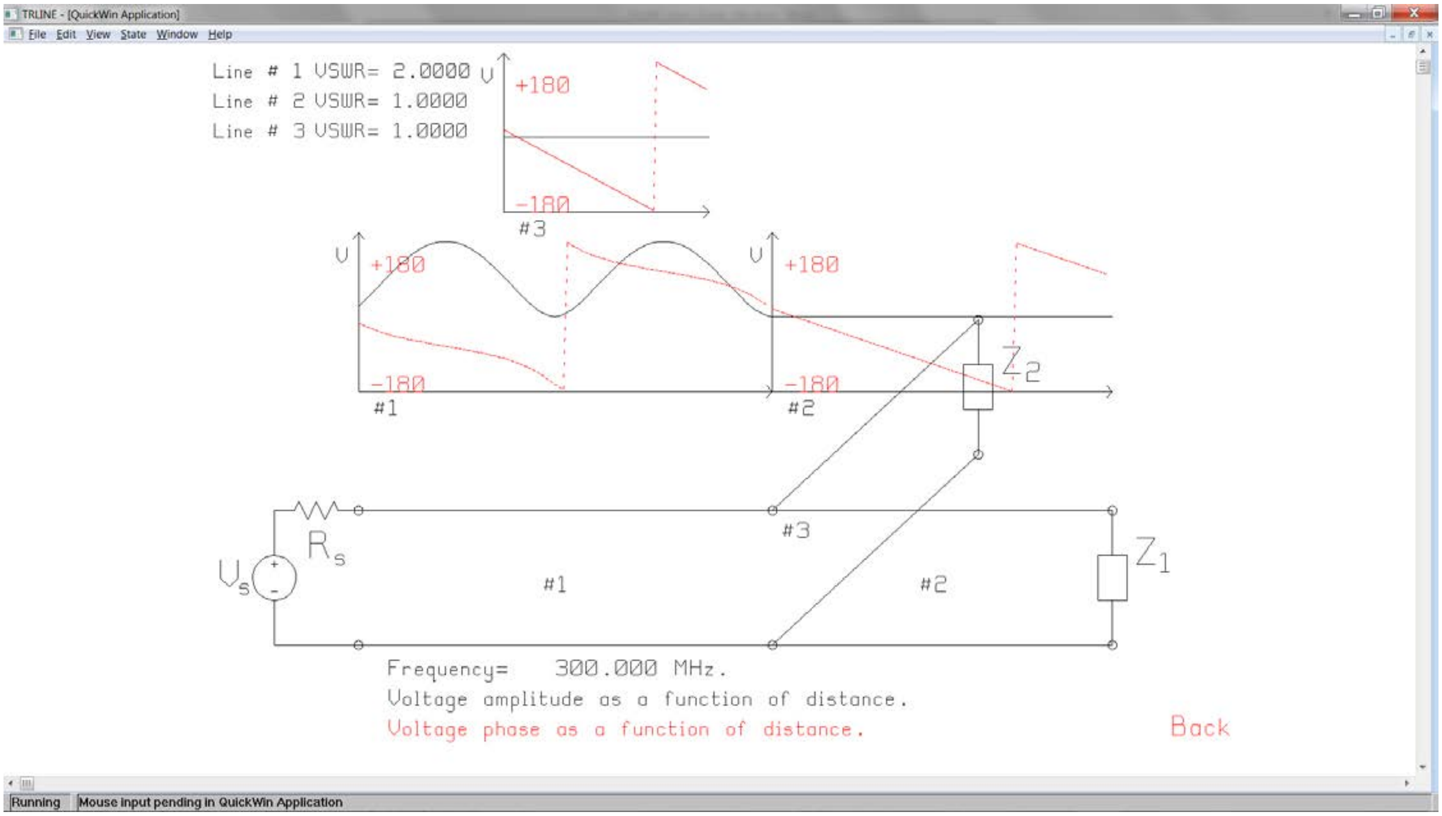


```
Line # 1 VSWR= 2.0000
Line # 2 VSWR= 1.0000
Line # 3 VSWR= 1.0000
```

```
Frequency=    300.000 MHz.
Voltage amplitude as a function of distance.
Current amplitude as a function of distance.
```

Fig. 2.11 The voltage and current on all the transmission lines.

In Fig. 2.9, click “Plot both the voltage and the current” to obtain the schematic of Fig. 2.11. We see the voltage in black and the current in blue. In the standing-wave pattern, where the voltage has a maximum, the current has a minimum. Note that both Kirchoff’s Voltage Law and Kirchoff’s Current Law are satisfied at the junction.

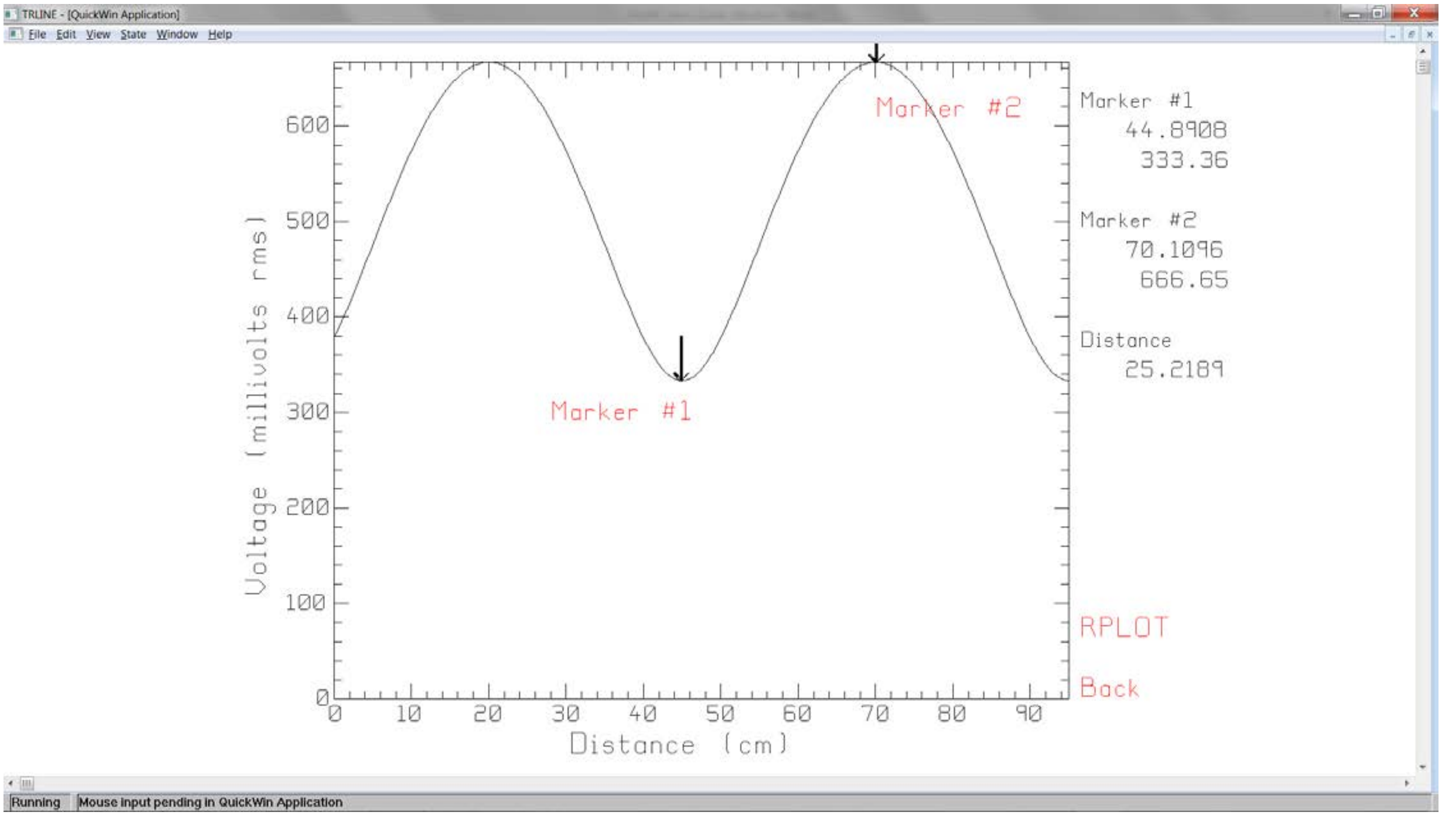


Line # 1 VSWR= 2.0000
Line # 2 VSWR= 1.0000
Line # 3 VSWR= 1.0000

Frequency= 300.000 MHz.
Voltage amplitude as a function of distance.
Voltage phase as a function of distance.

Fig. 2.12 The voltage including phase.

In Fig. 2.9, click “Plot the voltage including phase” to obtain the display of Fig. 2.12. The phase varies between -180 and +180 degrees. The lines that are matched have linear phase variation with distance, as expected of a simple travelling wave. The phase behavior of the voltage is more complicated on the unmatched line.



Marker #1
44.8908
333.36

Marker #2
70.1096
666.65

Distance
25.2189

Running
Mouse input pending in QuickWin Application

Fig. 2.13 The voltage as a function of position on line #1.

To obtain a labeled graph of voltage as a function of position on any one of the transmission lines, click the line name (in red) in the menu of Fig. 2.9. Click “Line #1” to obtain the graph of Fig. 2.13. We see a labeled voltage axis and a labeled distance axis. The graph shows a standing-wave pattern. The display includes two “markers” for reading back values. Click the mouse on the red string “Marker #1”, then click the mouse again on the desired position of the marker. The marker jumps to the new location and the distance and voltage are reported in the upper right hand corner of the screen. The distance between the markers is also reported, hence the markers are easily used to determine the distance from the load of the first standing-wave maximum and of the first minimum. This information is used to compute the load impedance from a knowledge of the standing-wave pattern shown in Fig. 2.13.

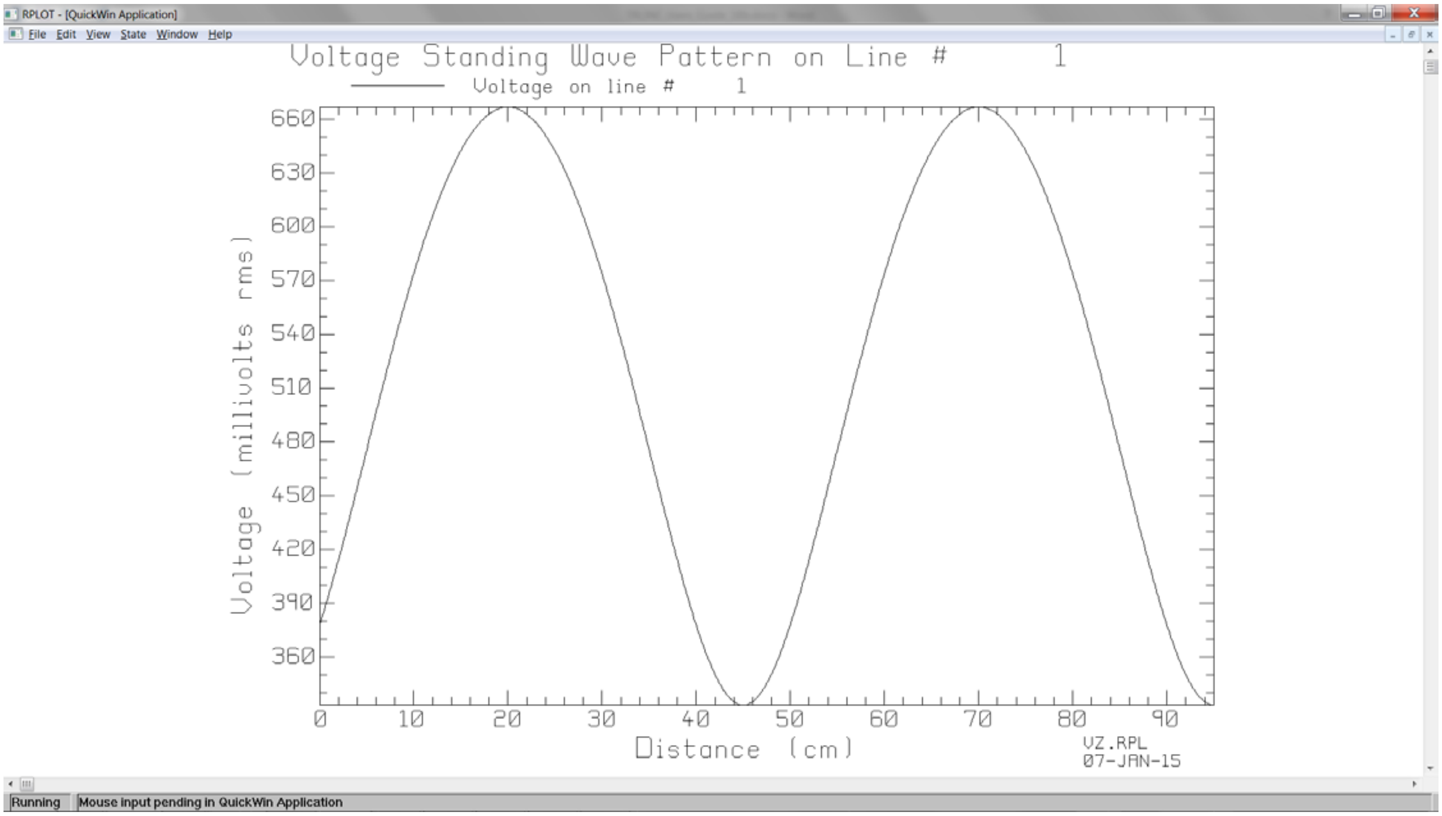
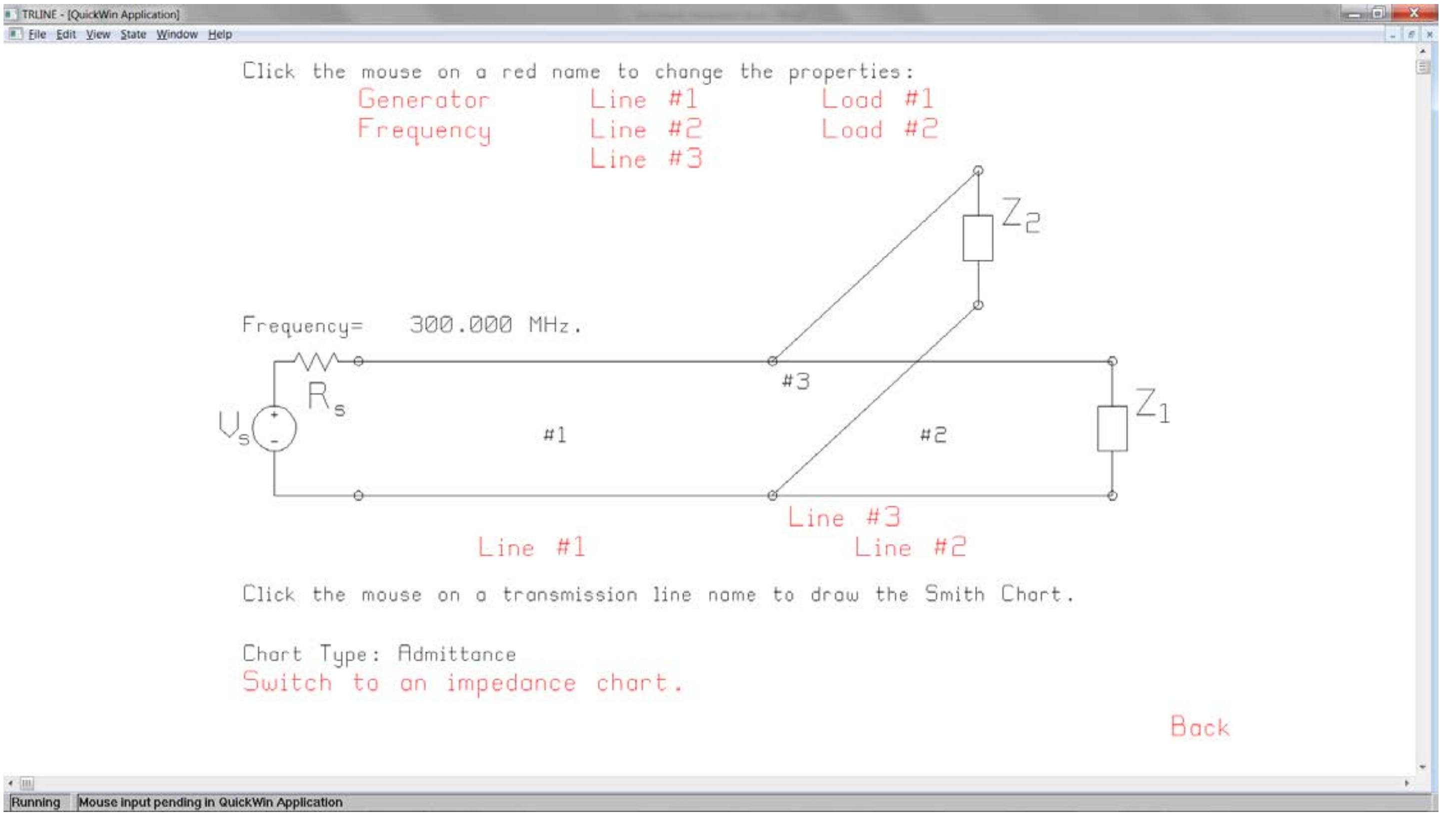


Fig. 2.14 RPLOT graph of the voltage standing wave on transmission line #1.

Click the RPLOT button in Fig. 2.13 to write a data file “vt.rpl” for graphing with the rectangular-graphing program called RPLOT. This program draws the standing wave in the format shown in Fig. 2.14. The RPLOT program provides the user with full control over the axis format, the axis titles, the graph titles, and so forth. The graph can be formatted by the user to be suitable for inclusion into a report or other document. RPLOT can be used to make an encapsulated postscript file of the graph, which looks much better than the bitmap shown in Fig 2.14. Note that when you click the RPLOT button in TRLINE, the execution of the TRLINE program is suspended until you exit from RPLOT. Then TRLINE resumes execution.



Click the mouse on a red name to change the properties:

Frequency= 300.000 MHz.

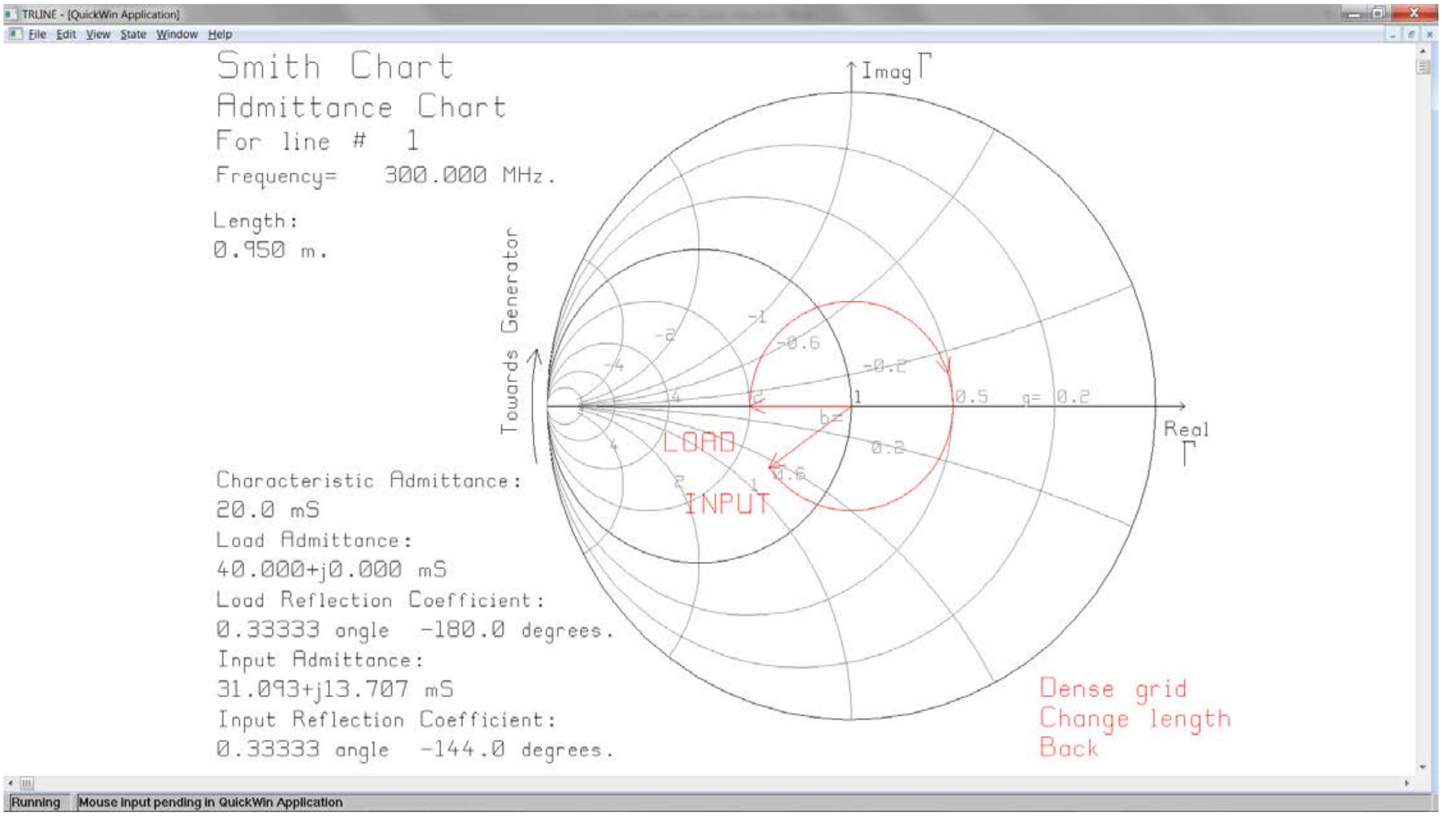
Click the mouse on a transmission line name to draw the Smith Chart.

Chart Type: Admittance

Fig. 2.15 The Smith Chart menu.

2.4.Smith Chart and Input Impedance

The last button on the transmission line menu in Fig. 2.9 is “Draw a Smith Chart as a function of line length”. Click this button to get the Smith Chart menu of Fig. 2.15. In the main menu of Fig. 2.2, if you click “Draw a Smith Chart” you will also get the Smith Chart menu of Fig. 2.15. This menu has the properties buttons across the top of the screen so that you can easily change the line lengths and so forth. The bottom of the menu has a button labeled “Switch to an impedance chart”, which is used to change the Smith Chart from the admittance format to the impedance format. Across the center in Fig. 2.15, below the circuit schematic, there is a button for each transmission line. If we click the mouse on the button for Line #1, we obtain the Smith Chart calculation of the input impedance shown in Fig. 2.16.



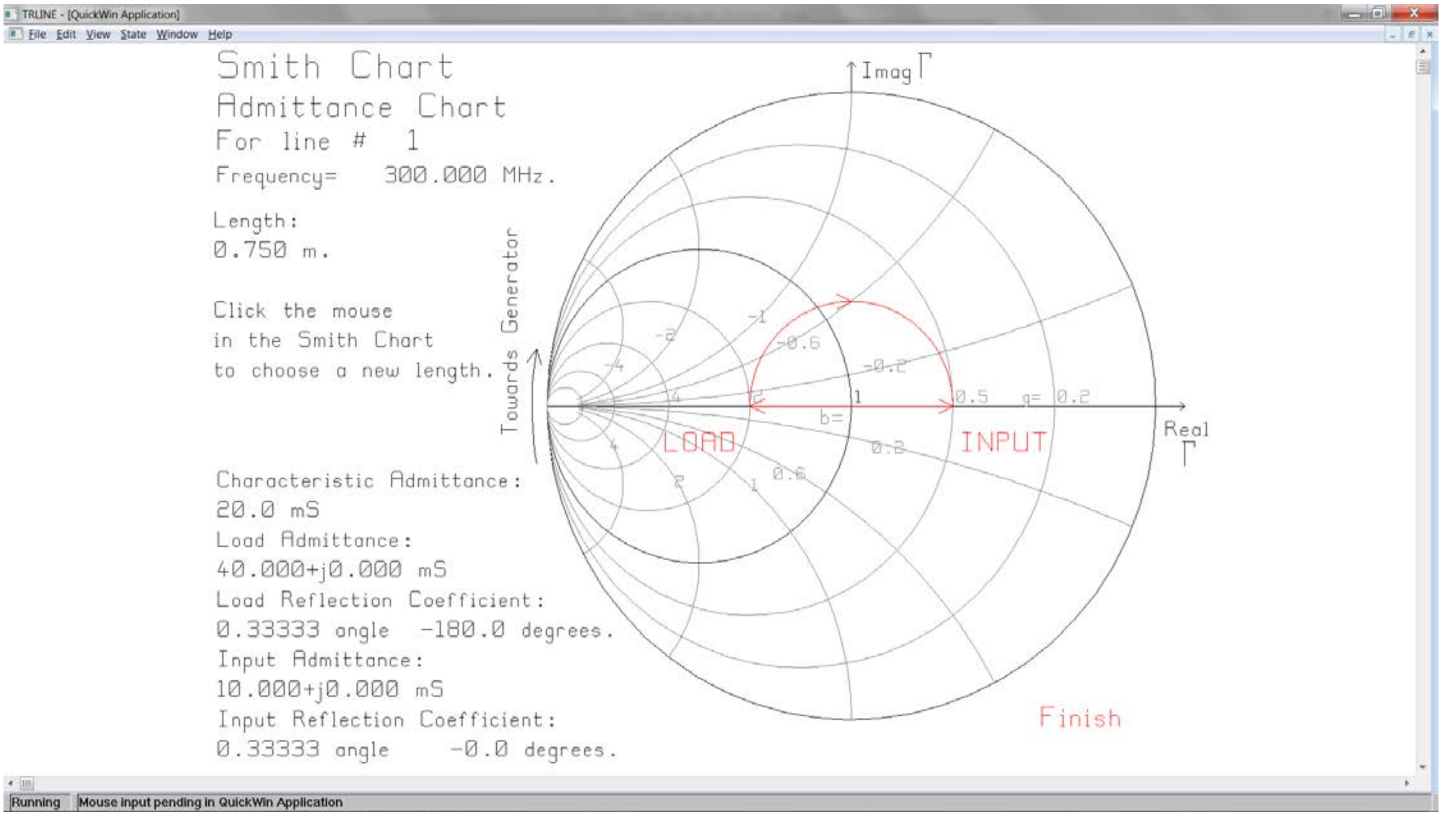
```
Smith Chart
Admittance Chart
For line #  1
Frequency=   300.000 MHz.

Length:
0.950 m.

Characteristic Admittance:
20.0 mS
Load Admittance:
40.000+j0.000 mS
Load Reflection Coefficient:
0.33333 angle  -180.0 degrees.
Input Admittance:
31.093+j13.707 mS
Input Reflection Coefficient:
0.33333 angle  -144.0 degrees.
```

Fig. 2.16 The Smith Chart for Line #1.

The Smith Chart of Fig. 2.16 shows the load impedance that terminates line #1, which is the parallel combination of the input impedance of line #2 and line #3. Since both of these lines have a 50 ohm characteristic impedance and are terminated with a 50 ohm matched load, the input impedance of each of these lines is 50 ohms, and the parallel combination is 25 ohms or 40 mS. Normalized to the 20 mS characteristic admittance of the transmission line, the 40 mS load admittance is equal to 2, so the LOAD admittance graphed in Fig. 2.16 is 2+j0. As we move along the transmission line from the load to the input, the admittance moves on a constant $|\Gamma|$ circle in a clockwise direction, as shown in Fig. 2.16. The INPUT impedance of the line is reported as 31.093+j13.707 in Fig. 2.16.



```
Smith Chart
Admittance Chart
For line #  1
Frequency=   300.000 MHz.

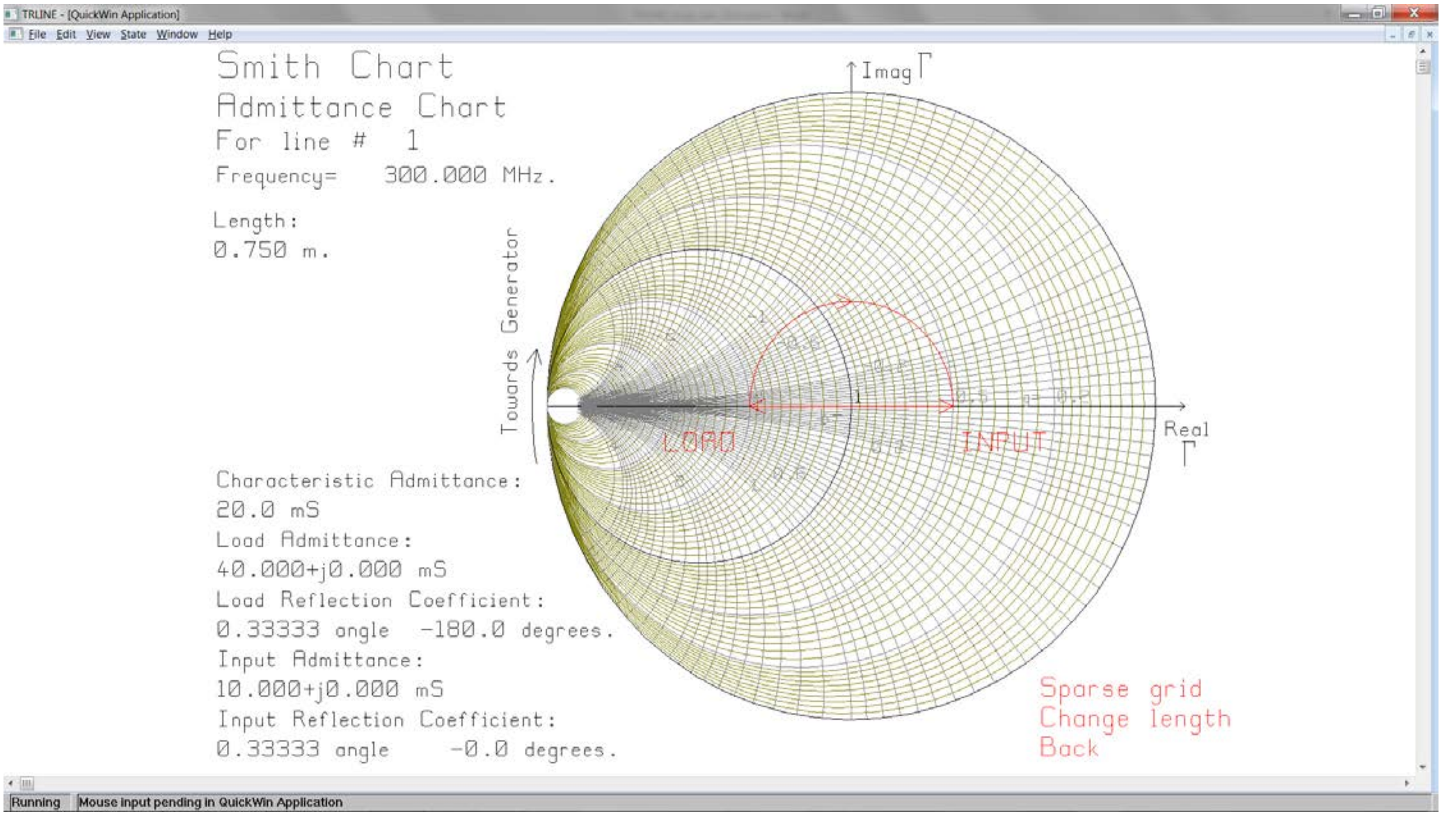
Length:
0.750 m.

Click the mouse
in the Smith Chart
to choose a new length.

Characteristic Admittance:
20.0 mS
Load Admittance:
40.000+j0.000 mS
Load Reflection Coefficient:
0.33333 angle  -180.0 degrees.
Input Admittance:
10.000+j0.000 mS
Input Reflection Coefficient:
0.33333 angle    -0.0 degrees.
```

Fig. 2.17 Changing the length of transmission line #1 to change the input admittance.

The “Change length” button in Fig. 2.16 is handy for modifying the length of the transmission line to bring the input admittance to a desired value. Click Change Length to get the Smith Chart of Fig. 2.17. Click the mouse within the Smith Chart circle. The program calculates the position of the mouse click and sets the length of the transmission line so that the input reflection coefficient has the angle associated with the mouse click. In Fig. 2.17 the user has click the mouse on the positive side of the real Γ axis, making the angle of the reflection coefficient zero. The program has adjusted the length of line #1 so that the input impedance of line #1 gives rise to a reflection coefficient with angle zero, that is, a reflection coefficient that is real and positive.



```
Smith Chart
Admittance Chart
For line #   1
Frequency=   300.000 MHz.

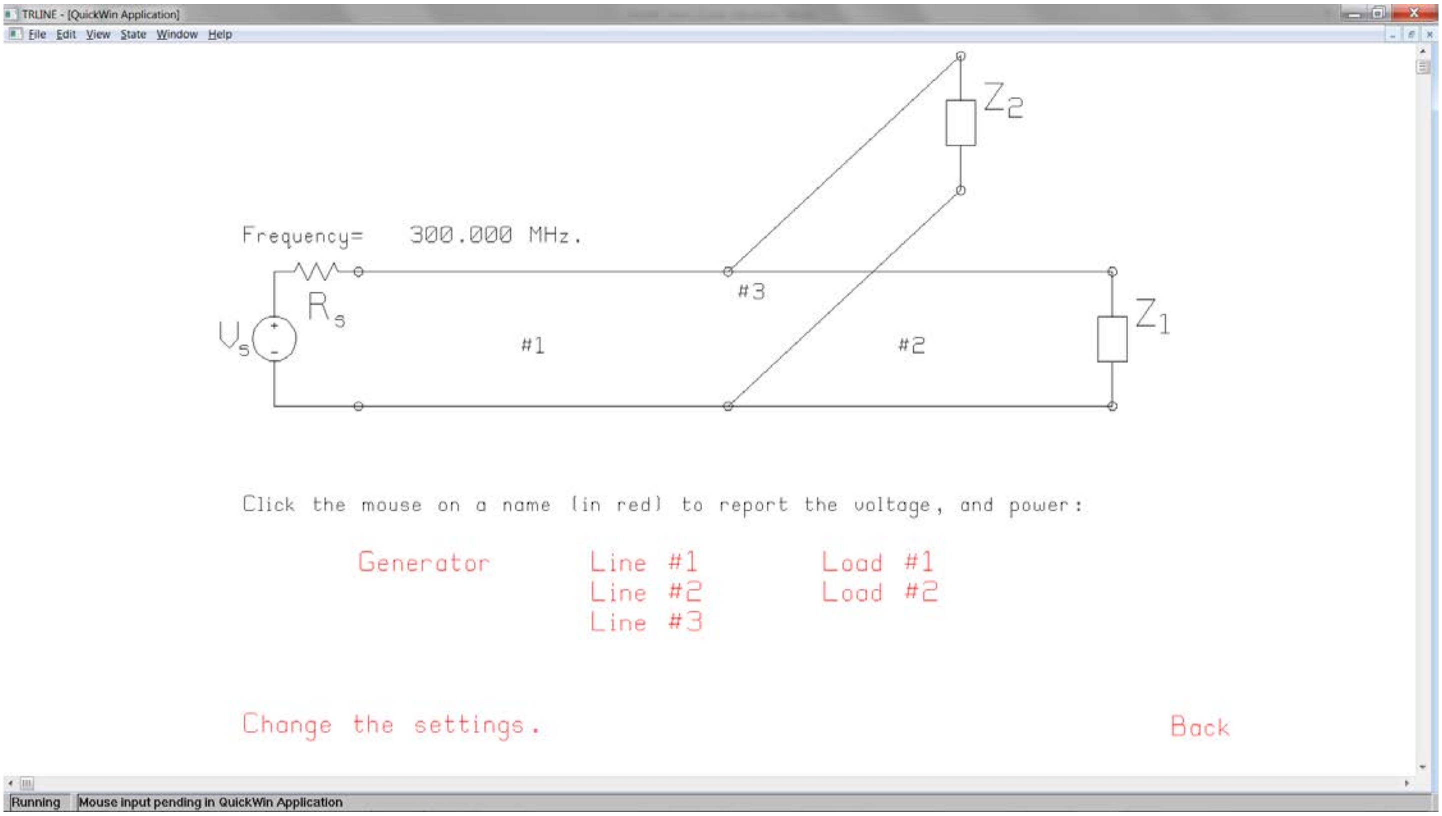
Length:
0.750 m.

Characteristic Admittance:
20.0 mS
Load Admittance:
40.000+j0.000 mS
Load Reflection Coefficient:
0.33333 angle  -180.0 degrees.
Input Admittance:
10.000+j0.000 mS
Input Reflection Coefficient:
0.33333 angle    -0.0 degrees.
```

```
Running    Mouse input pending in QuickWin Application
```

Fig. 2.18 The Smith Chart drawn with a dense grid of constant-g and constant-b contours, where y=g+jb.

The “Dense Grid” button at the lower right is used to increase the number of circles used for the Smith Chart axes. Fig. 2.18 illustrates the dense grid. The sparse grid of Fig. 2.16 is usually more effective on the computer screen. The “Back” button returns to the Smith Chart menu.



Frequency= 300.000 MHz.

Click the mouse on a name (in red) to report the voltage, and power:

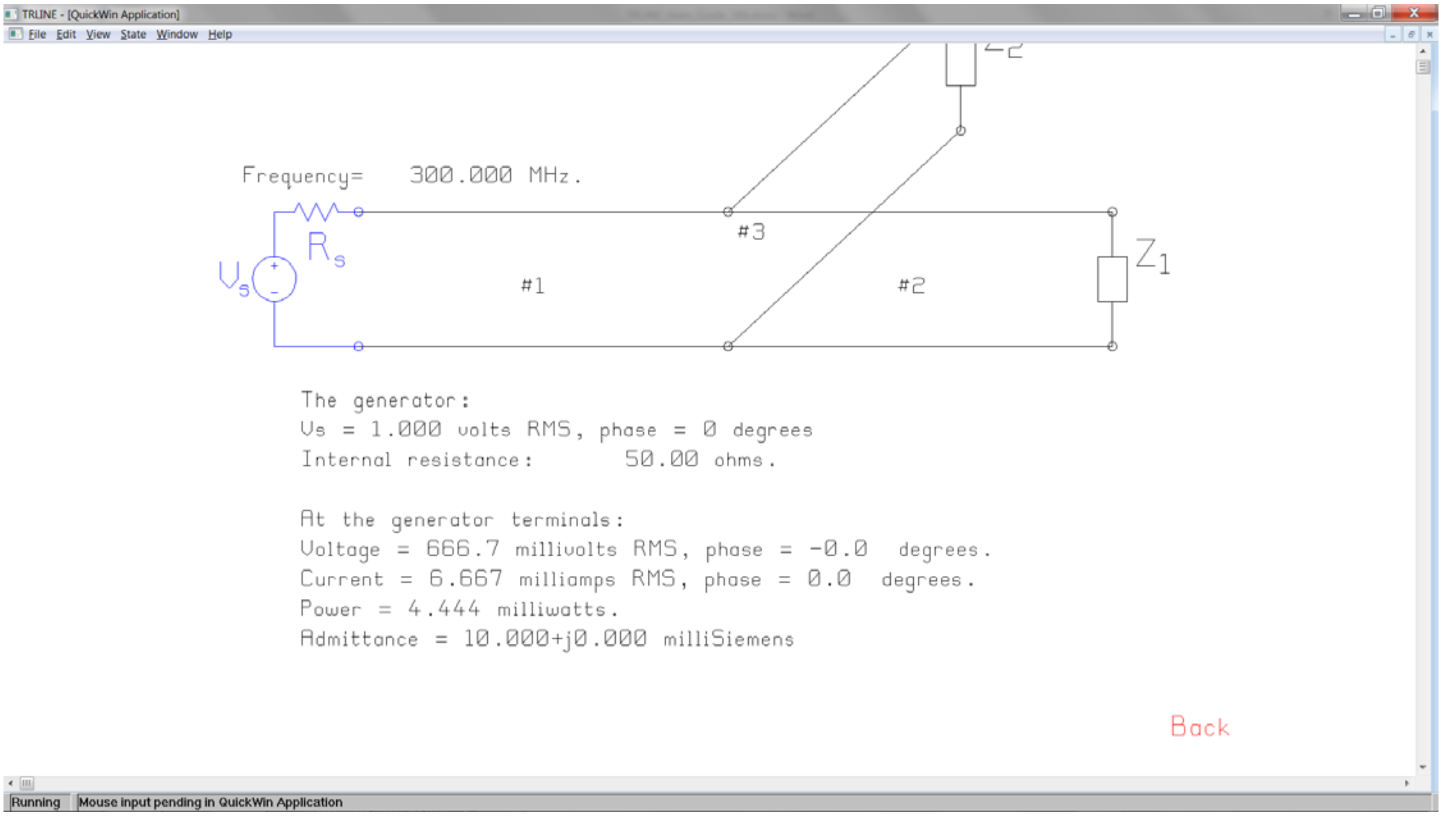
Running

Mouse input pending in QuickWin Application

Fig. 2.19 The power menu provides buttons to report the power flow in every part of the transmission line circuit.

2.5.The Power Menu

In the main menu of Fig. 2.2, click the button labeled “Find voltages, currents and power.” This gets the power menu of Fig. 2.19. This menu provide a button for each part of the circuit, to report on the power flow.



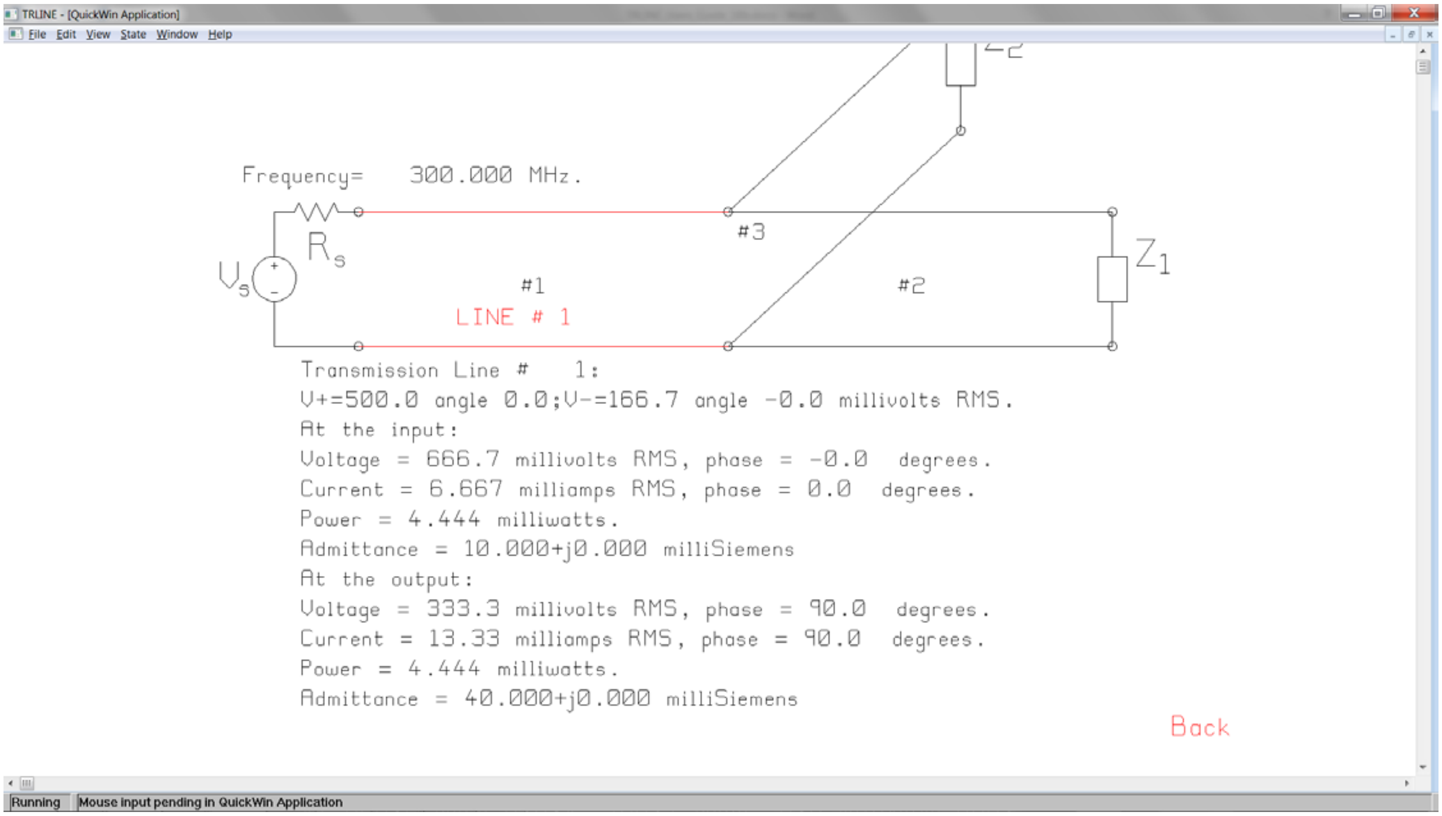
```
Frequency=   300.000 MHz.

The generator:
Vs = 1.000 volts RMS, phase = 0 degrees
Internal resistance:       50.00 ohms.

At the generator terminals:
Voltage = 666.7 millivolts RMS, phase = -0.0  degrees.
Current = 6.667 milliamps RMS, phase = 0.0  degrees.
Power = 4.444 milliwatts.
Admittance = 10.000+j0.000 milliSiemens
```

Fig. 2.20 The power flow report for the generator.

Click “Generator” to get the power delivered by the generator as in Fig. 2.20. This screen reports the voltage and current at the generator terminals, the input admittance into the transmission line circuit, and the power delivered by the generator to the circuit. Change the settings to impedance to have the program report input impedance.



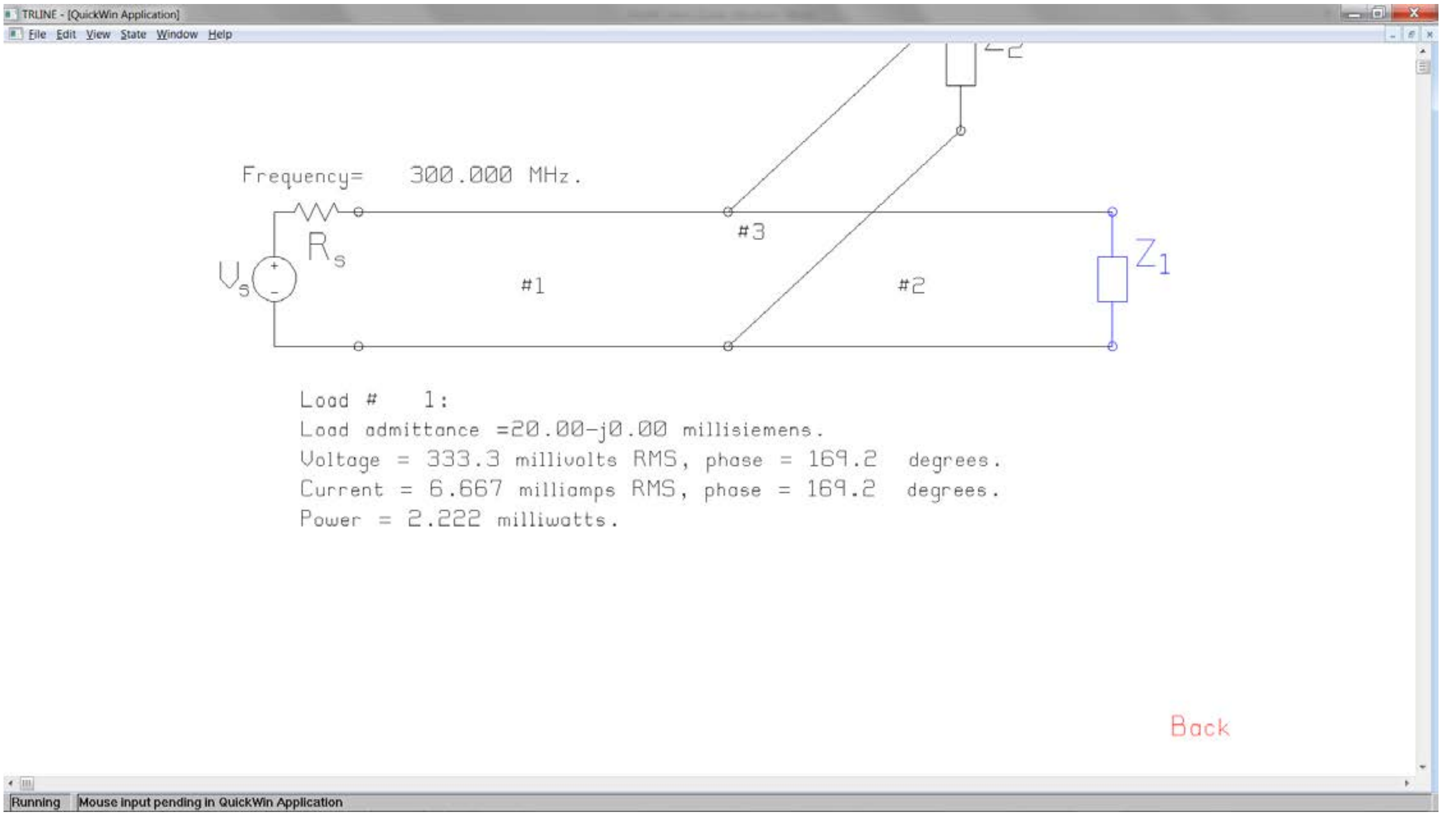
```
Frequency=   300.000 MHz.
Transmission Line #    1:
V+=500.0 angle 0.0;V-=166.7 angle -0.0 millivolts RMS.
At the input:
Voltage = 666.7 millivolts RMS, phase = -0.0  degrees.
Current = 6.667 milliamps RMS, phase = 0.0  degrees.
Power = 4.444 milliwatts.
Admittance = 10.000+j0.000 milliSiemens
At the output:
Voltage = 333.3 millivolts RMS, phase = 90.0  degrees.
Current = 13.33 milliamps RMS, phase = 90.0  degrees.
Power = 4.444 milliwatts.
Admittance = 40.000+j0.000 milliSiemens
```

Fig. 2.21 The power flow for line #1.

Click Line #1 in the power menu of Fig. 20 to obtain the report of Fig. 2.21. The voltage on the transmission line is given by

$$V(z) = V^+ e^{-j\beta z} + V^- e^{j\beta z}$$

where V^+ is the complex amplitude of positive-going voltage travelling wave and V^- is the complex amplitude of the negative-going wave. Distance z is zero at the left-hand end of the transmission line, and is equal to the length of the line at the right-hand end. TRLINE reports the values of V^+ and V^- below the circuit schematic. The voltage, current and power at the input of the line is reported, as well as the input admittance. The voltage, current and power at the output of the line is also reported. The output power is always equal to the input power because the transmission lines in TRLINE are lossless. The admittance at the output of the transmission line is also report and is equal to the input admittance of the remainder of the circuit lying to the right of the output port of the transmission line.



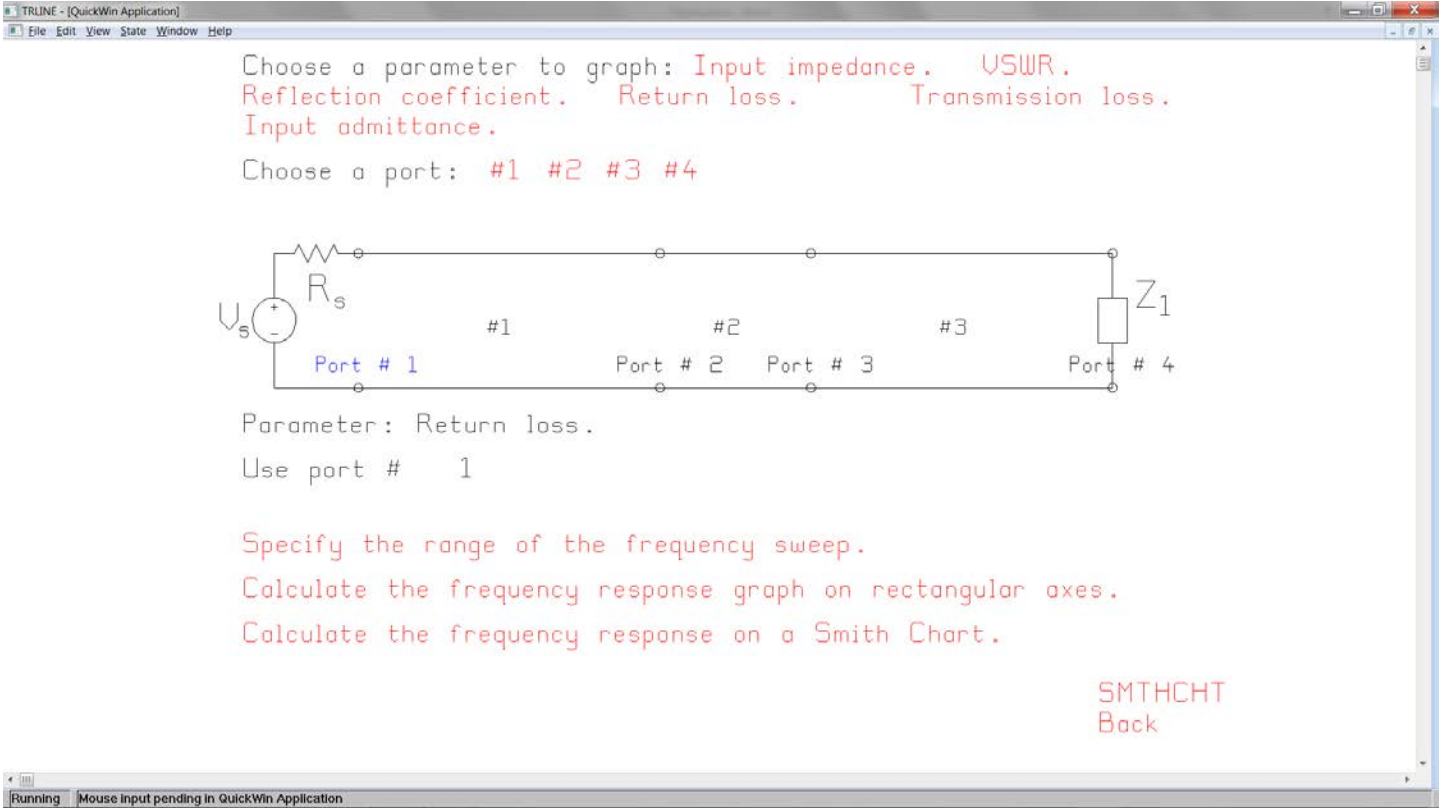
```
Load #   1:
Load admittance =20.00-j0.00 millisiemens.
Voltage = 333.3 millivolts RMS, phase = 169.2  degrees.
Current = 6.667 milliamps RMS, phase = 169.2  degrees.
Power = 2.222 milliwatts.
```

Fig. 2.22 The power report for load #1.

Click “Load #1” in Fig. 20 for the report on the power flow at load #1, in Fig. 2.22. The load admittance is given. The voltage and current at the load are given. The power flow into the load is given. Using the power flow menu we can determine how much power the source delivers, and how much of that power finds its way to each of the loads.

2.6.Frequency Response

Extensive calculations are needed to determine the behavior of a transmission line circuit as a function of frequency and such calculations are beyond pencil-and-paper homework in a fields-and-waves course or a microwave engineering course. Yet most real applications are concerned with the bandwidth over which a required performance is met. Thus, in an impedance matching problem, the bandwidth of the match for a return loss of better than 10 dB is often required.



Parameter: Return loss.

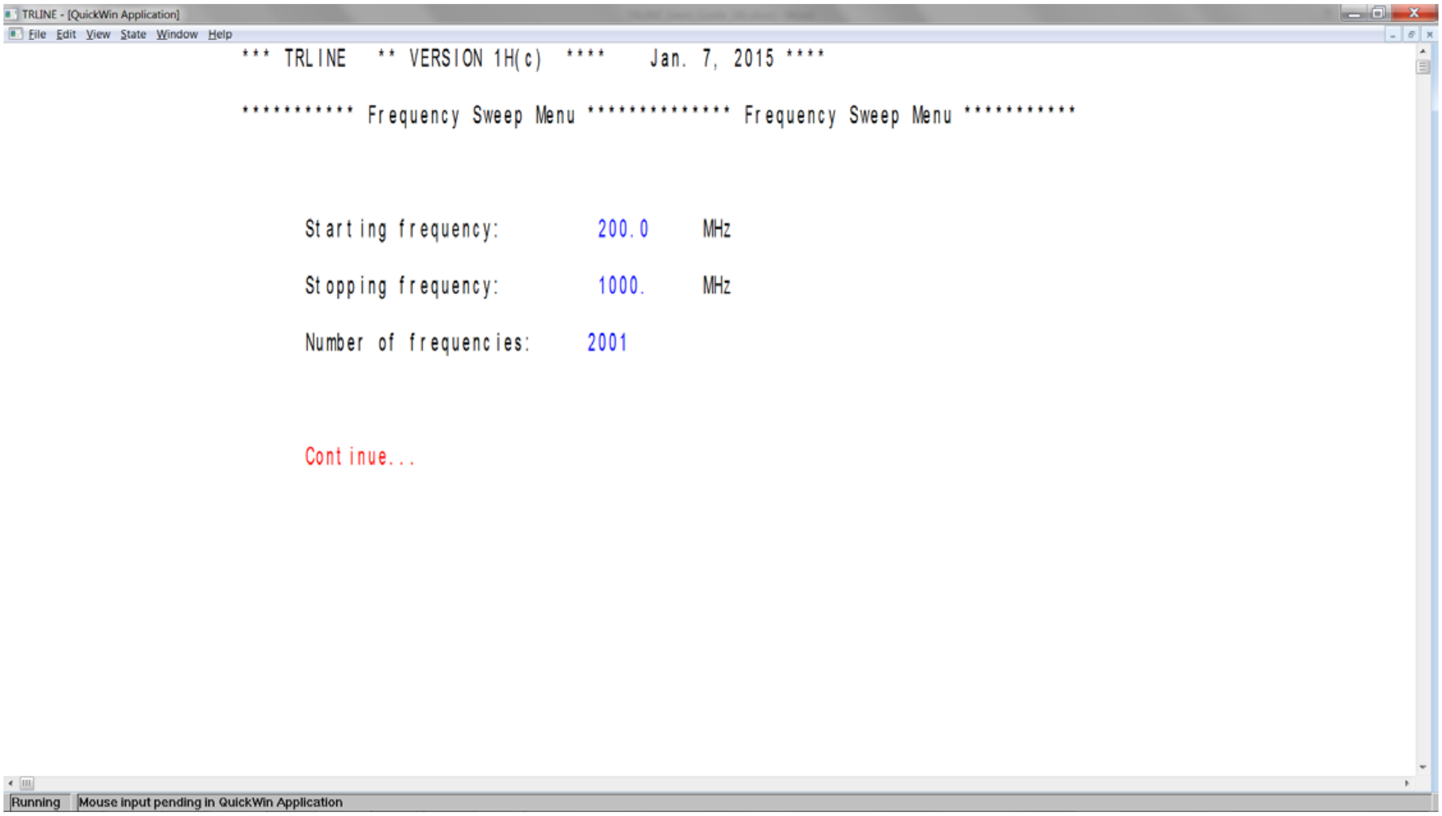
Use port # 1

Fig. 2.23 The frequency response menu for the quarter-wave transformer.

Click “Plot a parameter as a function of frequency” in the main menu of Fig. 2.2 to get the frequency response menu of Fig. 2.23, shown for the quarter-wave matching circuit template. To demonstrate frequency sweeping, the circuit is set up with line #3 with characteristic impedance 100 ohms terminated by a 100-ohm load. Line #1 is a 50-ohm line, and the transformer impedance is line #2. The characteristic impedance of line #2 is chosen as $\sqrt{50x100} = 70.71$ ohms. A perfect match is wanted at 600 MHz. With a wave speed of 299.79 meters per microsecond, the wavelength at 600 MHz is 0.49965 meters, and so the transformer length is chosen as 0.12491 m.

The program can plot five different parameters as a function of frequency: input impedance, VSWR, reflection coefficient, return loss and transmission loss. Choose a parameter by clicking the mouse on a parameter button at the top of the screen. For this demonstration choose Return Loss.

In Fig. 2.23, each junction represents a port. Parameter values are reported for the part of the circuit to the right of the port. Thus, the input impedance at port #1 is that for the entire circuit, whereas the input impedance at port #2 is that of line #2 connected to line #3, terminated with the load. Chose a port by clicking the mouse on one of the port buttons; for this demonstration choose Port #1.



```
*** TRLINE   ** VERSION 1H(c)  ****    Jan. 7, 2015 ****

*********** Frequency Sweep Menu ************** Frequency Sweep Menu ***********


     Starting frequency:       200.0     MHz

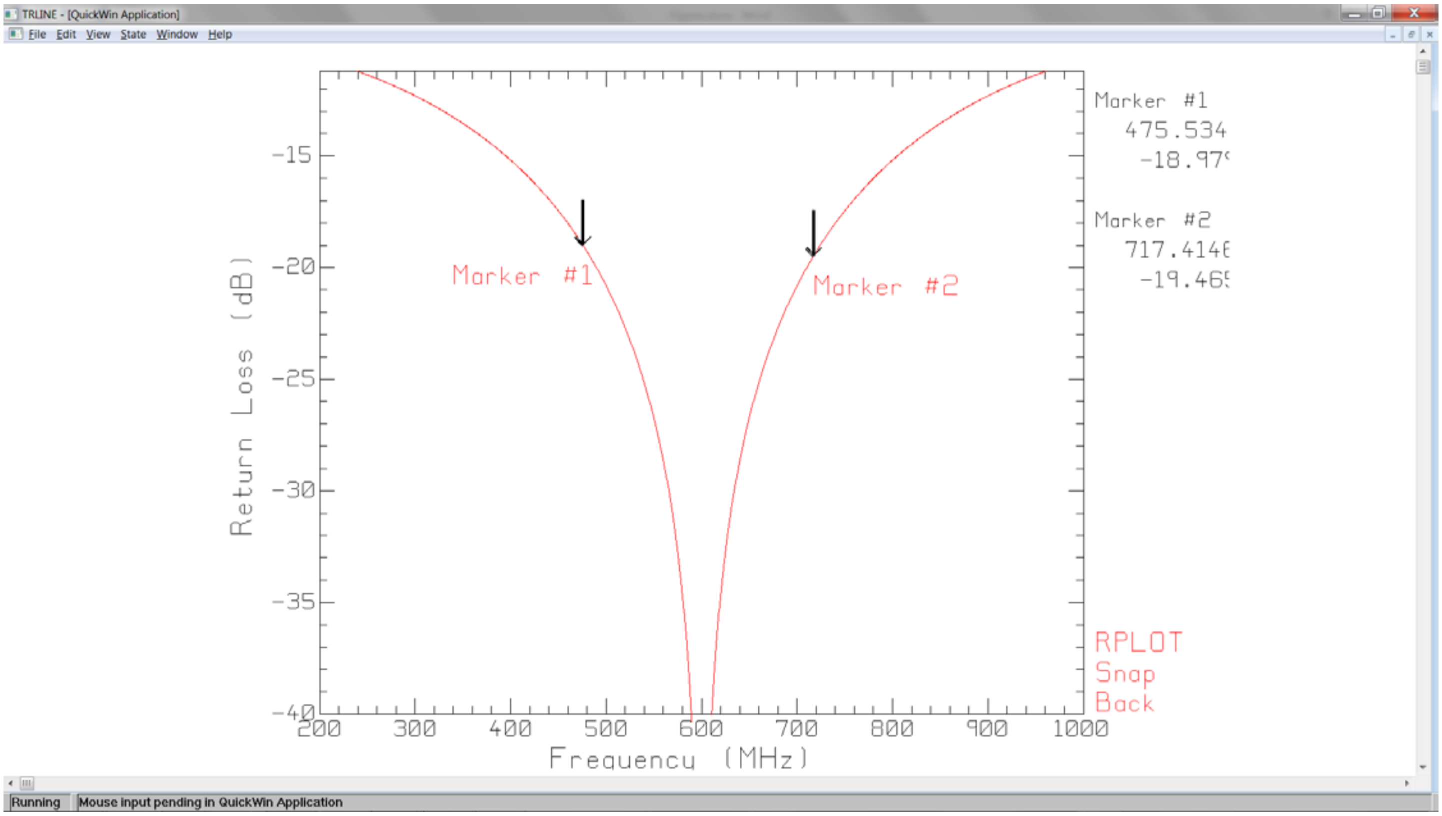
     Stopping frequency:       1000.     MHz

     Number of frequencies:   2001


     Continue...
```

Fig. 2.24 The frequency range menu.

In the sweep menu of Fig. 2.23, click on “Specify the range of the frequency sweep” to obtain the menu of Fig. 2.24, which has numerical “fields” for the starting frequency, the stopping frequency and the number of frequencies in between. The quarter-wave transformer circuit of Fig. 2.23 is designed to provide a perfect match at 600 MHz so set the frequency range to start at 200 MHz and finish at 1000 MHz. Then click “Calculate the frequency response” in the menu of Fig. 2.23.

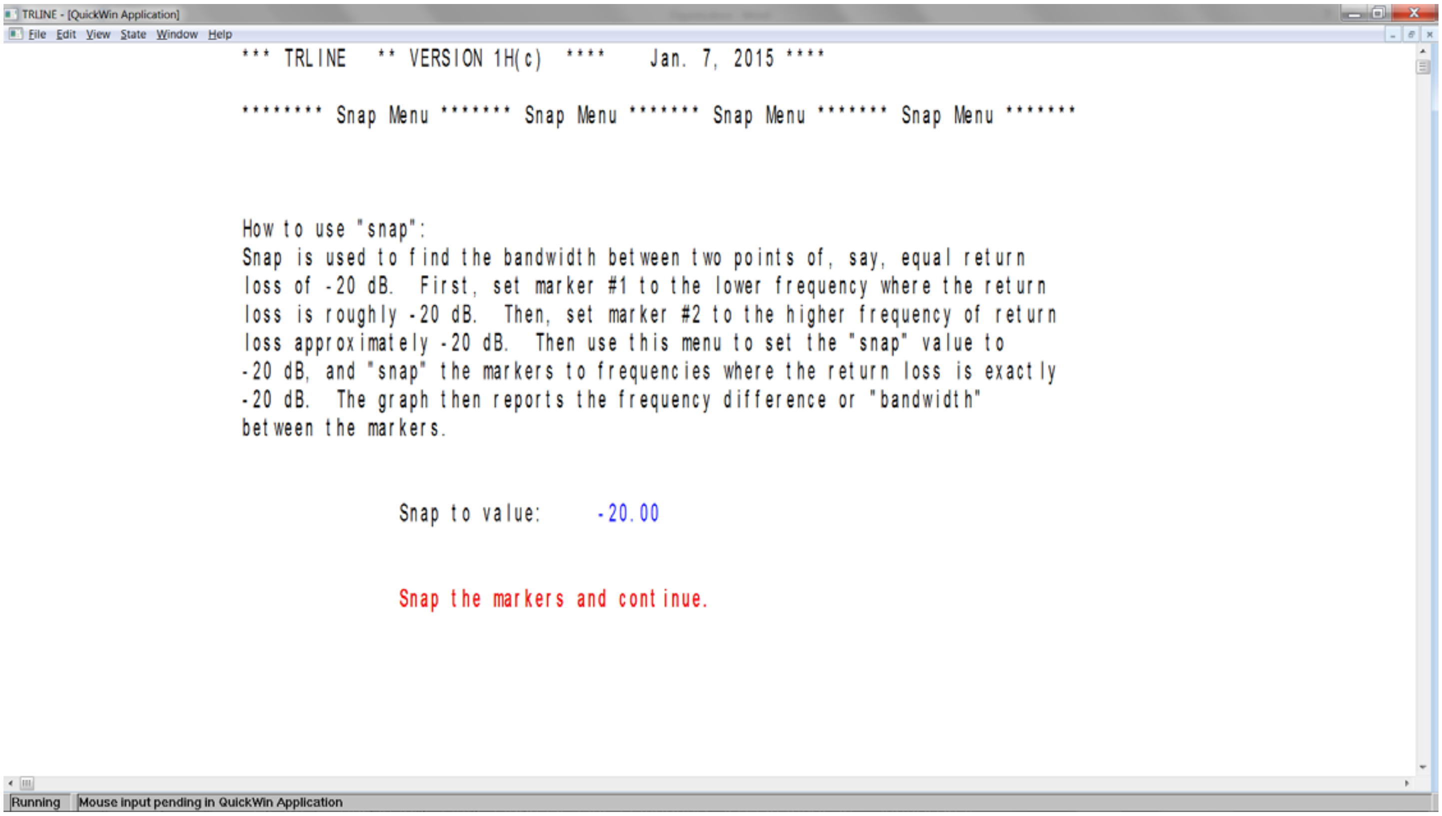


Running

Mouse input pending in QuickWin Application

Fig. 2.25 The return loss as a function of frequency.

Fig. 2.25 shows the return loss from 200 to 1000 MHz. The return loss is very large at the design frequency of 600 MHz. To determine the bandwidth for a 20 dB or better return loss, use the markers. Click on Marker #1, then click the mouse on the curve at approximately -20 dB, below 600 MHz. Similarly position Marker #2 at about -20 dB above the center frequency. Then click Snap at the lower right.



```
*** TRLINE  ** VERSION 1H(c)  ****   Jan. 7, 2015 ****

******** Snap Menu ******* Snap Menu ******* Snap Menu ******* Snap Menu *******

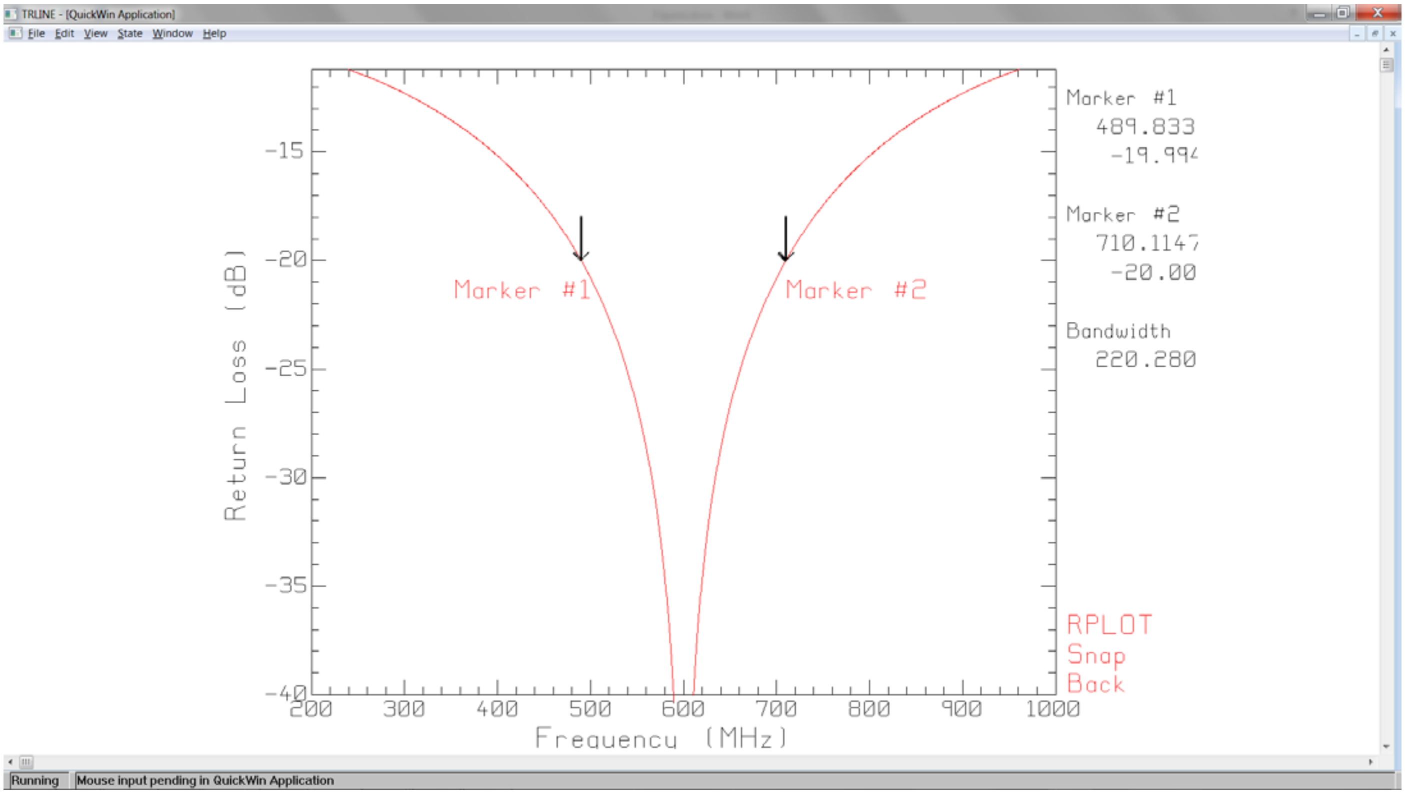

How to use "snap":
Snap is used to find the bandwidth between two points of, say, equal return
loss of -20 dB.  First, set marker #1 to the lower frequency where the return
loss is roughly -20 dB.  Then, set marker #2 to the higher frequency of return
loss approximately -20 dB.  Then use this menu to set the "snap" value to
-20 dB, and "snap" the markers to frequencies where the return loss is exactly
-20 dB.  The graph then reports the frequency difference or "bandwidth"
between the markers.


               Snap to value:     -20.00


               Snap the markers and continue.
```

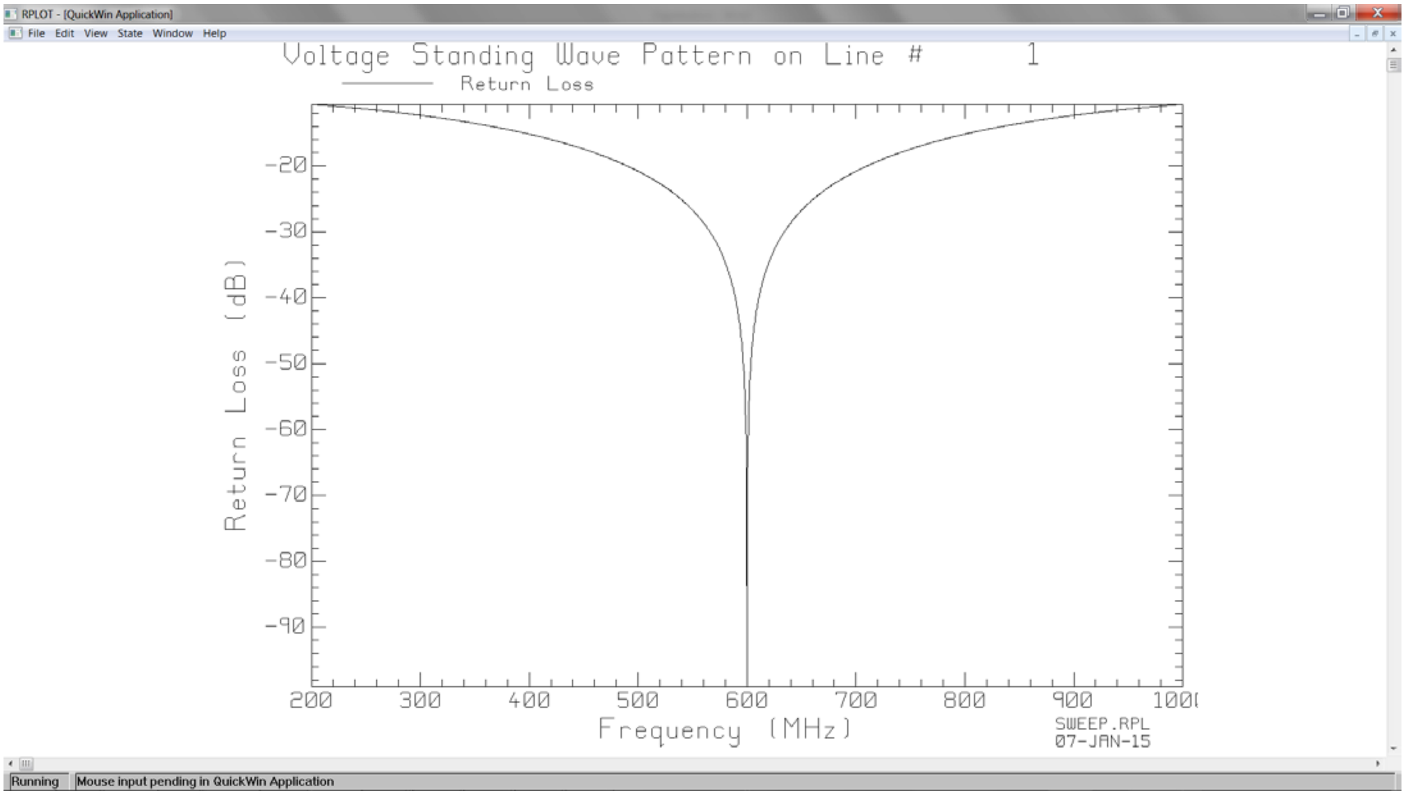
Fig. 2.26 The snap menu lets the user enter a snap value, in this case -20 dB.

The snap menu lets the user enter the desired value for the return loss at the marker locations, in this case -20 dB. Click “Snap the markers” to continue.



Fig, 2.27 The programs snaps the markers to -20 dB and reports the bandwidth between the markers as 220.26 MHz.

Fig. 2.27 shows that the TRLINE program positions the markers at -20 dB, and reports the bandwidth between the markers as 220.26 MHz.



Mouse input pending in QuickWin Application

Fig. 2.28 Click the RPLOT button to run RPLOT to graph the return loss as a function of frequency.

In Fig. 2.27, click the RPLOT button to create a file called “sweep.rpl” and then run RPLOT to graph the frequency sweep data, as shown in Fig. 2.28. Execution of TRLINE is suspended until the user exits from the RPLOT program. RPLOT lets the user set all the parameters associated with the display, such as the range of the horizontal axis and of the vertical axis, the titles and legends, and so forth. Expert users can collect several different frequency sweep curves into one rpl file to visually compare the bandwidths of various matching schemes.

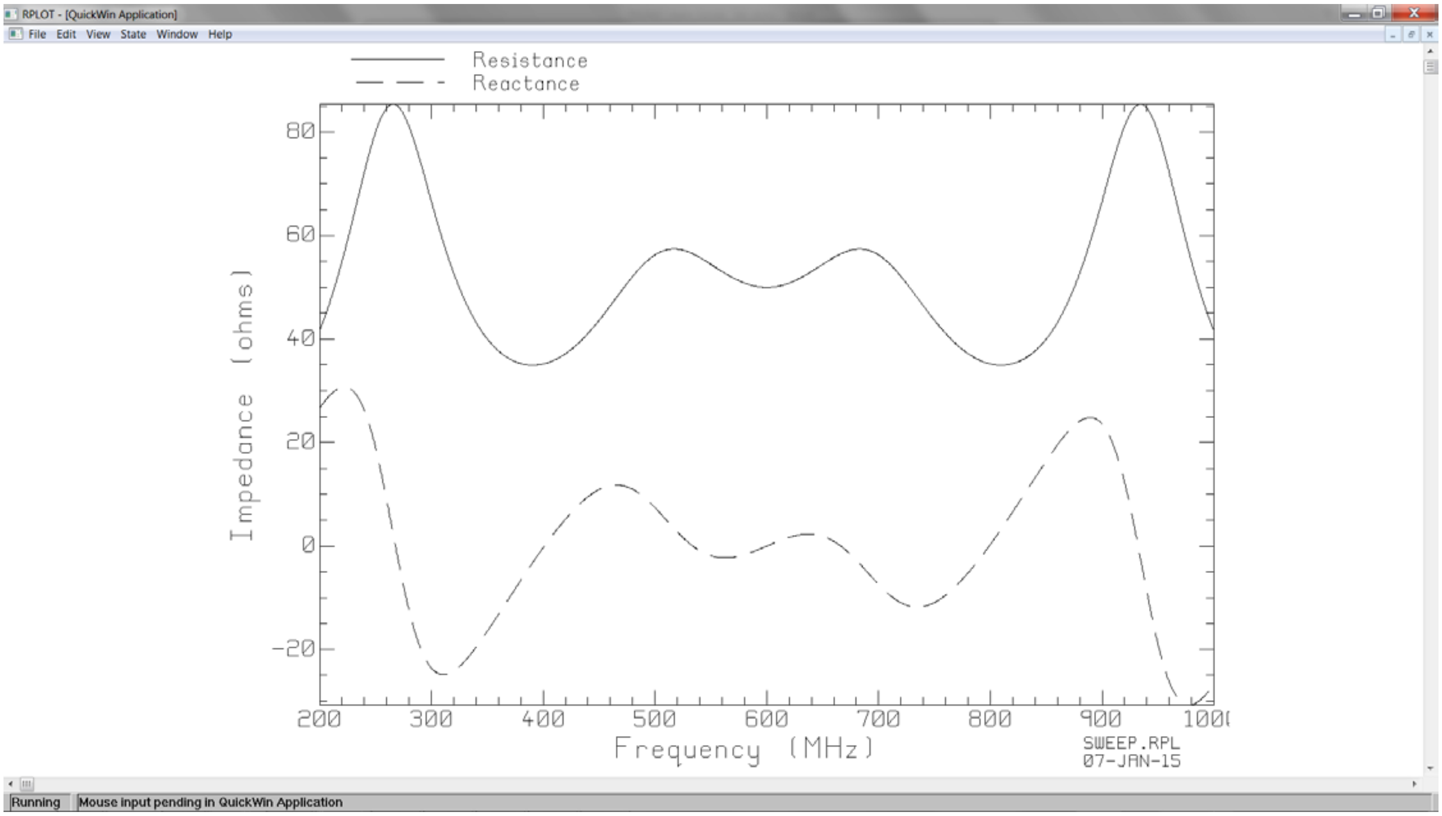
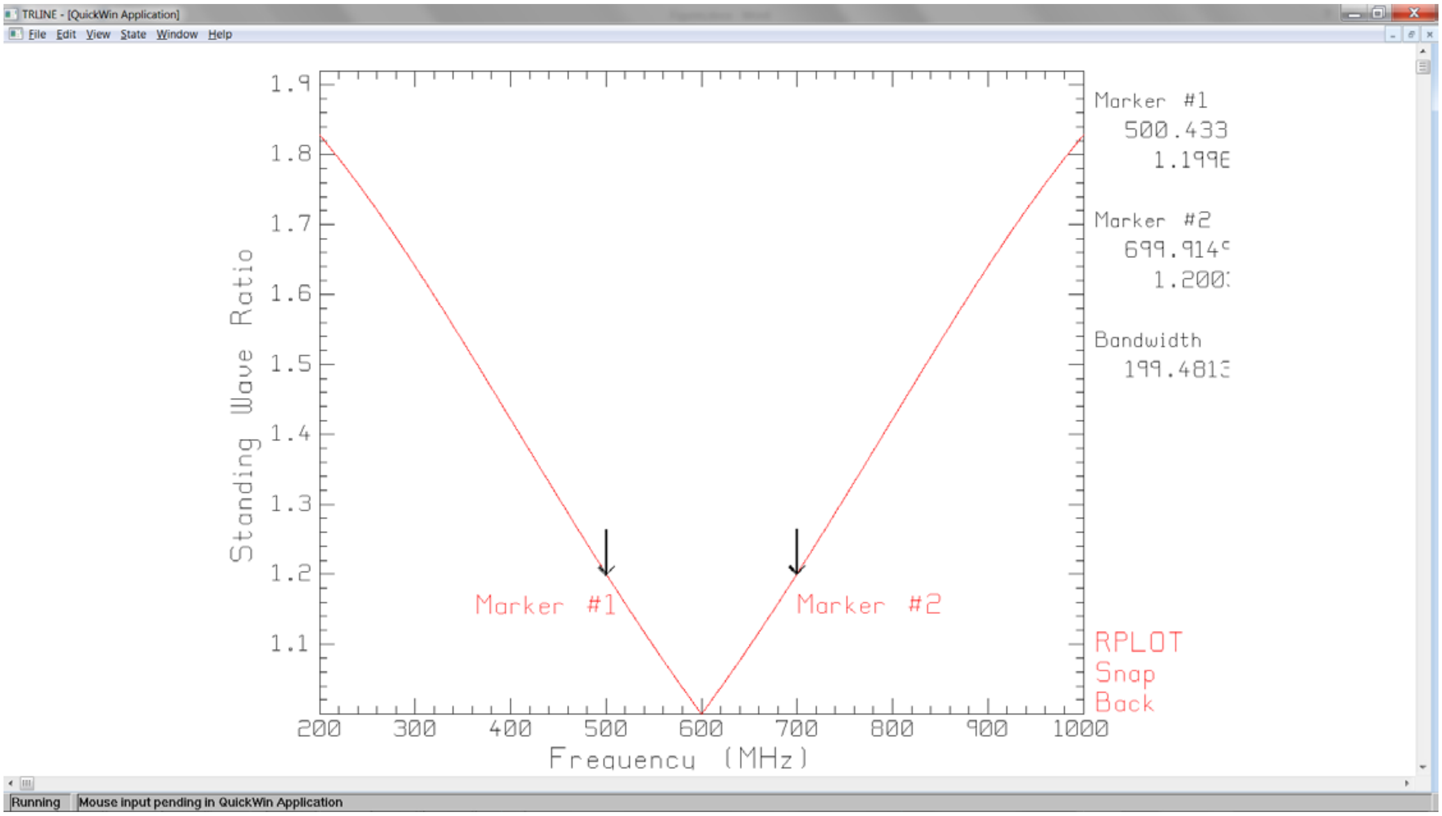


Fig. 2.29 The input impedance as a function of frequency.

In the sweep menu of Fig. 2.23, choose Input Impedance as the parameter and then click on “Calculate the frequency response”. The TRLINE program creates a file called sweep.rpl that contains the real and imaginary parts of the input impedance at the specified port, and then runs RPLOT to graph the input impedance as shown in Fig. 2.29. At 600 MHz, the graph shows that the input impedance is 50+j0 ohms, a perfect match. The execution of TRLINE is suspended while RPLOT is running. Terminate RPLOT to continue with TRLINE. Note that TRLINE can also graph input admittance as a function of frequency



```
Marker #1
  500.433
    1.199
Marker #2
  699.914
    1.200
Bandwidth
  199.481
```

Fig. 2.30 The VSWR as a function of frequency.

Choose the VSWR in the menu of Fig. 2.23 then clicking “Calculate the frequency response”. TRLINE graphs the VSWR at the specified port as shown in Fig. 2.30. The markers can be used to determine the bandwidth for a given VSWR value, such as 1.2. The VSWR is unity at the design frequency of 600 MHz but rises rapidly as we move away from the design frequency.

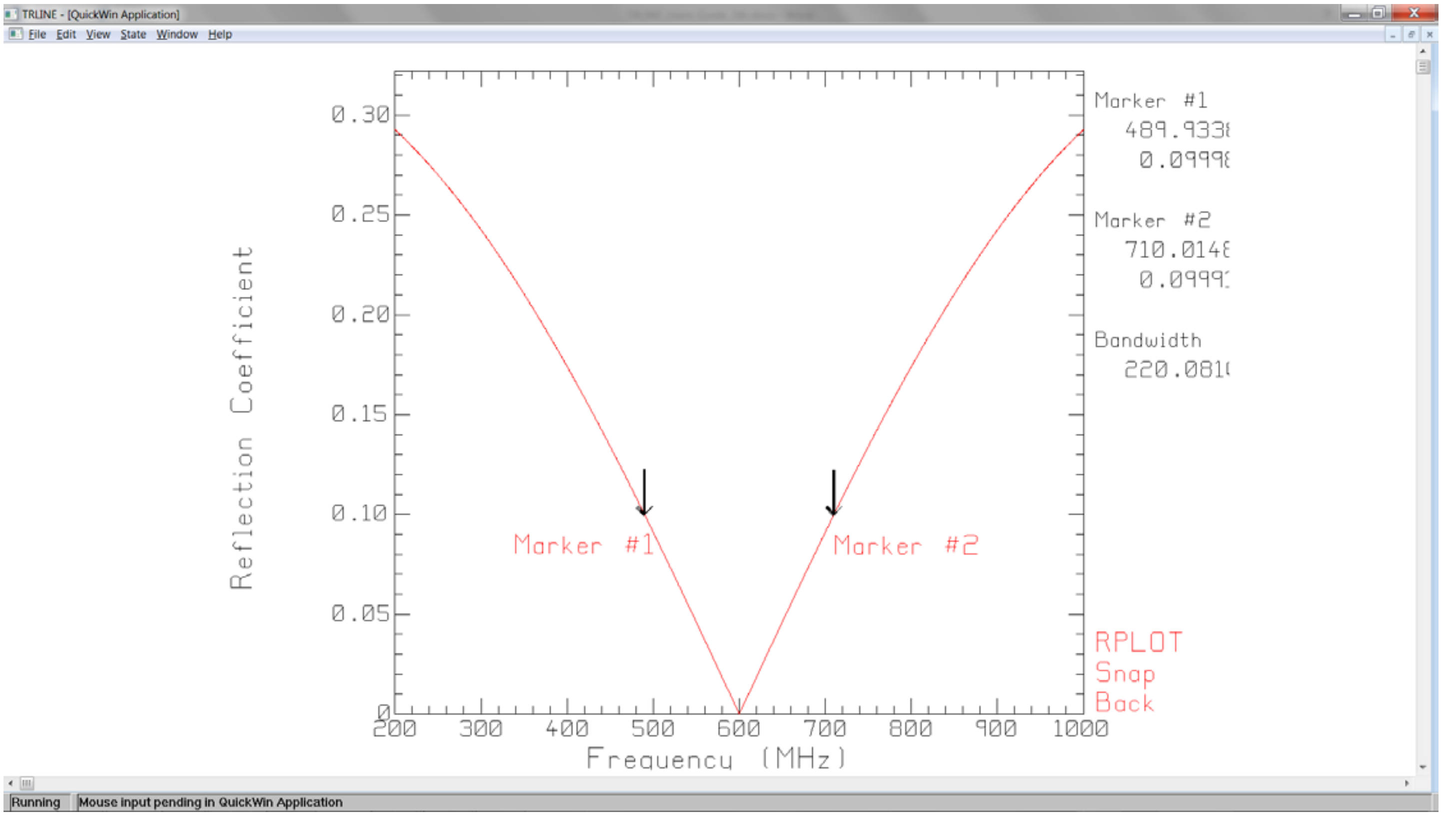
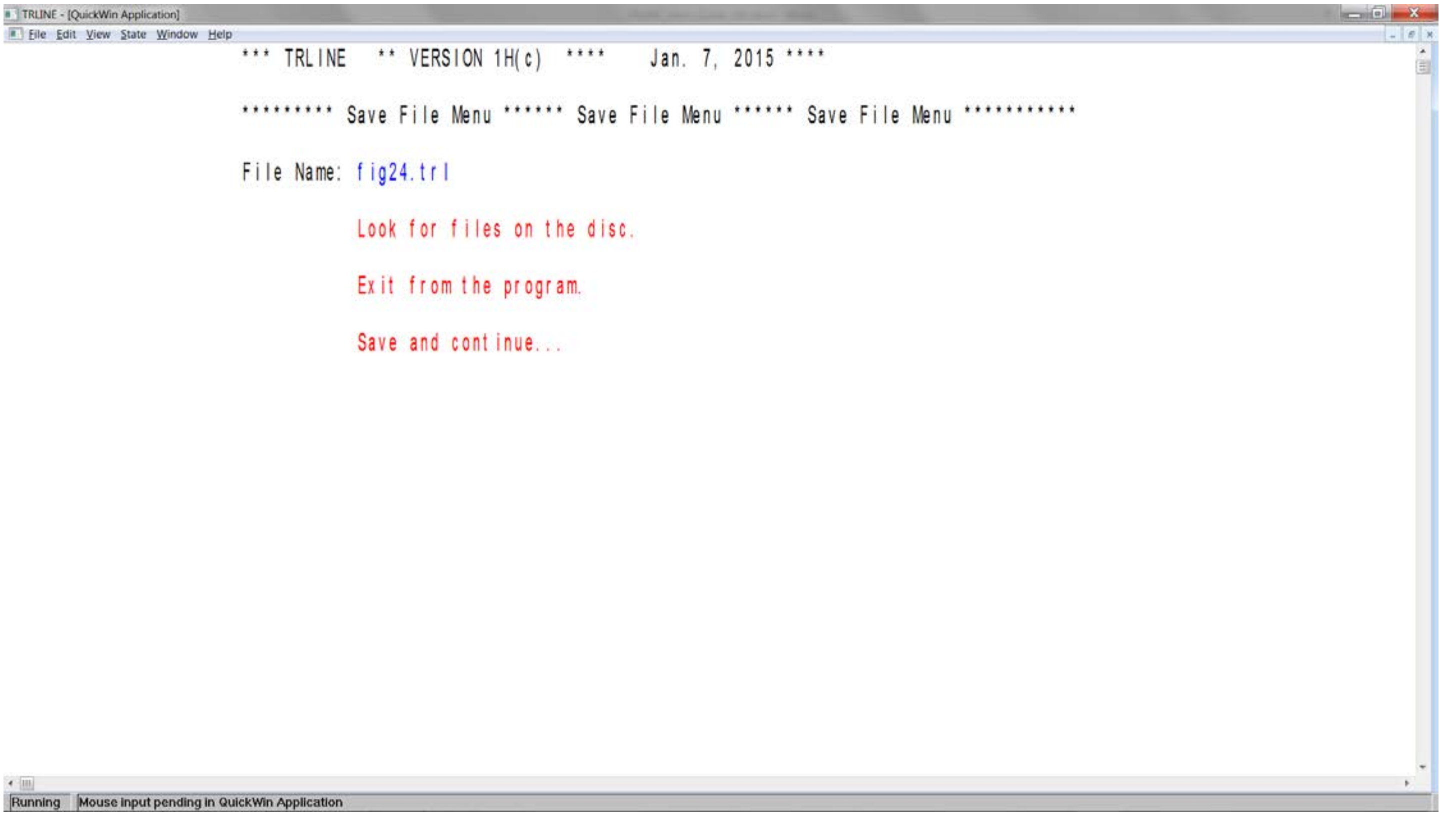


Fig. 2.31 The reflection coefficient as a function of frequency.

Choose “reflection coefficient” in the frequency response menu of Fig. 2.23 and then clicking “Calculate…” to get the reflection coefficient magnitude as a function of frequency as in Fig. 2.31. Here the markers have been “snapped” to show the bandwidth for a reflection coefficient of less than 0.1; round off error in the program finds the reflection coefficient as 0.0999, close to 0.1.

The TRLINE program can also calculate transmission loss and this feature will be demonstrated in conjunction with the Chebyshev filter, below.



```
*** TRLINE   ** VERSION 1H(c)  ****    Jan. 7, 2015 ****

********* Save File Menu ****** Save File Menu ****** Save File Menu ***********

File Name: fig24.trl

           Look for files on the disc.

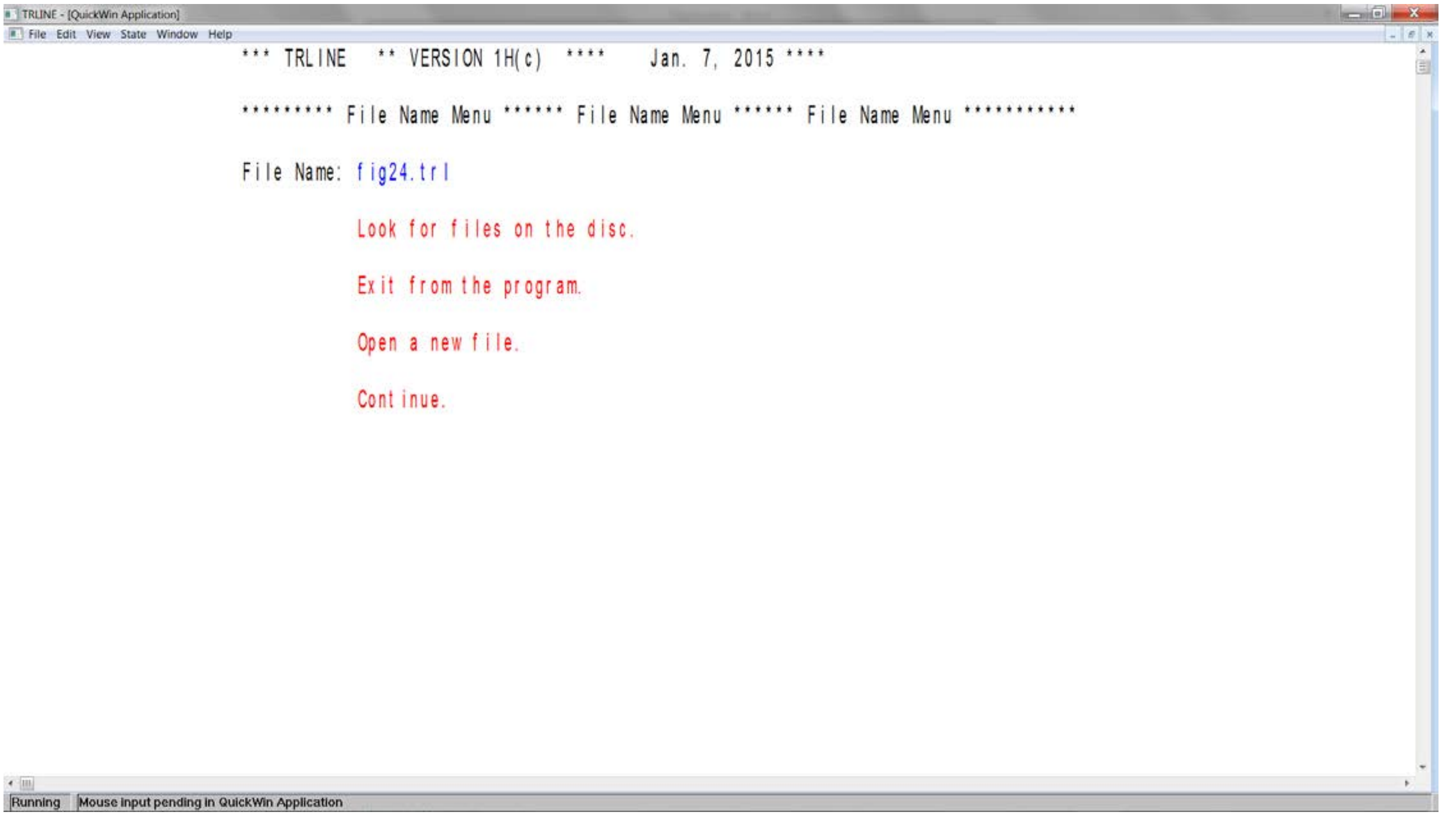
           Exit from the program.

           Save and continue...
```

Fig. 2.32 In the main menu of Fig. 2, click “Save the circuit” to get the “save file name” menu.

2.7.Saving the Circuit to a File

When all the parameters of a circuit have been set using the menu system, it is convenient to save the circuit to a data file, so that it can be recalled later, including all the parameter values. The main menu of Fig. 2.2 has a button labelled “Save the circuit to a file” which is used to create a data file with extension “trl”, containing all the information about a circuit. When TRLINE is re-started at a later time, the entry menu of Fig. 2.1 is shown, and you can click “read a saved circuit” to recall your circuit.



```
*** TRLINE   ** VERSION 1H(c)  ****    Jan. 7, 2015 ****

********* File Name Menu ****** File Name Menu ****** File Name Menu ***********

File Name: fig24.trl

               Look for files on the disc.

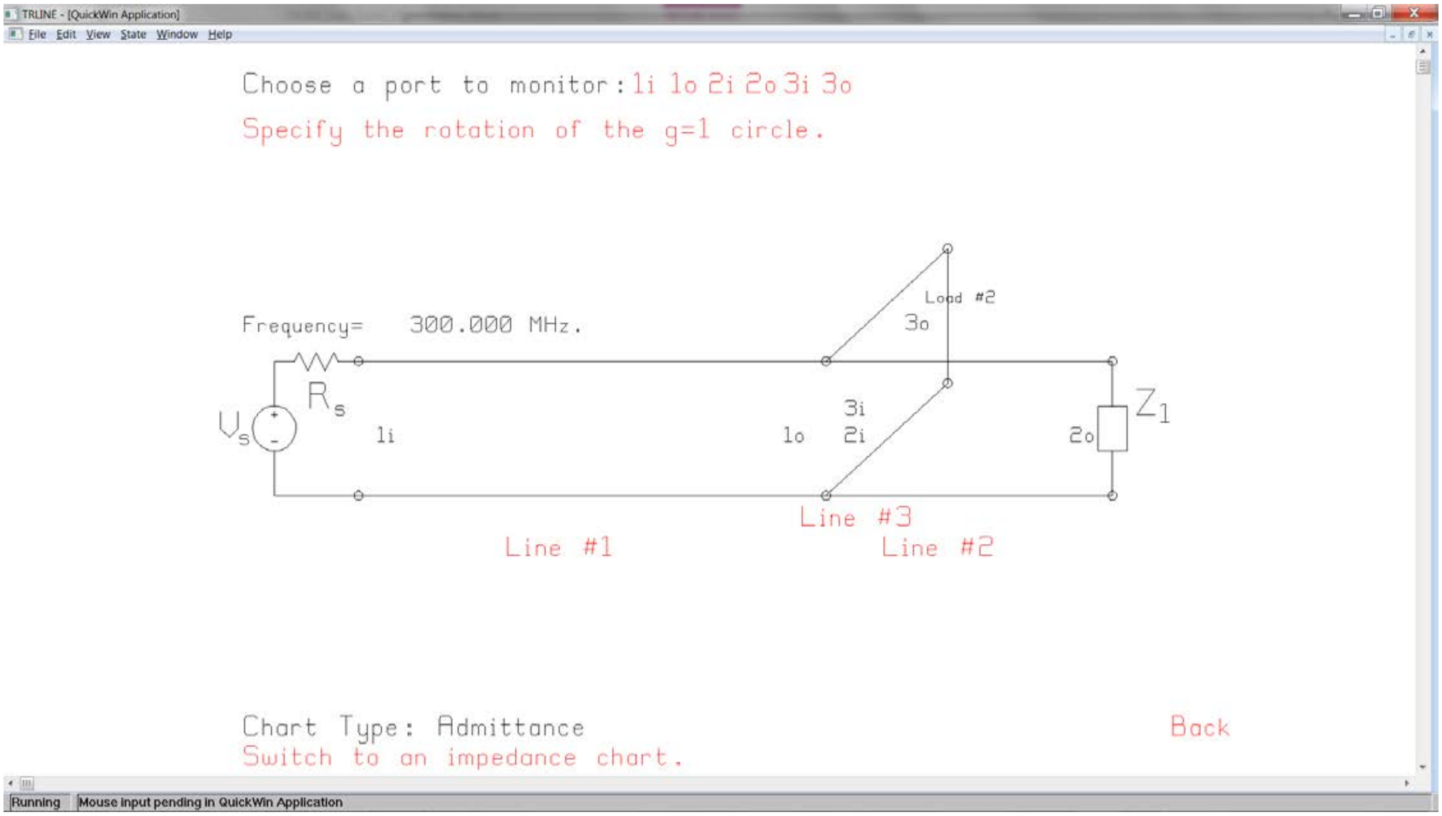
               Exit from the program.

               Open a new file.

               Continue.
```

Fig. 2.33 You can specify the name of the trl file for a saved circuit when you start the program.

The menu of Fig. 2.33 lets you enter the file name for your saved circuit, then reads the circuit and shows the main menu. You can re-start your work from where you left it when you saved the circuit.



```
Choose a port to monitor: 1i 1o 2i 2o 3i 3o
Specify the rotation of the g=1 circle.

Chart Type: Admittance
Switch to an impedance chart.
```

Fig. 3.1 The Smith Chart Calculations menu.

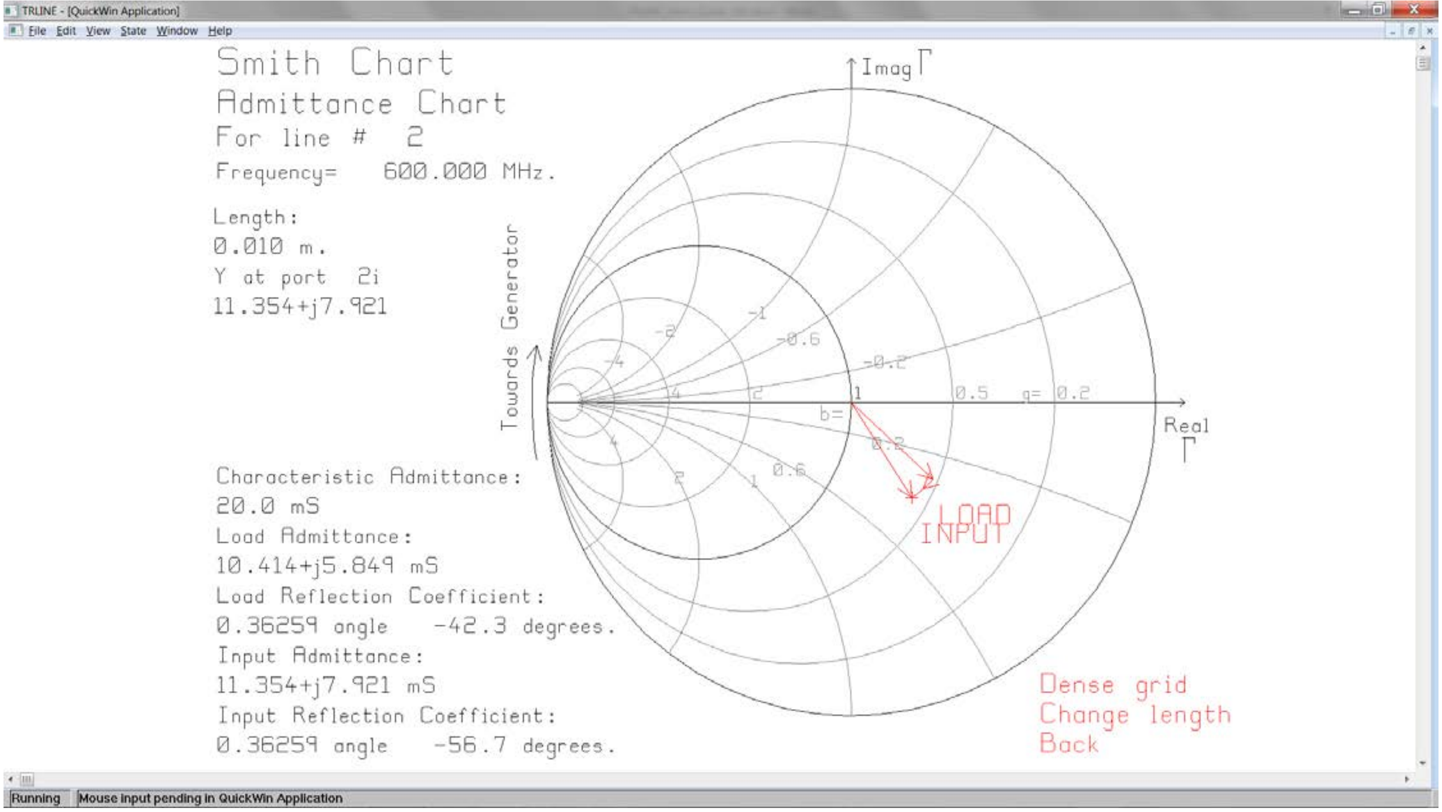
3. Interactive Calculations with TRLINE

The main menu in Fig. 2.2 provides a Smith Chart Calculations button. This invokes the menu of Fig. 3.1. You can use this menu to design single and double stub matching circuits interactively. Each transmission line has an input port and an output port. Thus for transmission line #1, the input port is 1i and the output port is 1o. TRLINE monitors the impedance at a specified port by drawing a “+” for the impedance on the Smith Chart, as shown in the following

3.1. Single Stub Matching

Fig. 3.1 shows the single stub matching circuit. Line #1 is the input line and is 20 cm long. In this example, the load is Z_1=73-j41 ohms. All three lines have characteristic impedance 50 ohms and speed of travel 300 meters per microsecond. The branch, which is line #3, is the tuning stub, and the problem is to choose the length of line #2 and the length of the stub to obtain a perfect impedance match to a 50-ohm line at 600 MHz.

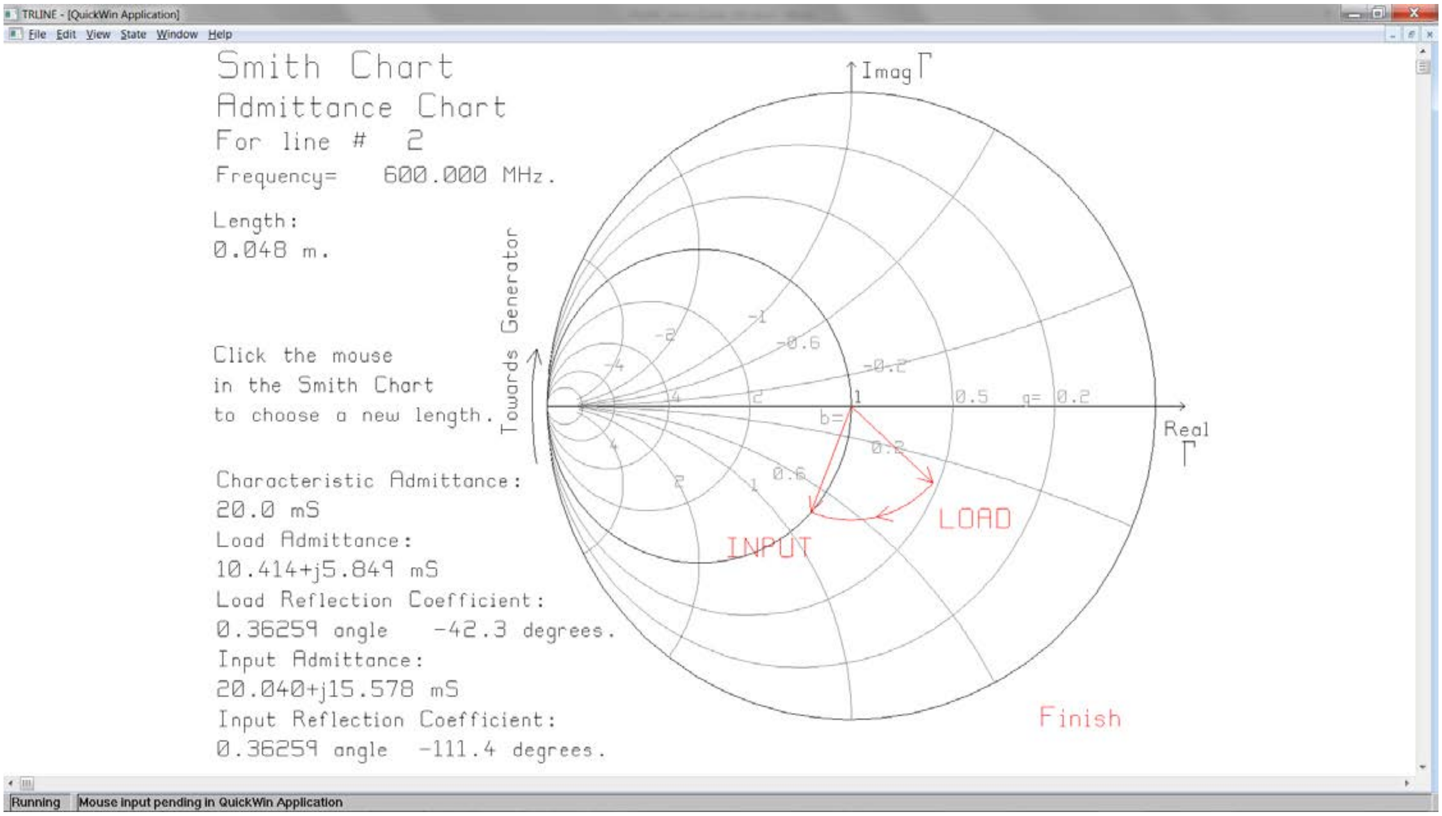
Start with a short line length and a short stub length. Set the length of lines #2 and #3 in Fig. 3.1 to 1 cm. The first step in designing the single stub tuning circuit is to set the length of line #2 so that the input admittance to line #2 lies on the g=1 circle on the admittance chart. Change the settings so that TRLINE displays admittance. Then click on “Line #2” in Fig. 3.1 to see the Smith Chart for line #2, which is shown in Fig. 3.2.



Smith Chart
Admittance Chart
For line # 2
Frequency= 600.000 MHz.
Length:
0.010 m.
Y at port 2i
11.354+j7.921
Characteristic Admittance:
20.0 mS
Load Admittance:
10.414+j5.849 mS
Load Reflection Coefficient:
0.36259 angle -42.3 degrees.
Input Admittance:
11.354+j7.921 mS
Input Reflection Coefficient:
0.36259 angle -56.7 degrees.

Fig. 3.2 The starting point for line #2.

Fig. 3.2 shows the Smith Chart for line #2. This shows the LOAD admittance and the INPUT admittance, close together on the Smith Chart because of the short length selected for line #2. Click on Change length and click the mouse inside the Smith Chart circle to adjust the length of line #2 until the INPUT admittance lies on the g=1 circle.



Smith Chart

Admittance Chart

For line # 2

Frequency= 600.000 MHz.

Length:
0.048 m.

Click the mouse in the Smith Chart to choose a new length.

Characteristic Admittance:
20.0 mS

Load Admittance:
10.414+j5.849 mS

Load Reflection Coefficient:
0.36259 angle -42.3 degrees.

Input Admittance:
20.040+j15.578 mS

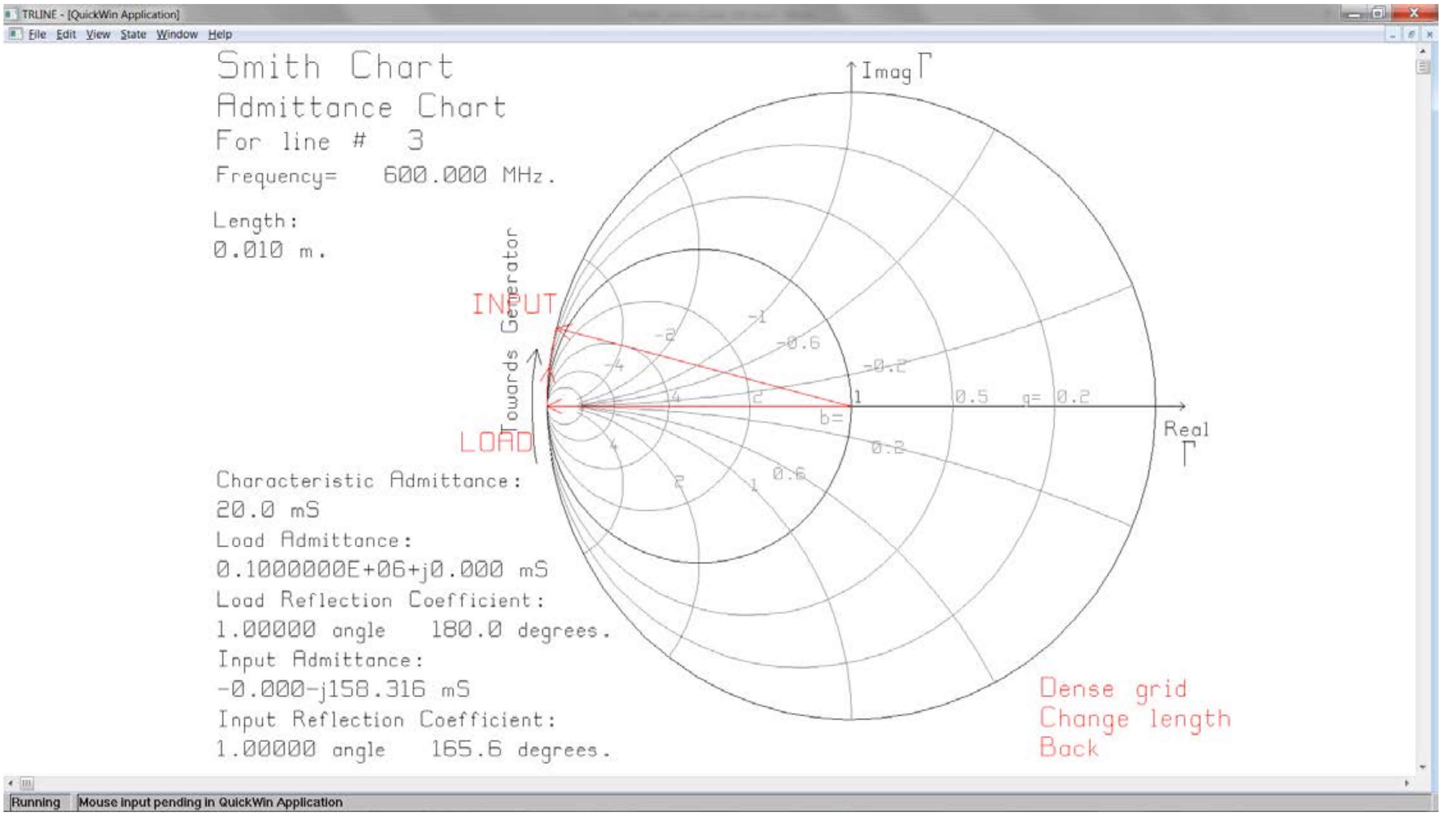
Input Reflection Coefficient:
0.36259 angle -111.4 degrees.

Running

Mouse input pending in QuickWin Application

Fig. 3.3 Use the “Change length” function to adjust the length of line #2 so that the input admittance lies on the g=1 circle.

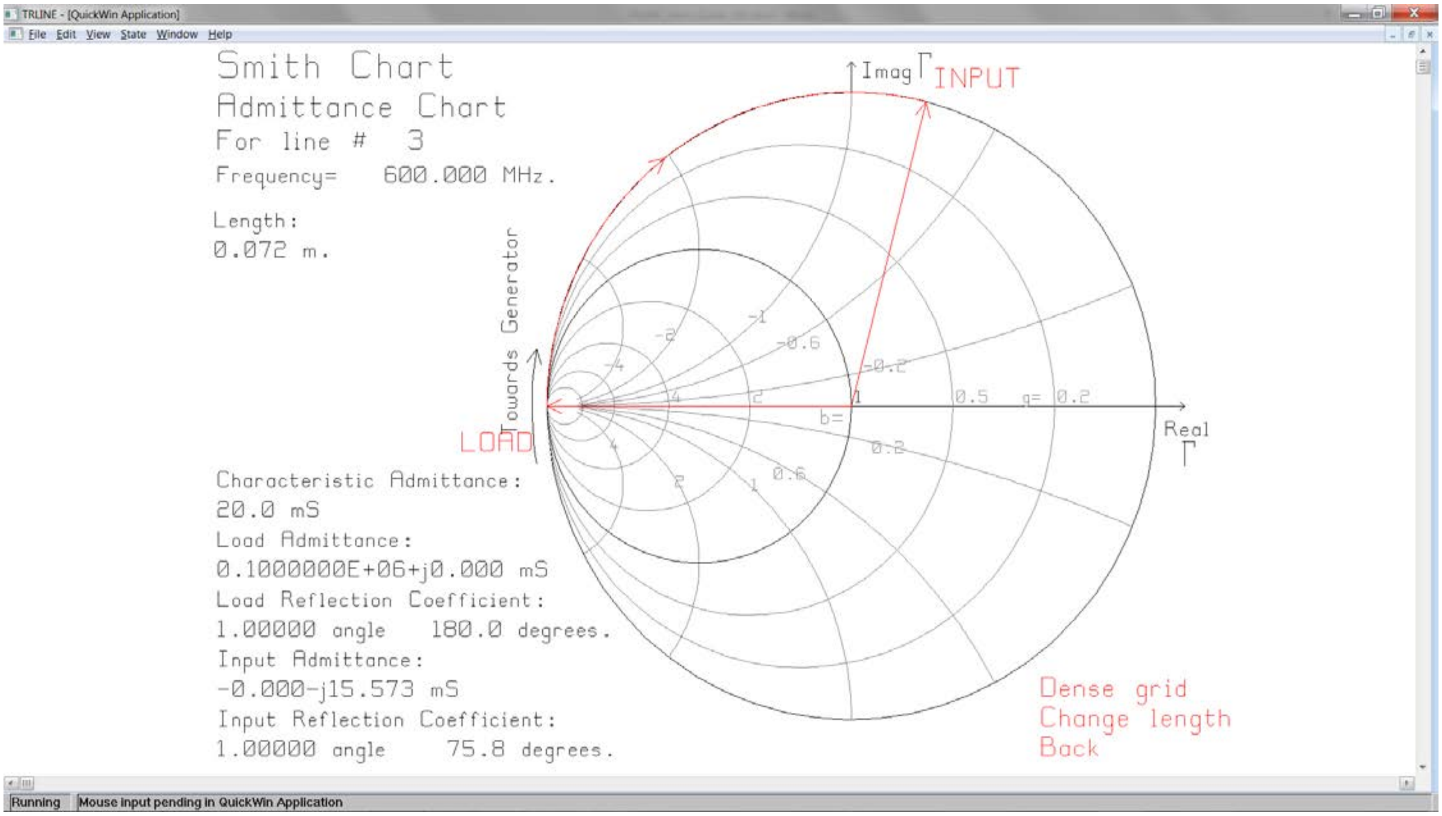
Fig. 3.3 shows the Smith Chart for line #2, after the length of line #2 has been adjusted. The input admittance is 20.040+j15.578 mS, not quite on the g=1 circle, which would require g=20 mS. Choosing the length with the mouse does not provide fine enough control to obtain a real part of exactly 20 mS. The length could be adjusted manually using the transmission line properties buttons in the main menu, to obtain a real part of exactly 20 mS. Also note that there is a second solution. A longer transmission line could put the input admittance on the g=1 circle in the top half of the Smith Chart.



```
Smith Chart
Admittance Chart
For line #  3
Frequency=   600.000 MHz.
Length:
0.010 m.
Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
-0.000-j158.316 mS
Input Reflection Coefficient:
1.00000 angle   165.6 degrees.
```

Fig. 3.4 The Smith Chart for line #3 with a stub length of 1 cm.

The next step is to adjust the stub length to cancel the susceptance of +15.578 mS, so we want the stub input admittance to be 0-j15.578 mS. Draw the Smith Chart for the stub, Line #3. Fig. 3.4 shows the Smith Chart with a 1 cm line length. The Load admittance is infinity, corresponding to a short circuit. The input admittance of the 1 cm line is –j158.316 mS, much larger than the desired value of –j15.578 mS. Click on the Change length button.



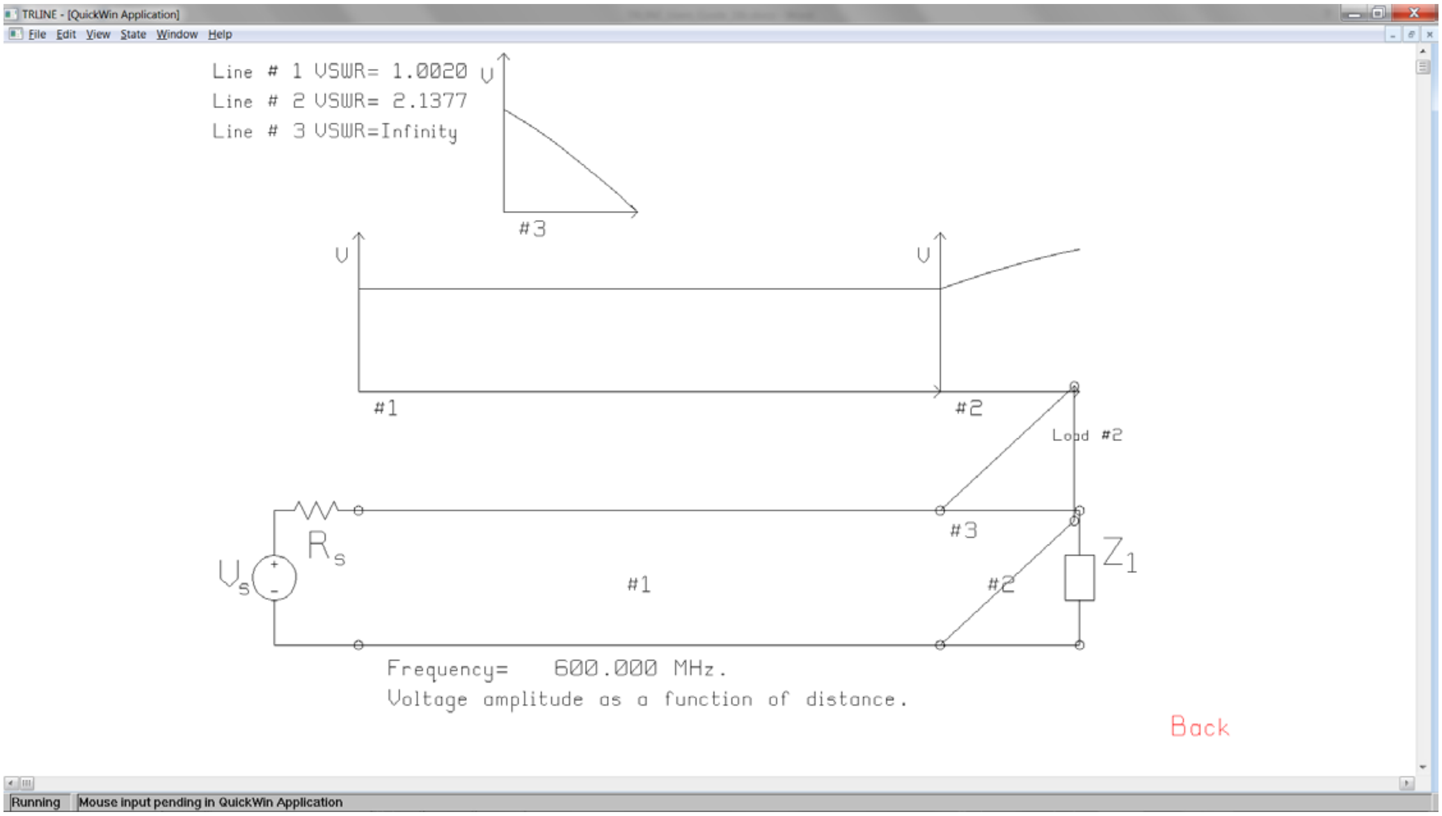
```
Smith Chart
Admittance Chart
For line #   3
Frequency=    600.000 MHz.

Length:
0.072 m.

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
-0.000-j15.573 mS
Input Reflection Coefficient:
1.00000 angle    75.8 degrees.
```

Fig. 3.5 Adjust the length of line #3 for an input admittance close to –j15.578 mS.

Fig. 3.5 shows the Smith Chart for line #3 after the Change length function has been used to adjust the length to 0.072 m, for an input admittance of -j15.573 mS, close to the desired value of –j15.578 mS.

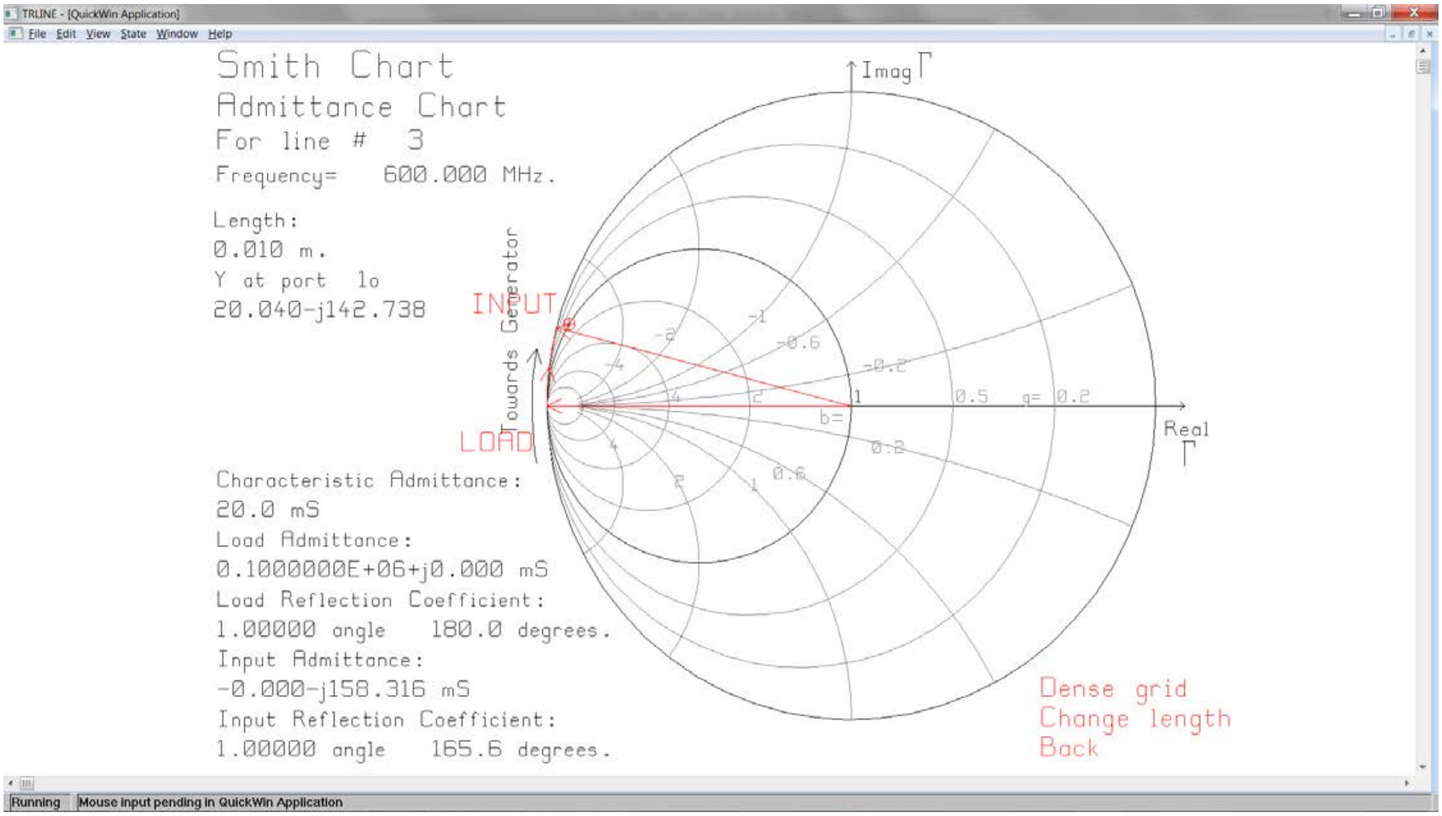


```
Line # 1 VSWR= 1.0020
Line # 2 VSWR= 2.1377
Line # 3 VSWR=Infinity

Frequency=    600.000 MHz.
Voltage amplitude as a function of distance.
```

Fig. 3.6 Verify that the VSWR on the input line is close to unity.

To verify that we have a match, go back to the main menu, and select “Plot V(z)” and then “Plot the voltage amplitude on all lines” to obtain Fig. 3.6. Line #1 shows that it is well matched, with an almost-constant voltage amplitude along the line. The VSWR is reported as 1.0020. Making fine adjustments to the line length and the stub length can obtain a perfect match of 1.0000.



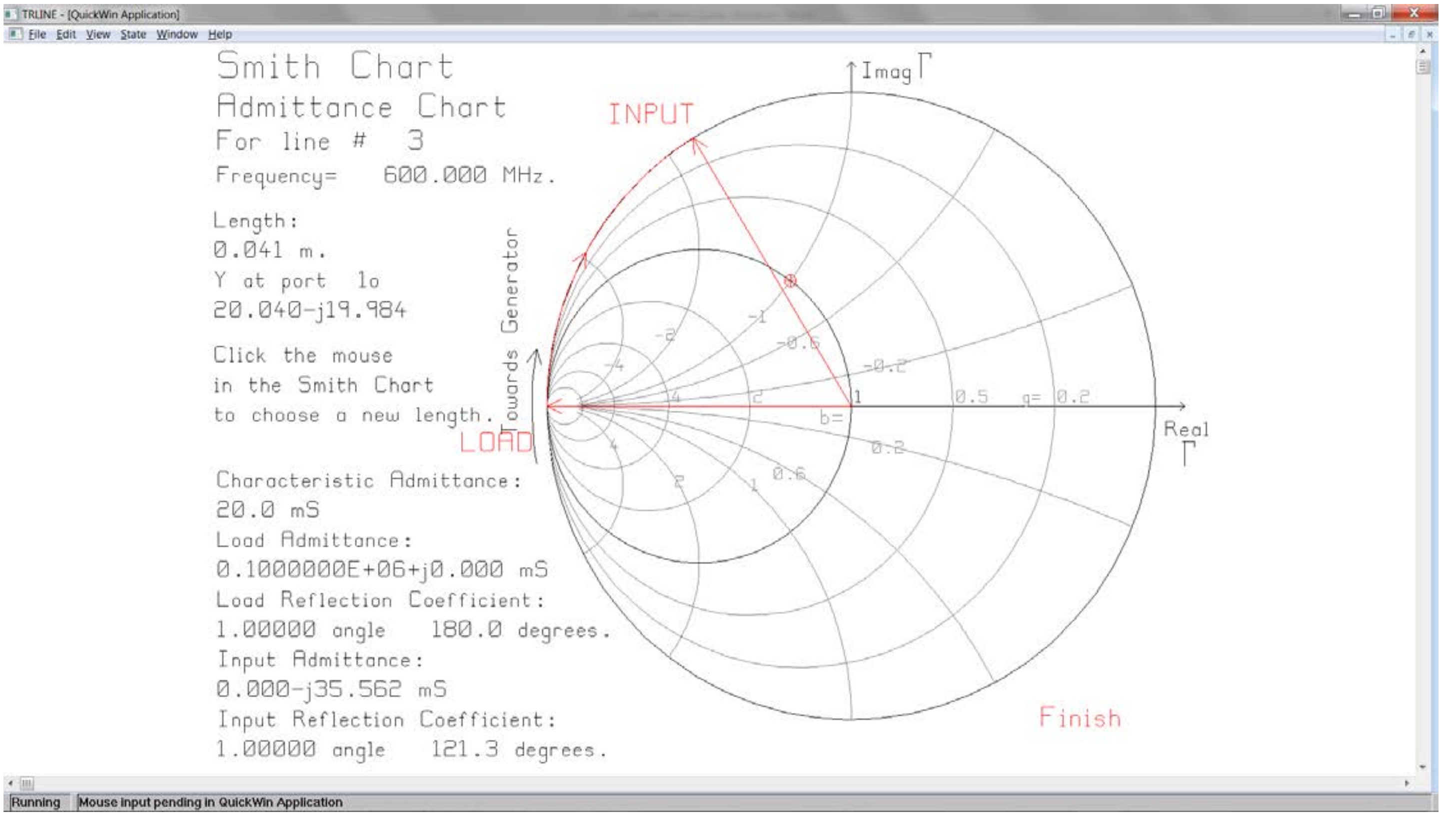
```
Smith Chart
Admittance Chart
For line #  3
Frequency=   600.000 MHz.

Length:
0.010 m.
Y at port  1o
20.040-j142.738

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
-0.000-j158.316 mS
Input Reflection Coefficient:
1.00000 angle   165.6 degrees.
```

Fig. 3.7 Monitor the impedance at the output of line #1 to adjust the stub length.

Another way to adjust the length of the tuning stub is to monitor the impedance at the output of line #1. In the Smith Chart Calculations menu of Fig. 3.1 click on port “1o” as the port to monitor. With the length of line #2 set to 0.048 m as in Fig. 3.3, draw the Smith Chart for Line #3, the tuning stub, as in Fig. 3.7. The admittance at port 1o appears as a small cross enclosed in a circle on the g=1 circle, near the arrowhead of the INPUT arrow in the figure. Use the Change length function to make the stub longer.



```
Smith Chart
Admittance Chart
For line #   3
Frequency=   600.000 MHz.

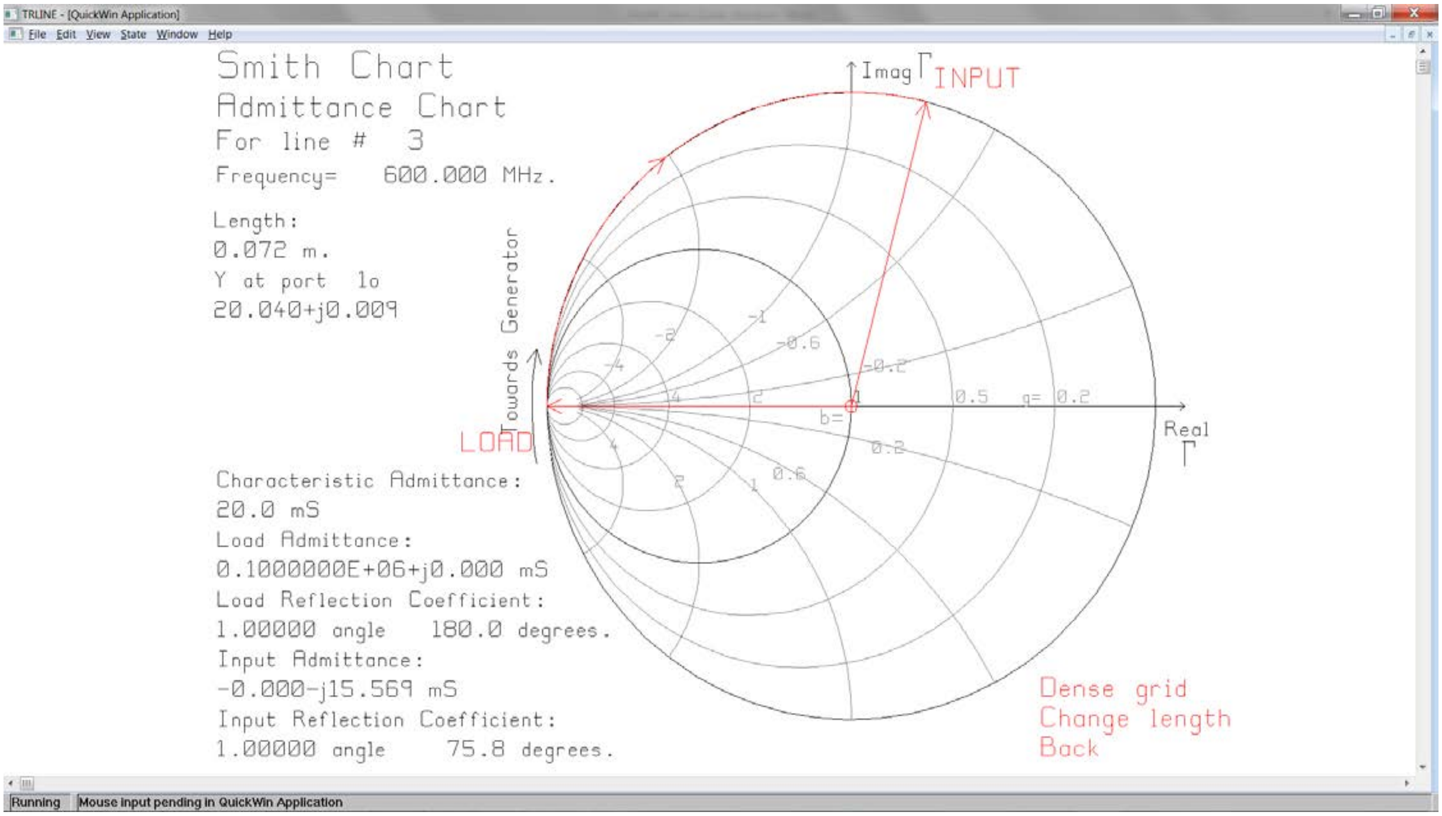
Length:
0.041 m.
Y at port  1o
20.040-j19.984

Click the mouse
in the Smith Chart
to choose a new length.

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
0.000-j35.562 mS
Input Reflection Coefficient:
1.00000 angle   121.3 degrees.
```

Fig. 3.8 The Smith Chart for Line #3 with a longer stub length.

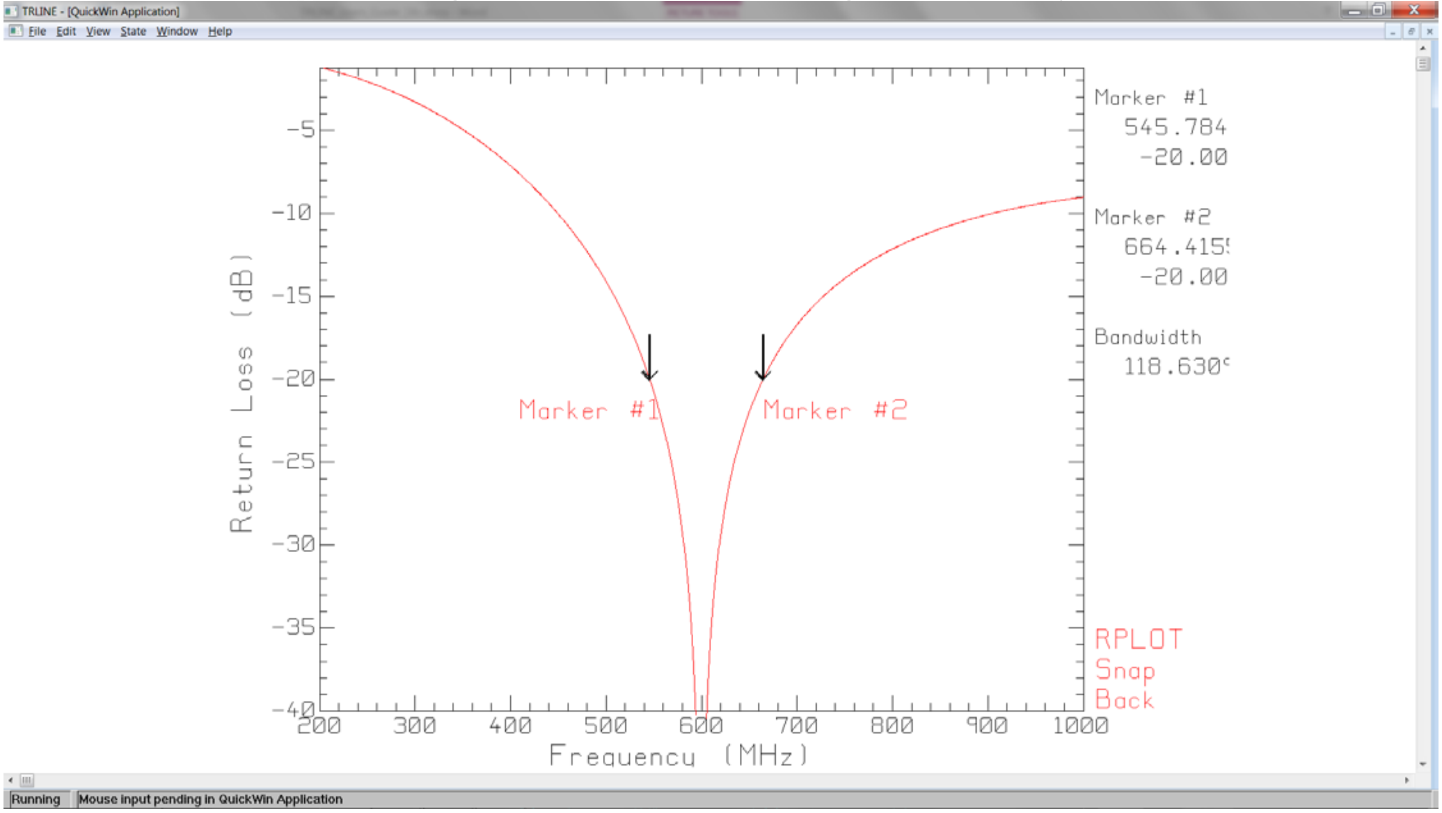
As the length of the stub is increased, the admittance at port 1o moves around the g=1 circle. For example, in Fig. 3.8 we see the Smith Chart for a stub length of 0.041 m. The input admittance is on the g=1 circle, at approximately 1-j1 mS. Making the stub longer move input admittance around the g=1 circle towards the origin.



```
Smith Chart
Admittance Chart
For line #  3
Frequency=   600.000 MHz.
Length:
0.072 m.
Y at port  1o
20.040+j0.009
Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
-0.000-j15.569 mS
Input Reflection Coefficient:
1.00000 angle    75.8 degrees.
```

Fig. 3.9 Adjust the length of line #3 to move the admittance at port #1o around the g=1 circle to the origin.

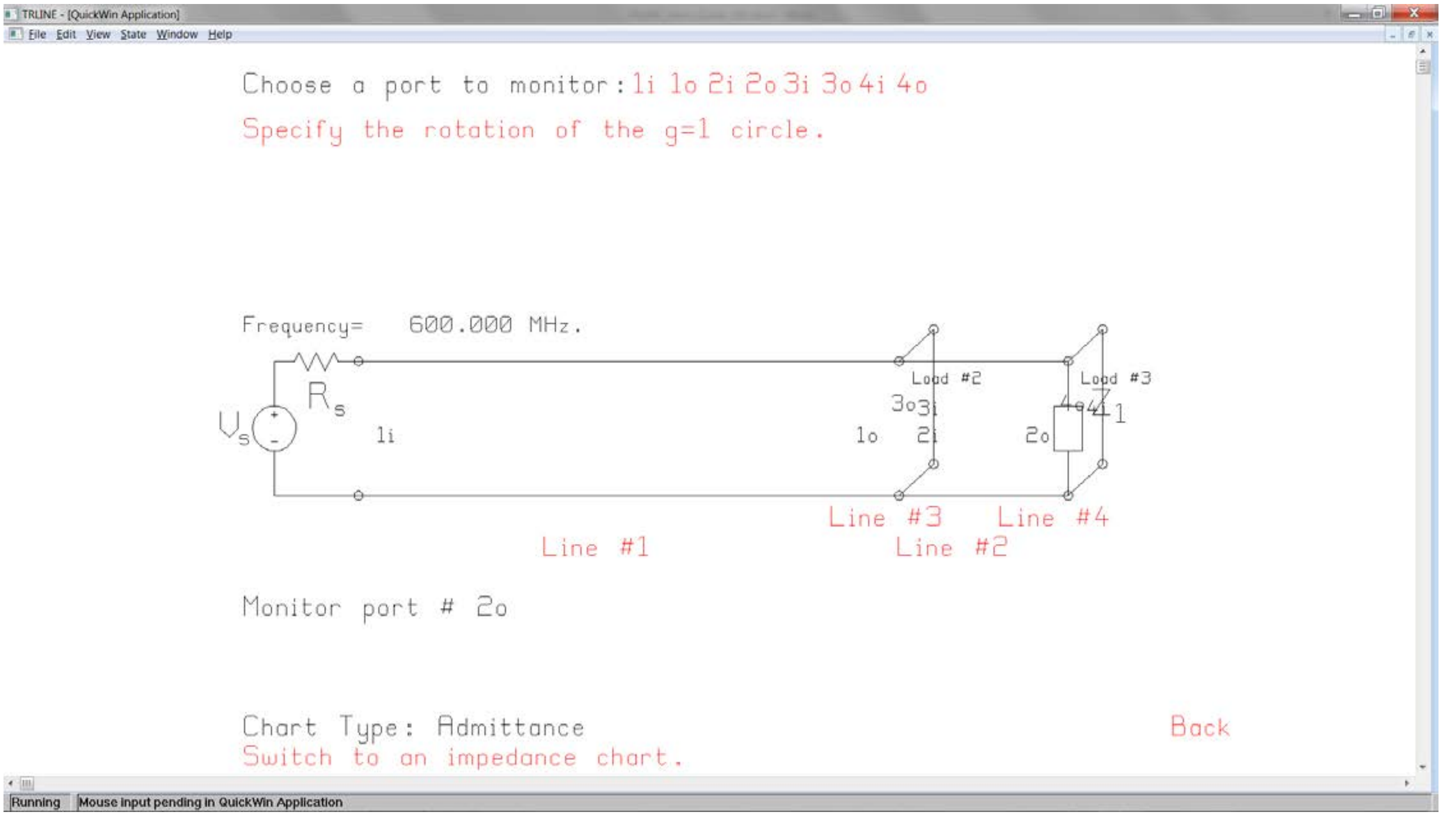
Fig. 3.9 shows that the length of line #3 can be adjusted to put the admittance at port #1o very close to the origin. With a line length of 0.072 m, the admittance is 20.040+j0.009 mS, close to a perfect match. The admittance at port 1o appears in Fig. 40 as a small cross at the origin surrounded by a small circle.



```
Marker #1
 545.784
  -20.00
Marker #2
 664.415
  -20.00
Bandwidth
 118.630
```

Fig. 3.10 The bandwidth of the match.

To assess the bandwidth, select “Plot a parameter as a function of frequency from the main menu, and set the frequency range to 200 to 1000 MHz. Display the return loss at port #1, and snap the markers to -20 dB, as shown in Fig. 3.10. The bandwidth is 118.63 MHz for a return loss of 20 dB or better.



Choose a port to monitor: 1i 1o 2i 2o 3i 3o 4i 4o

Specify the rotation of the g=1 circle.

Frequency= 600.000 MHz.

Monitor port # 2o

Chart Type: Admittance

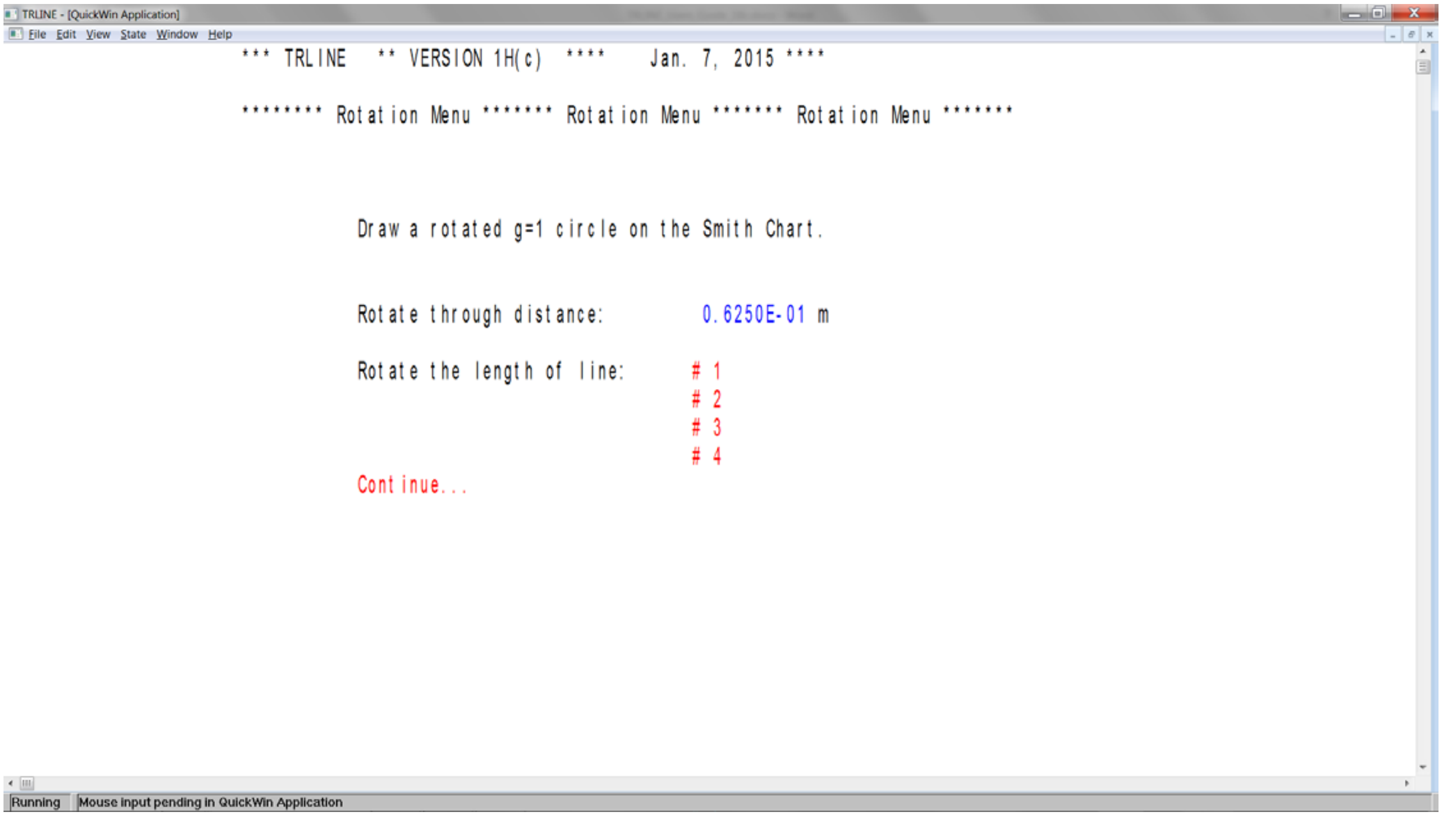
Switch to an impedance chart.

Mouse input pending in QuickWin Application

Fig 3.11 The double stub matching circuit.

3.2.Double Stub Matching

We can design a double-stub matching circuit interactively with TRLINE. The circuit is shown in Fig. 3.11. The lines have speed of travel 300 meters per microsecond, and characteristic impedance 50 ohms. The load is Z_1=73-j41 ohms and the frequency is 600 MHz. The input line length is 20 cm. The stubs are to be separated by 0.0625 m, or about 1/8 of the wavelength at 600 MHz, which is the length of line #2 in Fig. 3.11. Start by setting the stub lengths to be short, say 2 cm, as shown in Fig. 42. Choose the Smith Chart Calculations function in the main menu to get Fig. 3.11.



```
*** TRLINE   ** VERSION 1H(c)   ****    Jan. 7, 2015 ****

******** Rotation Menu ******* Rotation Menu ******* Rotation Menu *******



           Draw a rotated g=1 circle on the Smith Chart.

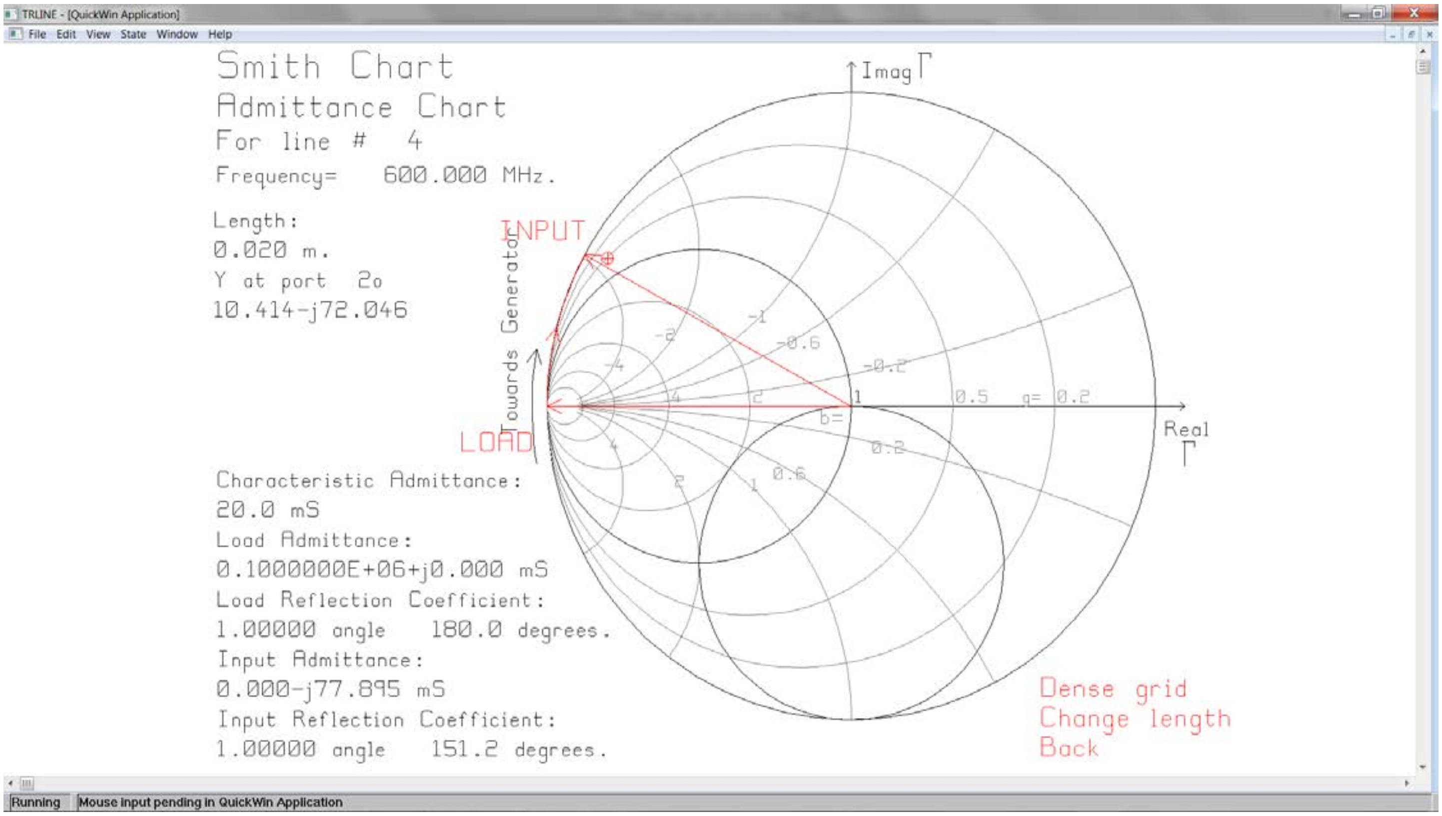

           Rotate through distance:          0.6250E-01 m

           Rotate the length of line:       # 1
                                            # 2
                                            # 3
                                            # 4
           Continue...
```

Running
Mouse input pending in QuickWin Application

Fig. 3.12 The rotation menu.

To design double-stub matching we need to rotate the g=1 circle by the length of line #2. Click on “Specify the rotation of the g=1 circle” in Fig. 3.11 to obtain the rotation menu of Fig. 3.12. Click on “#2” to set the rotation of the g=1 circle to the length of line #2, which is 0.0625 m, then click Continue. Then in the menu of Fig. 3.11, choose the port to monitor as the output port of line #2, which is port “2o”.



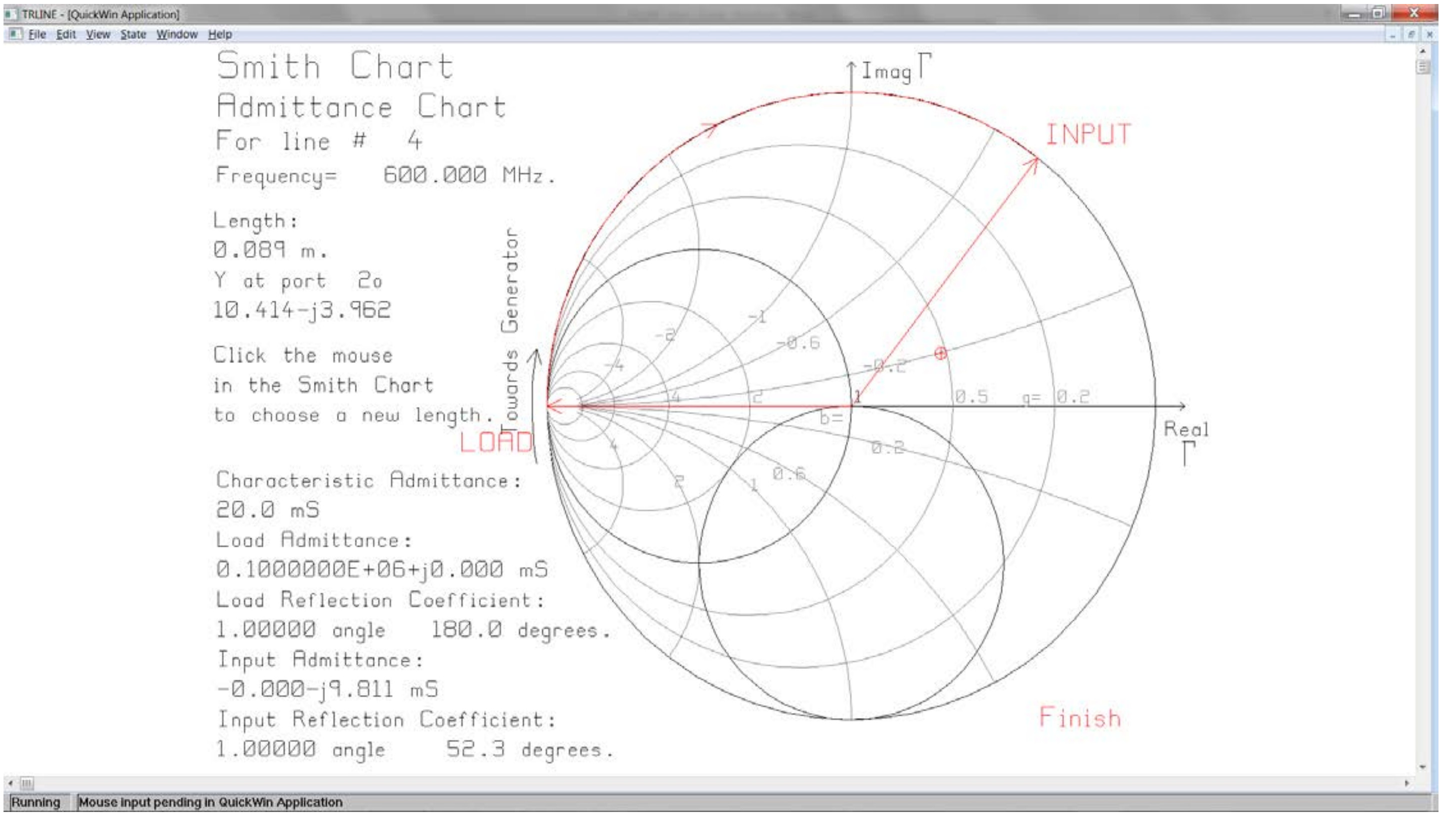
Smith Chart
Admittance Chart
For line # 4
Frequency= 600.000 MHz.

Length:
0.020 m.
Y at port 2o
10.414-j72.046

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle 180.0 degrees.
Input Admittance:
0.000-j77.895 mS
Input Reflection Coefficient:
1.00000 angle 151.2 degrees.

Fig. 3.13 The Smith Chart for line #4, which is the stub connected across the load.

In the Smith Chart Calculations menu, click Line #4 to display the Smith Chart for the tuning stub connected across the load. This is shown in Fig. 3.13. The admittance at port #2o is reported as 10.414-j72.046, and appears as a target symbol (a small cross enclosed in a circle) near the INPUT arrowhead in Fig. 3.13. We want to move the admittance at port #2 onto the rotated g=1 circle. Click Change length and make the tuning stub longer.



Smith Chart
Admittance Chart
For line # 4
Frequency= 600.000 MHz.

Length:
0.089 m.
Y at port 2o
10.414-j3.962

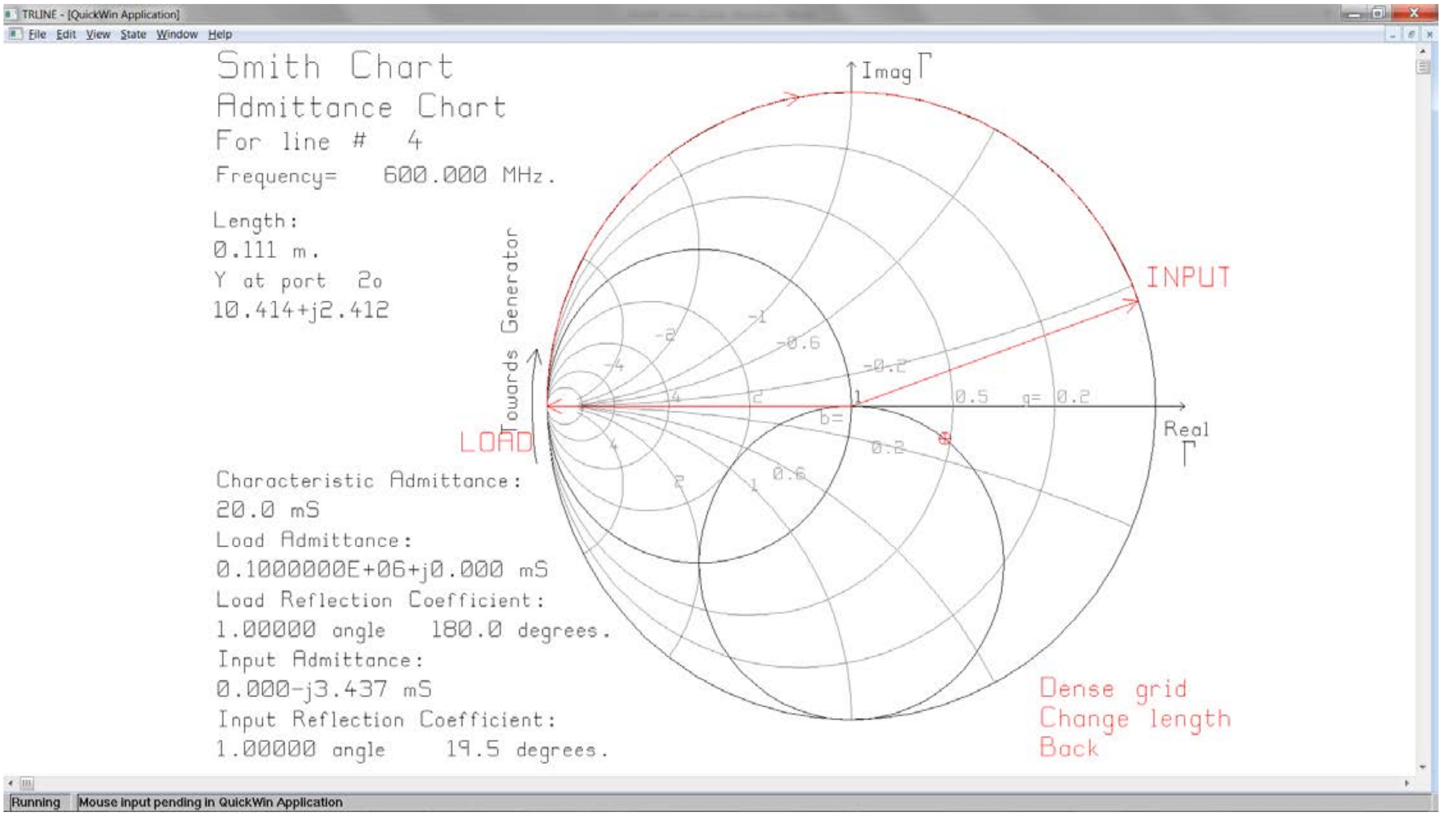
Click the mouse
in the Smith Chart
to choose a new length.

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle 180.0 degrees.
Input Admittance:
-0.000-j9.811 mS
Input Reflection Coefficient:
1.00000 angle 52.3 degrees.

Running | Mouse input pending in QuickWin Application

Fig. 3.14 Change the length of the tuning stub with the Change length function.

As we increase the length of the tuning stub, the admittance at port 2o moves around the Smith Chart towards the rotated g=1 circle. In Fig. 3.14 we see that for a stub length of 0.089 m the normalized admittance at port 2o appears as the target symbol at approximately 0.5-j0.2 mS. The stub is not long enough to put the admittance on the rotated g=1 circle, so make the stub longer.



Smith Chart
Admittance Chart
For line # 4
Frequency= 600.000 MHz.

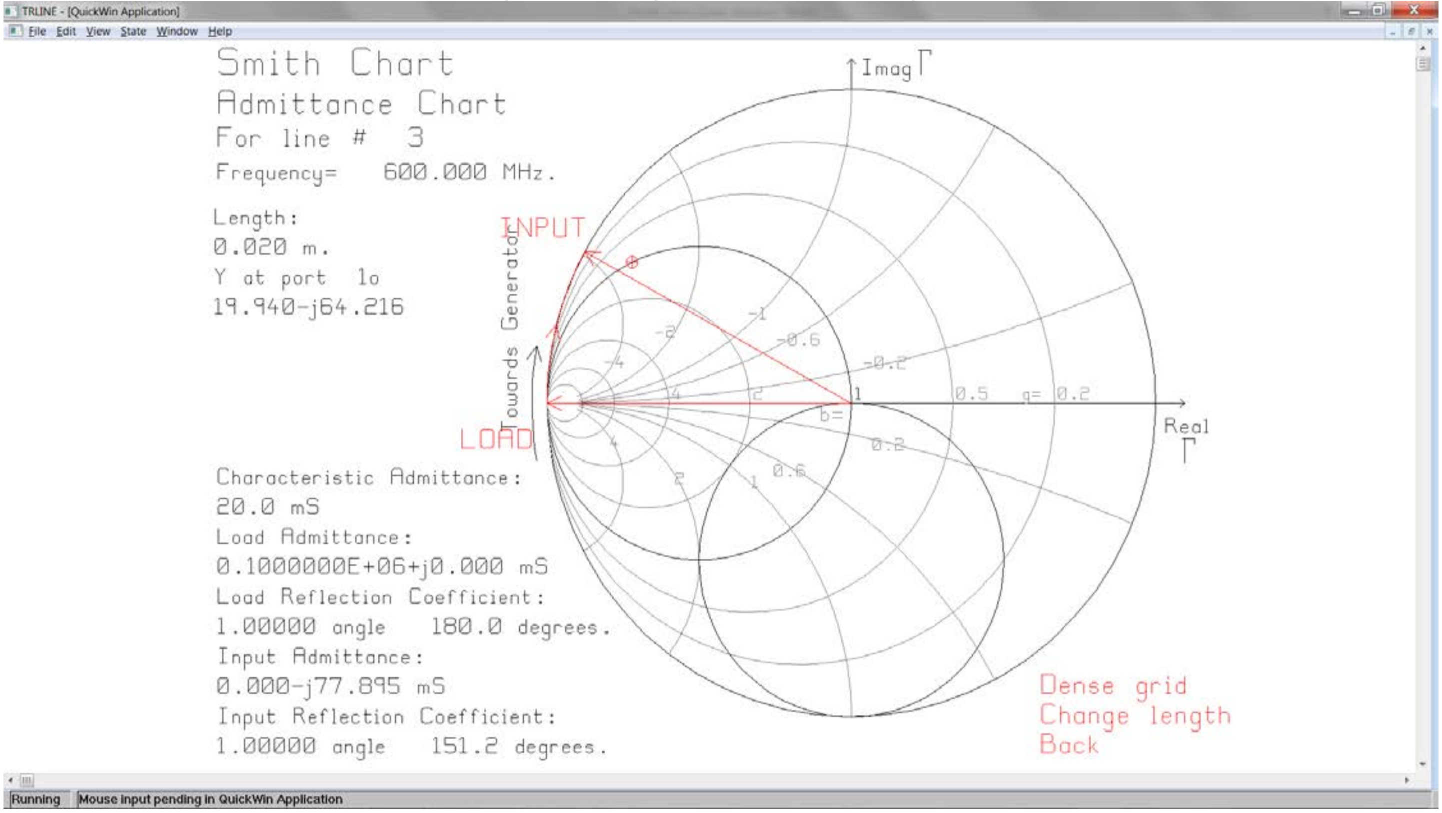
Length:
0.111 m.
Y at port 2o
10.414+j2.412

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle 180.0 degrees.
Input Admittance:
0.000-j3.437 mS
Input Reflection Coefficient:
1.00000 angle 19.5 degrees.

Dense grid
Change length
Back

Fig. 3.15 With the tuning stub length set of 0.111 m, the admittance at port #2o lies on the rotated g=1 circle.

Continue to increase the length of the tuning stub until the admittance at port #2o moves onto the rotated g=1 circle. Fig. 3.15 shows that with a stub length of 0.111 m, we are on the rotated g=1 circle. Note that there is a second solution for a longer stub length, not shown in Fig. 3.14.



Smith Chart
Admittance Chart
For line # 3
Frequency= 600.000 MHz.

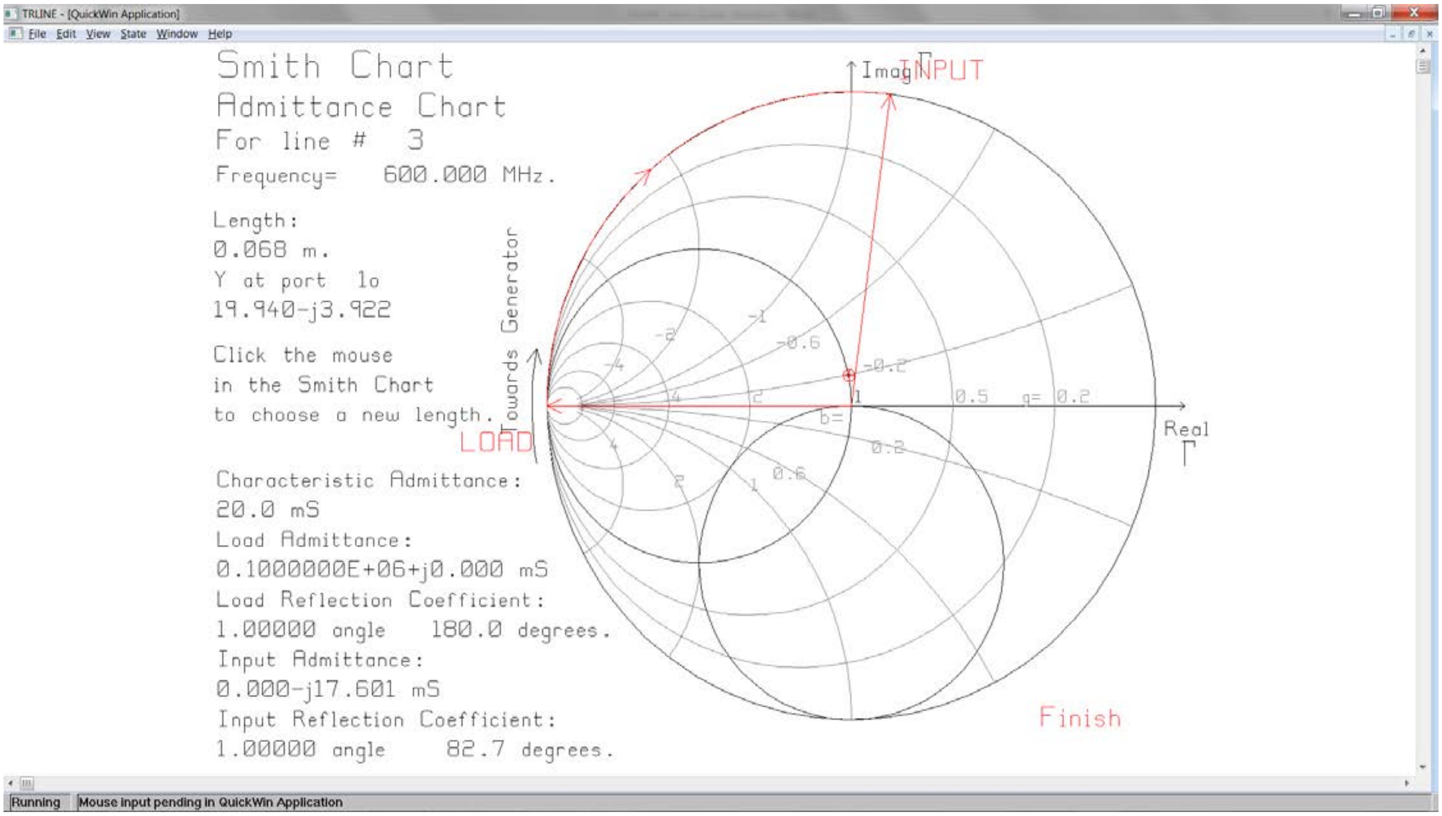
Length:
0.020 m.
Y at port 1o
19.940-j64.216

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle 180.0 degrees.
Input Admittance:
0.000-j77.895 mS
Input Reflection Coefficient:
1.00000 angle 151.2 degrees.

Dense grid
Change length
Back

Fig. 3.16 Monitor port #1o and draw the Smith Chart for the second tuning stub.

Change the port to the admittance seen at the output of line #1, port #1o. Then draw the Smith Chart for the second tuning stub, which is line #3. The admittance at port #1o lies on the g=1 circle at a normalized value of approximately 1-j3.5, shown as a cross enclosed in a circle in Fig. 3.16. Increase the length of line #3 to move the admittance at port #1o around the g=1 circle to the center of the Smith Chart.



Smith Chart
Admittance Chart
For line # 3
Frequency= 600.000 MHz.

Length:
0.068 m.
Y at port 1o
19.940-j3.922

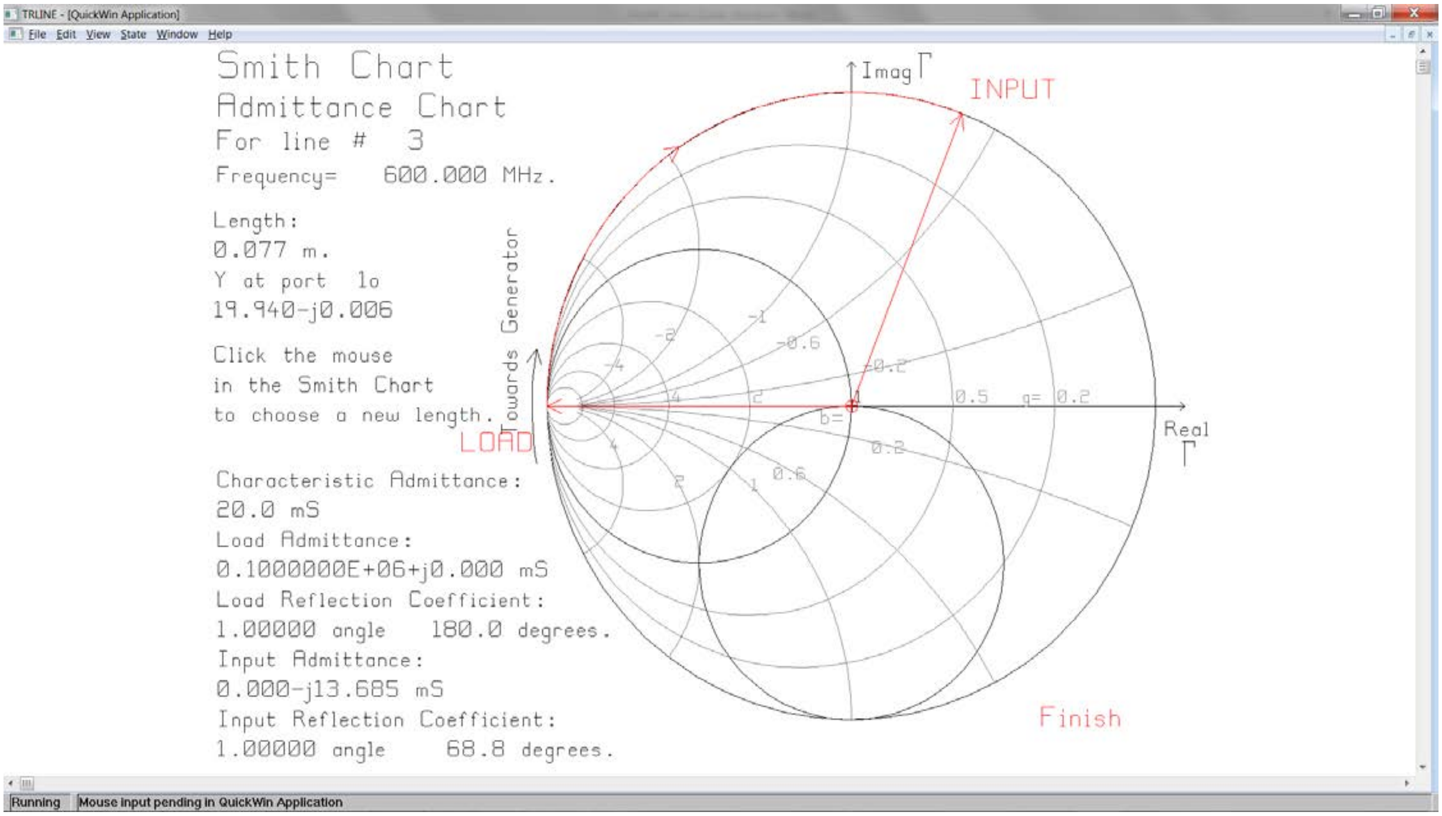
Click the mouse
in the Smith Chart
to choose a new length.

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle 180.0 degrees.
Input Admittance:
0.000-j17.601 mS
Input Reflection Coefficient:
1.00000 angle 82.7 degrees.

Running | Mouse input pending in QuickWin Application

Fig. 3.17 A tuning stub length of 0.068 m is not long enough to put the admittance at port #1o at the center of the Smith Chart.

Fig. 3.17 shows that as the length of the stub increases, the admittance at port #1o moves around the g=1 circle towards the origin. With a stub length of 0.068 m, the normalized admittance is about 1-j0.2. The stub is not long enough so continue to increase the length to move the port admittance to the origin.



```
Smith Chart
Admittance Chart
For line #  3
Frequency=   600.000 MHz.

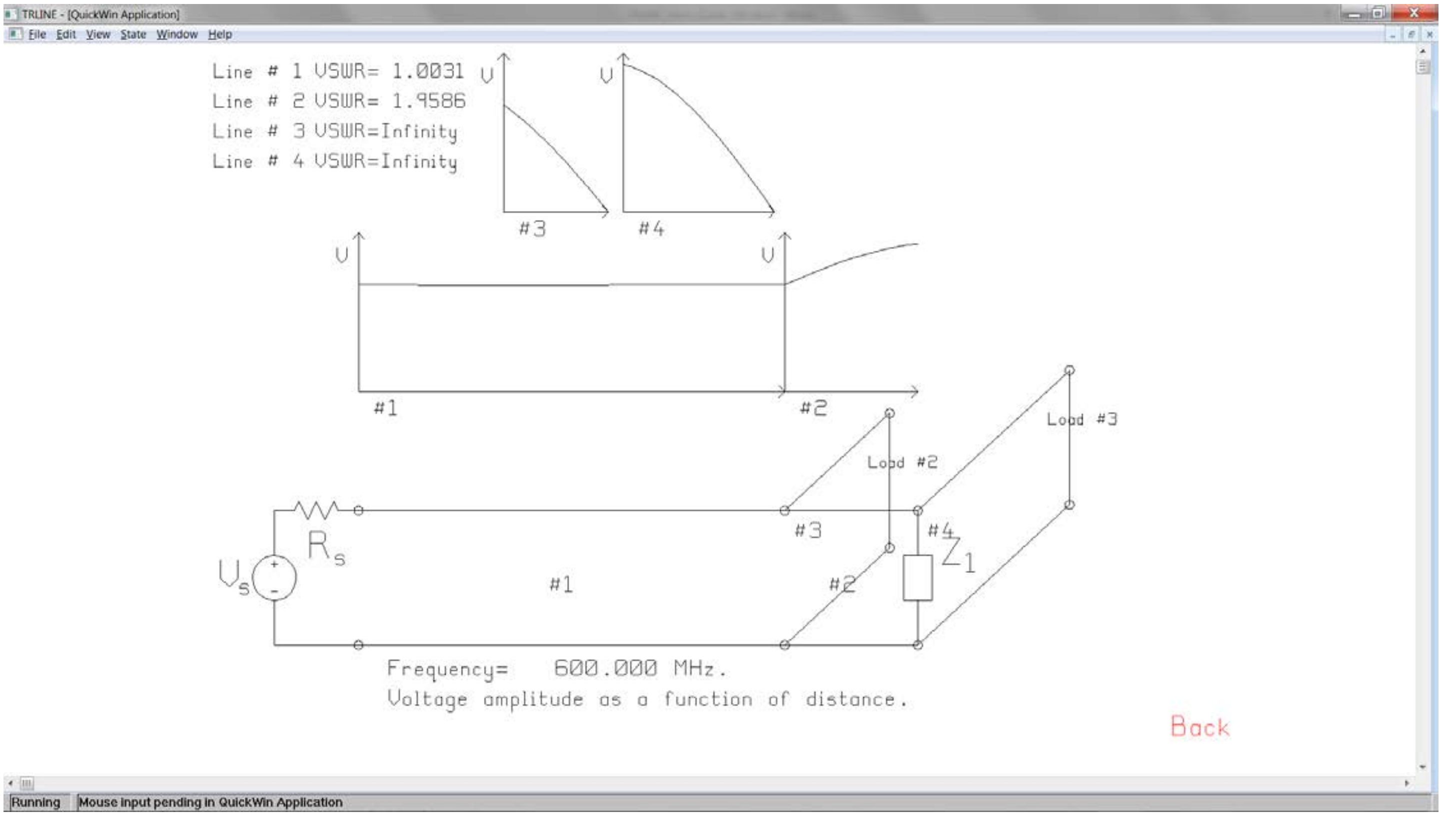
Length:
0.077 m.
Y at port  1o
19.940-j0.006

Click the mouse
in the Smith Chart
to choose a new length.

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
0.000-j13.685 mS
Input Reflection Coefficient:
1.00000 angle    68.8 degrees.
```

Fig. 3.18 A stub length of 0.077 m makes the admittance at port 1o equal to 19.939-j0.006 mS.

Fig. 3.18 shows that with a stub length of 0.077 m, the input admittance is very close to the center of the Smith Chart. The design of the double-stub matching circuit is complete.



```
Line # 1 VSWR= 1.0031
Line # 2 VSWR= 1.9586
Line # 3 VSWR=Infinity
Line # 4 VSWR=Infinity

Frequency=   600.000 MHz.
Voltage amplitude as a function of distance.
```

Fig. 3.19 The VSWR on the input line is 1.0031, which is a good match.

Fig. 3.19 shows the voltage waveforms on the transmission lines. The voltage is almost constant with distance on line #1, so we have a good match. The VSWR on line #1 is 1.0031.

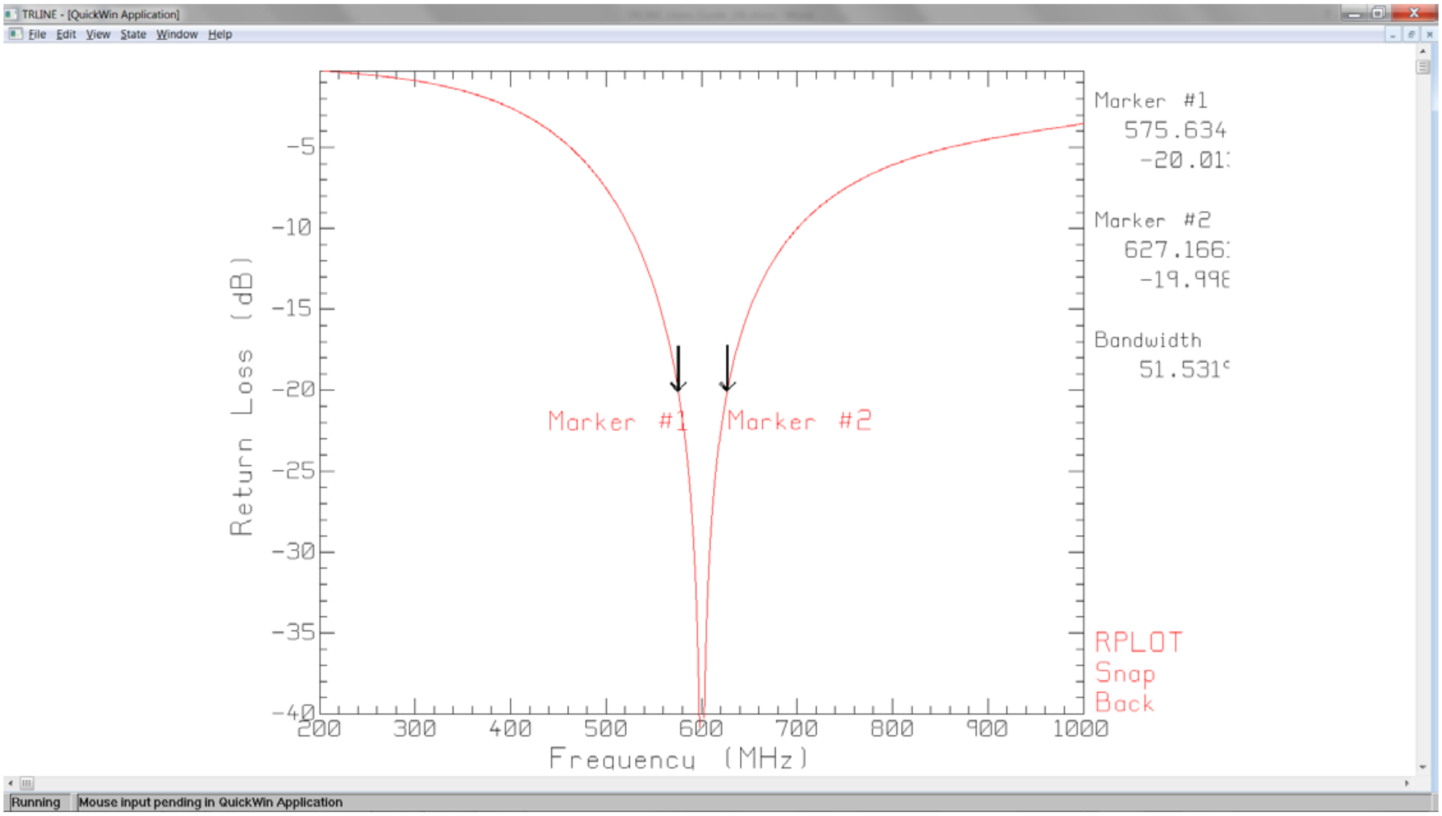
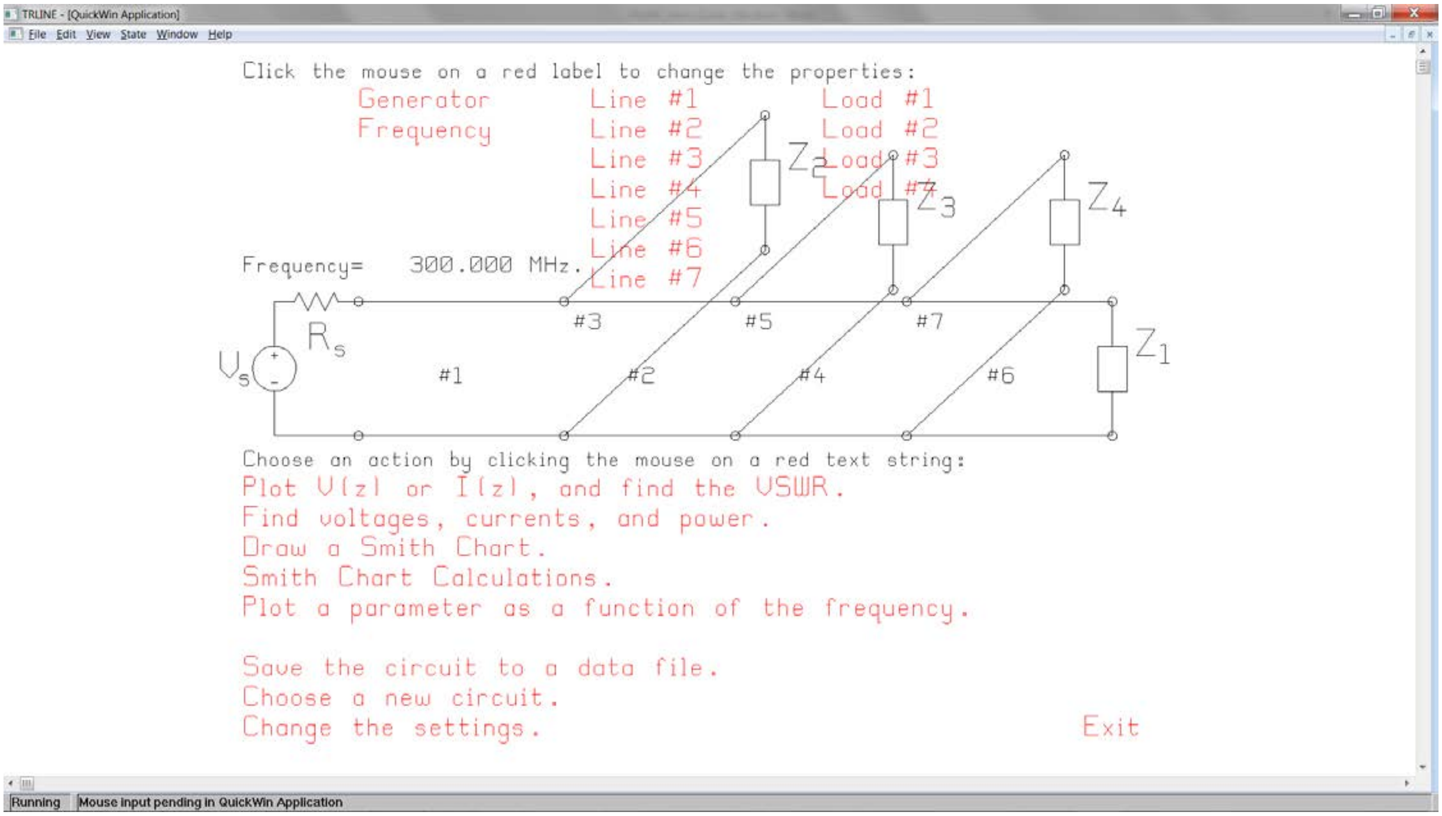


Fig. 3.20 The bandwidth of the match for a return loss of 20 dB or better is 51.53 MHz.

Use the frequency sweep function to assess the bandwidth of the match as 51.53 MHz for a return loss of 20 dB or better, as shown in Fig. 3.20.



Click the mouse on a red label to change the properties:

Frequency= 300.000 MHz.

Choose an action by clicking the mouse on a red text string:

Plot V(z) or I(z), and find the VSWR.
Find voltages, currents, and power.
Draw a Smith Chart.
Smith Chart Calculations.
Plot a parameter as a function of the frequency.

Save the circuit to a data file.
Choose a new circuit.
Change the settings.

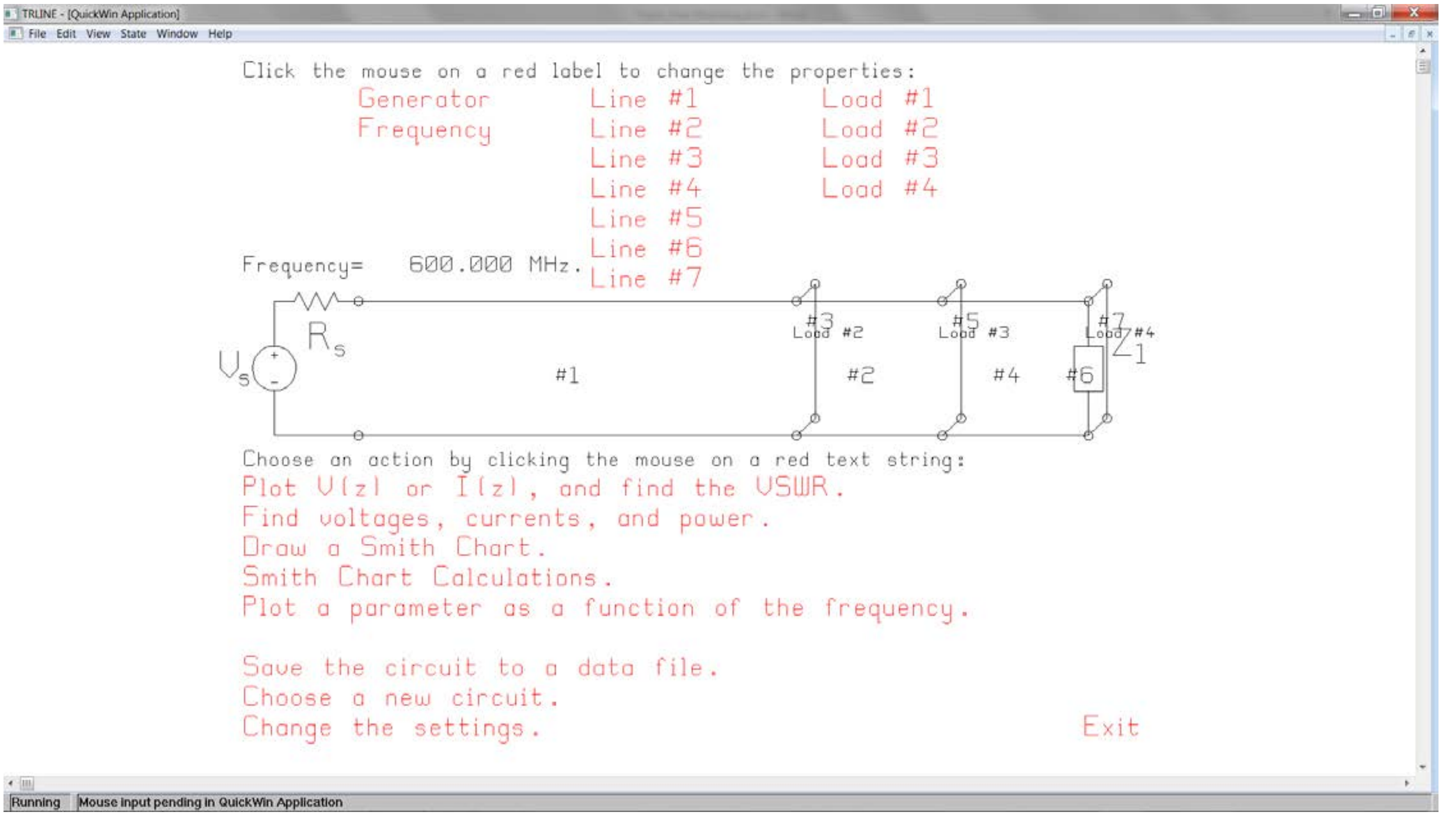
Running
Mouse input pending in QuickWin Application

Fig. 3.21 TRLINE's triple-stub matching circuit template.

3.3.Triple Stub Matching

Triple stub matching can be used to match loads which are impossible to match using double-stub matching. Fig. 3.21 shows TRLINE's circuit template for triple-stub matching. There are three stubs, which are lines #3, 5 and 7 in Fig. 3.21. The circuit includes a length of transmission line between stub #3 (line #7) and the load, but we don't need this line so set it to a short length, say 0.01 cm. Line #1 is the input line and we want to design the triple-stub tuner to obtain a perfect match at the output of line #1.

Consider a load of Z_1=12.5+j12.5 ohms. The frequency is 600 MHz and the transmission lines have speed of travel 30 cm/ns, and characteristic impedance 50 ohms. The stubs are to be separated by one-tenth of wavelength. Since the wavelength is 0.5 m, the length of lines #2 and #4 is set to 5 cm. Set the loads on the stubs to zero impedance, corresponding to stubs terminated with short-circuits. Set the length of the stubs to 1 cm as the starting point for the design.



Click the mouse on a red label to change the properties:

Generator
Frequency
Line #1
Line #2
Line #3
Line #4
Line #5
Line #6
Line #7
Load #1
Load #2
Load #3
Load #4

Frequency= 600.000 MHz.

Choose an action by clicking the mouse on a red text string:

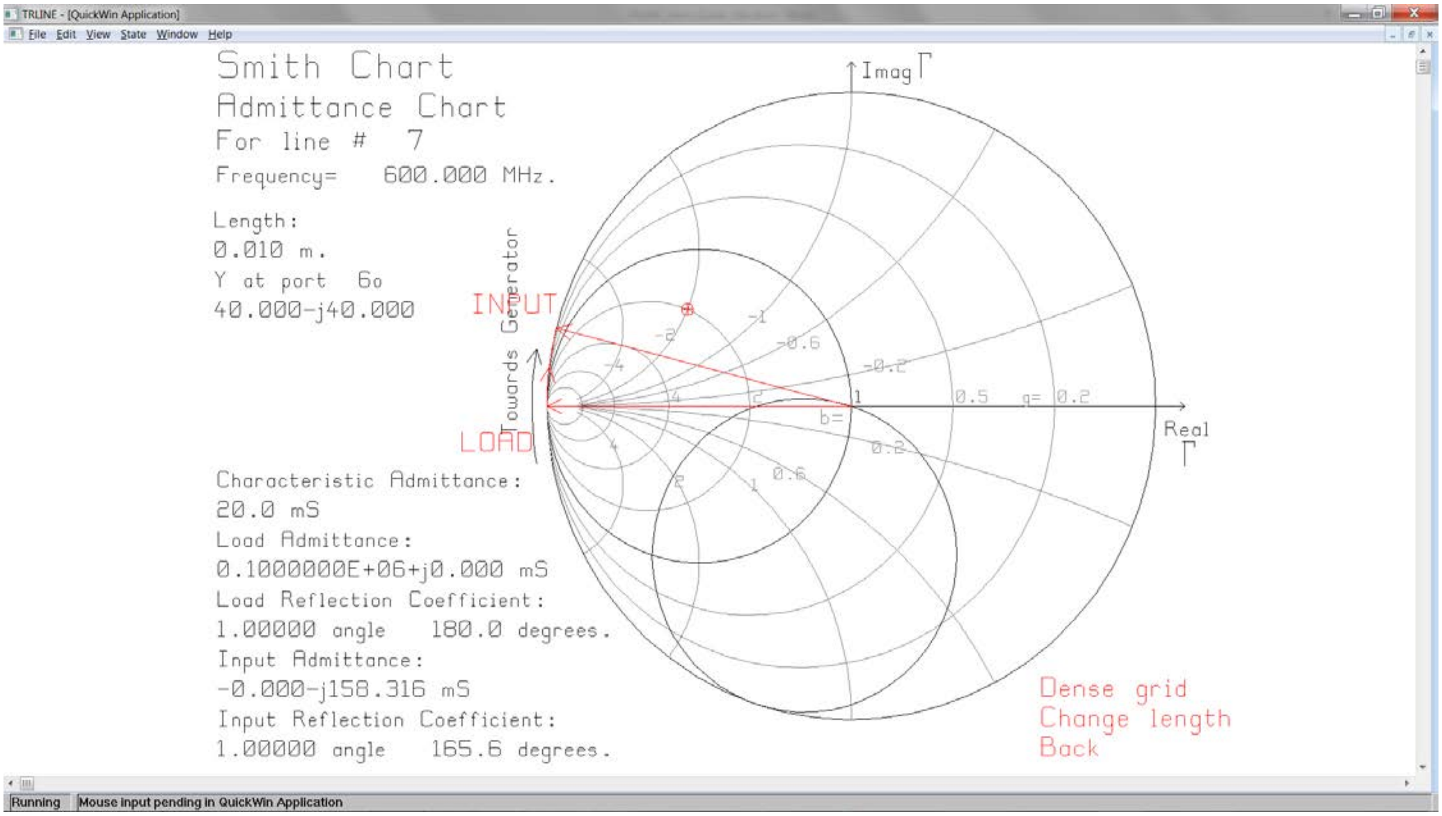
Plot V(z) or I(z), and find the VSWR.
Find voltages, currents, and power.
Draw a Smith Chart.
Smith Chart Calculations.
Plot a parameter as a function of the frequency.

Save the circuit to a data file.
Choose a new circuit.
Change the settings.
Exit

Fig. 3.22 The triple-stub circuit is set up to design the triple-stub tuner.

Fig. 3.22 shows the circuit with 5 cm spacing between the stubs, and the stubs set to short circuit terminations and to 1 cm length. In the design, stub #3 and the line joining stub #2 to stub #3 (line #4 in the TRLINE circuit template) are to be used to move the admittance to a point on the Smith Chart that can be matched with a double stub tuner, made up of stub #1 (line #3 in Fig 53) and stub #2 (line #5), and the line joining the two stubs (line #2).

Choose the Smith Chart Calculations menu to start the design. Choose the rotation of the g=1 circle to be the length of line #2, the line between stub #1 and stub #2.



```
Smith Chart
Admittance Chart
For line #  7
Frequency=   600.000 MHz.

Length:
0.010 m.
Y at port  6o
40.000-j40.000

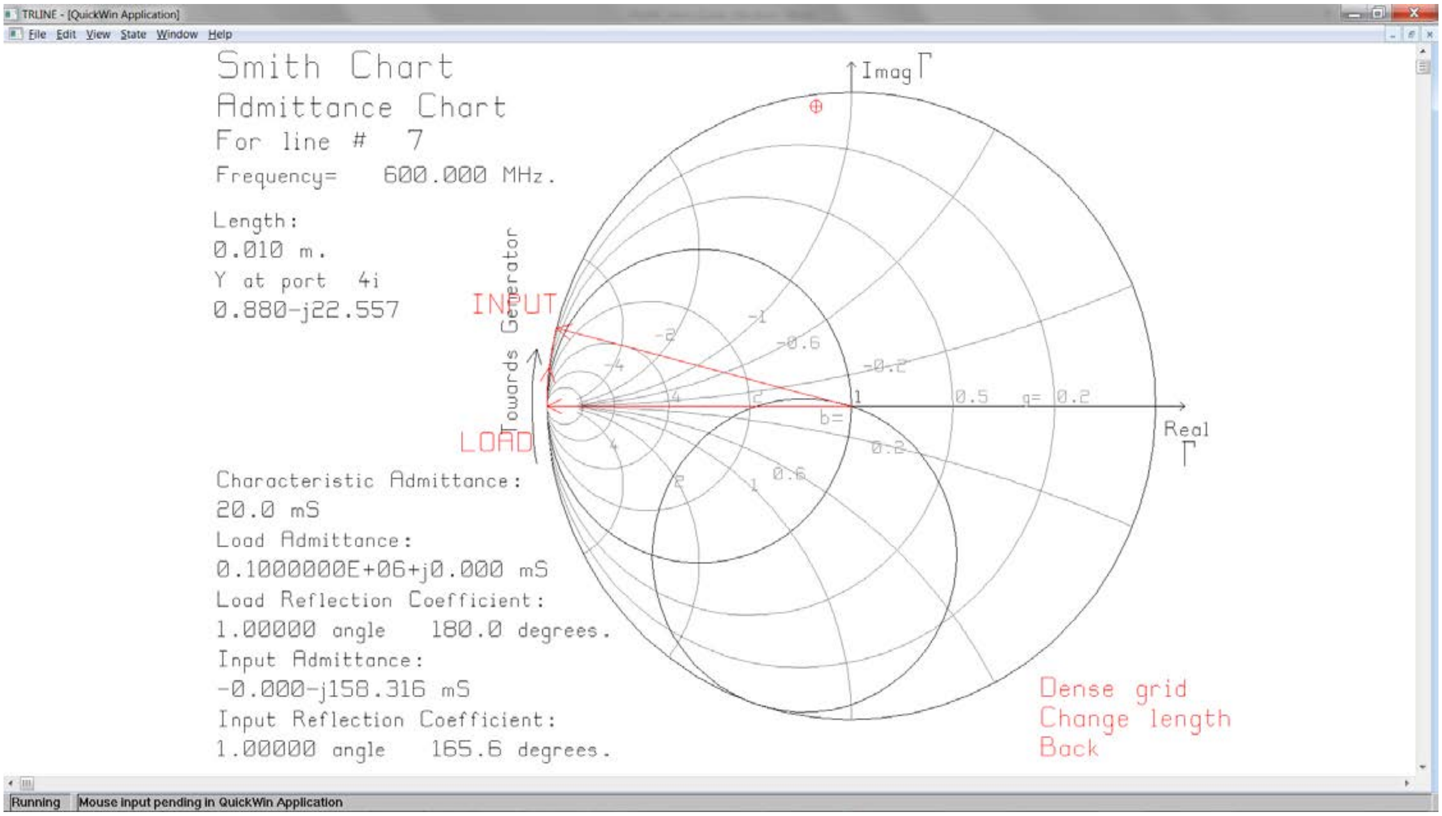
Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
-0.000-j158.316 mS
Input Reflection Coefficient:
1.00000 angle   165.6 degrees.
```

```
Mouse input pending in QuickWin Application
```

Fig. 3.23 The load admittance is 40-j40 mS or normalized admittance 2-j2 on the lines of characteristic admittance 20 mS.

The load admittance is Y_1=40-j40 mS. To show where the load admittance lies on the Smith Chart, choose to monitor port “6o”, where the load is connected, and then draw the Smith Chart for Line #7, shown in Fig. 3.23. The target symbol at normalized admittance 2-j2 is the load that we are trying to match. Note that the constant-g circle for g=2 intersects the rotated g=1 circle, so it is possible to match this load with a double-stub tuner with a 5 cm stub spacing.

Stub #3 can move the admittance anywhere on the g=2 circle. Line #4 in Fig. 3.23 rotates the g=2 circle towards the generator by the length of line #4, which is one-tenth of the wavelength. TRLINE does not have the feature of drawing the rotated g=2 circuit; this would be a stepping stone in triple-stub design.



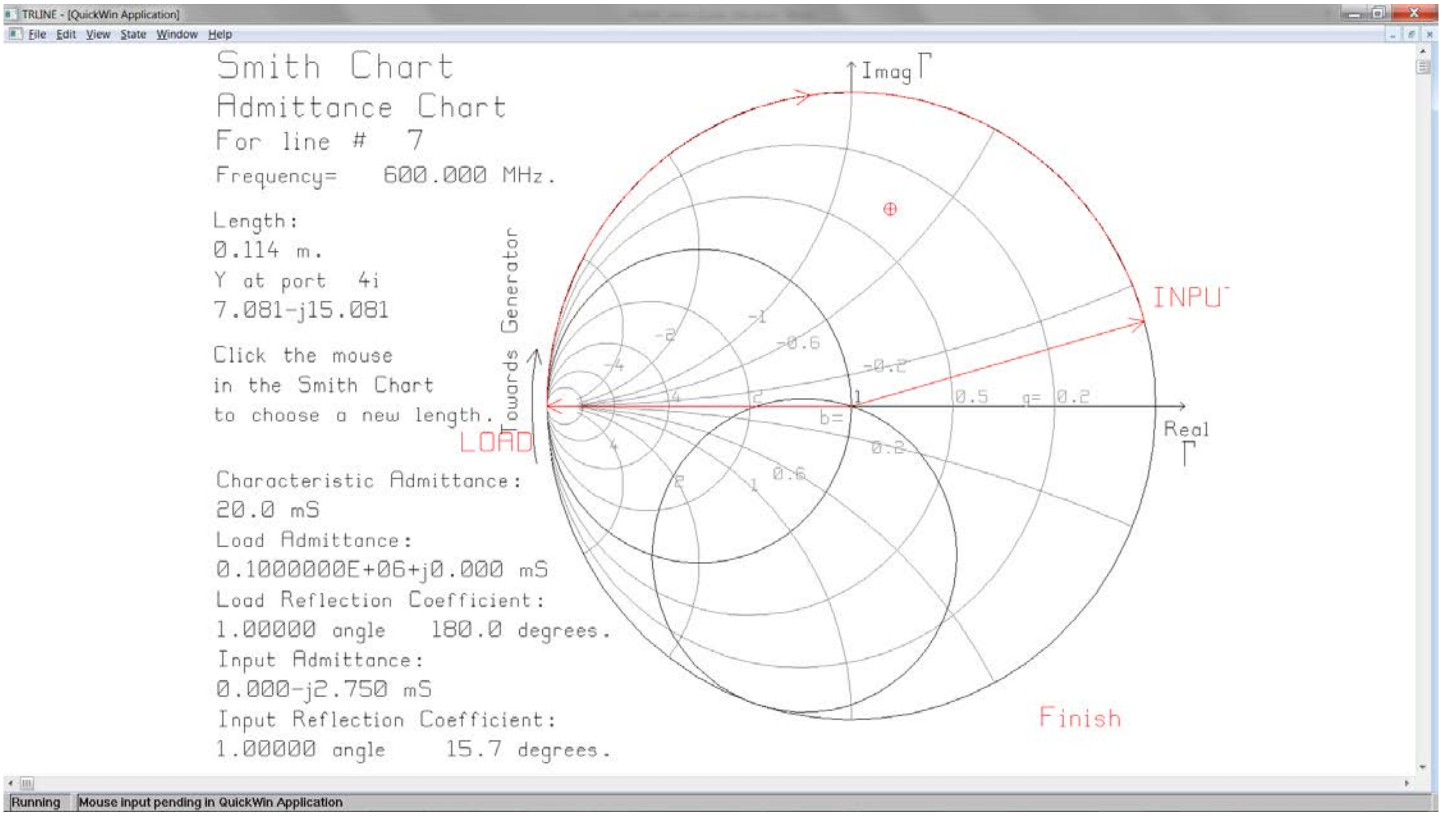
Smith Chart
Admittance Chart
For line # 7
Frequency= 600.000 MHz.

Length:
0.010 m.
Y at port 4i
0.880-j22.557

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle 180.0 degrees.
Input Admittance:
-0.000-j158.316 mS
Input Reflection Coefficient:
1.00000 angle 165.6 degrees.

Fig. 3.24 The Smith Chart for stub #3 (line #7) with a 1 cm stub length, showing the admittance at port 4i.

To set the length of stub #3, monitor the input to line #4 in Fig. 3.24, which is port 4i. This is the load that must be matched by the double-stub tuner made up of lines #2, 3 and 5 in Fig. 53. Fig. 3.24 shows the Smith Chart for stub #3, which is line #7. The admittance at port 4i is the target symbol at the top of the Smith Chart. We want to change the length of the stub with the “change length” function to move this admittance to a desirable location.



```
Smith Chart
Admittance Chart
For line #  7
Frequency=   600.000 MHz.

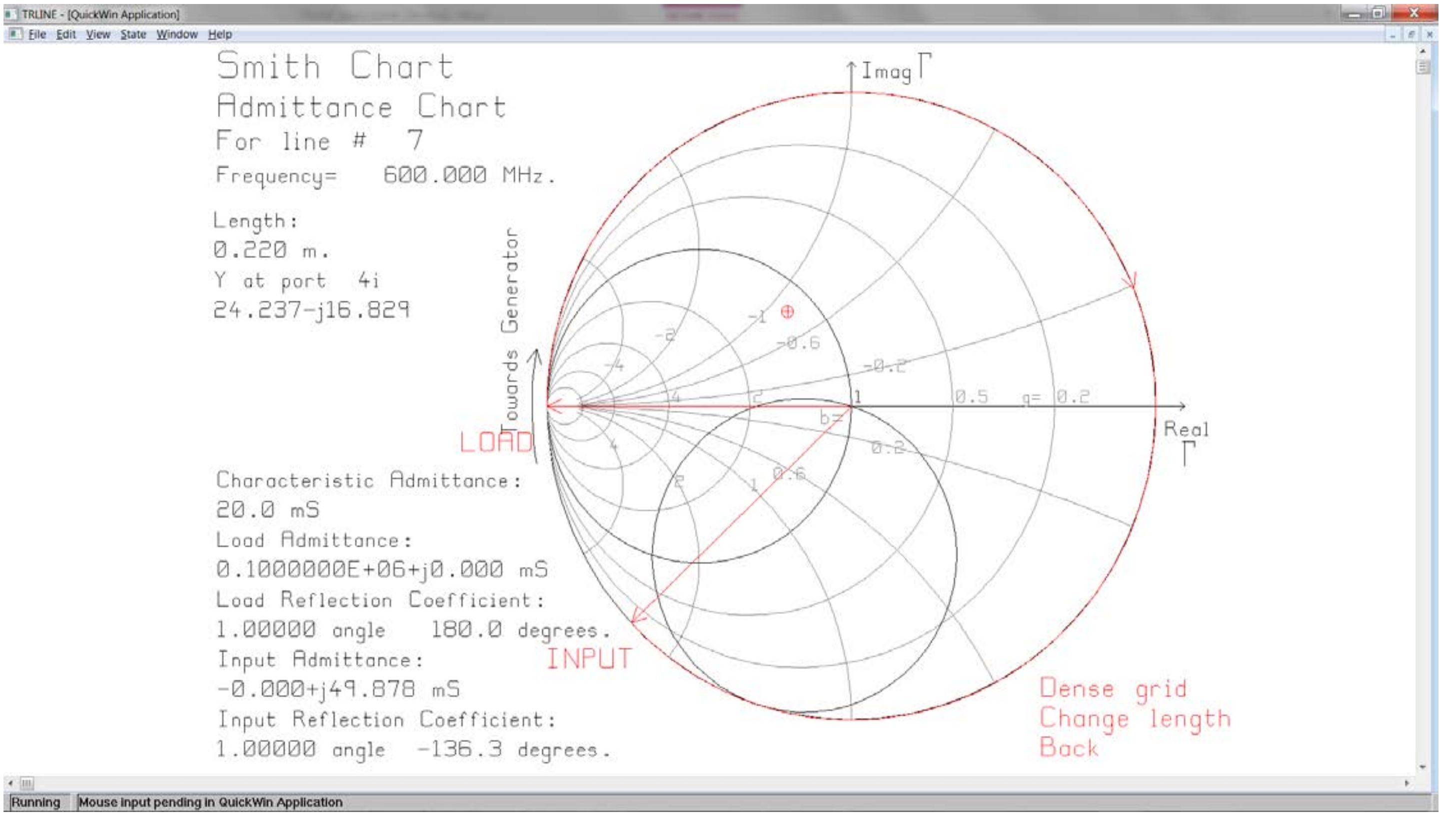
Length:
0.114 m.
Y at port  4i
7.081-j15.081

Click the mouse
in the Smith Chart
to choose a new length.

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle  180.0 degrees.
Input Admittance:
0.000-j2.750 mS
Input Reflection Coefficient:
1.00000 angle   15.7 degrees.
```

Fig 3.25 Change the length of stub #3 to get close to the rotated g=1 circle.

As we change the length of stub #3, the monitored admittance at port 4i moves on a circle. Fig. 3.25 shows the admittance with stub #3 set to 0.114 m. But the admittance can be moved closer to the rotated g=1 circle by making the stub longer. There is no unique solution for choosing the length of stub #3: we want the admittance at port 4i to be one that can be matched by stub #1 and stub #2 as a double-stub matching circuit. The criterion to be used here is that the admittance at port 4i be as close as possible to the rotated g=1 circle.



Smith Chart
Admittance Chart
For line # 7
Frequency= 600.000 MHz.

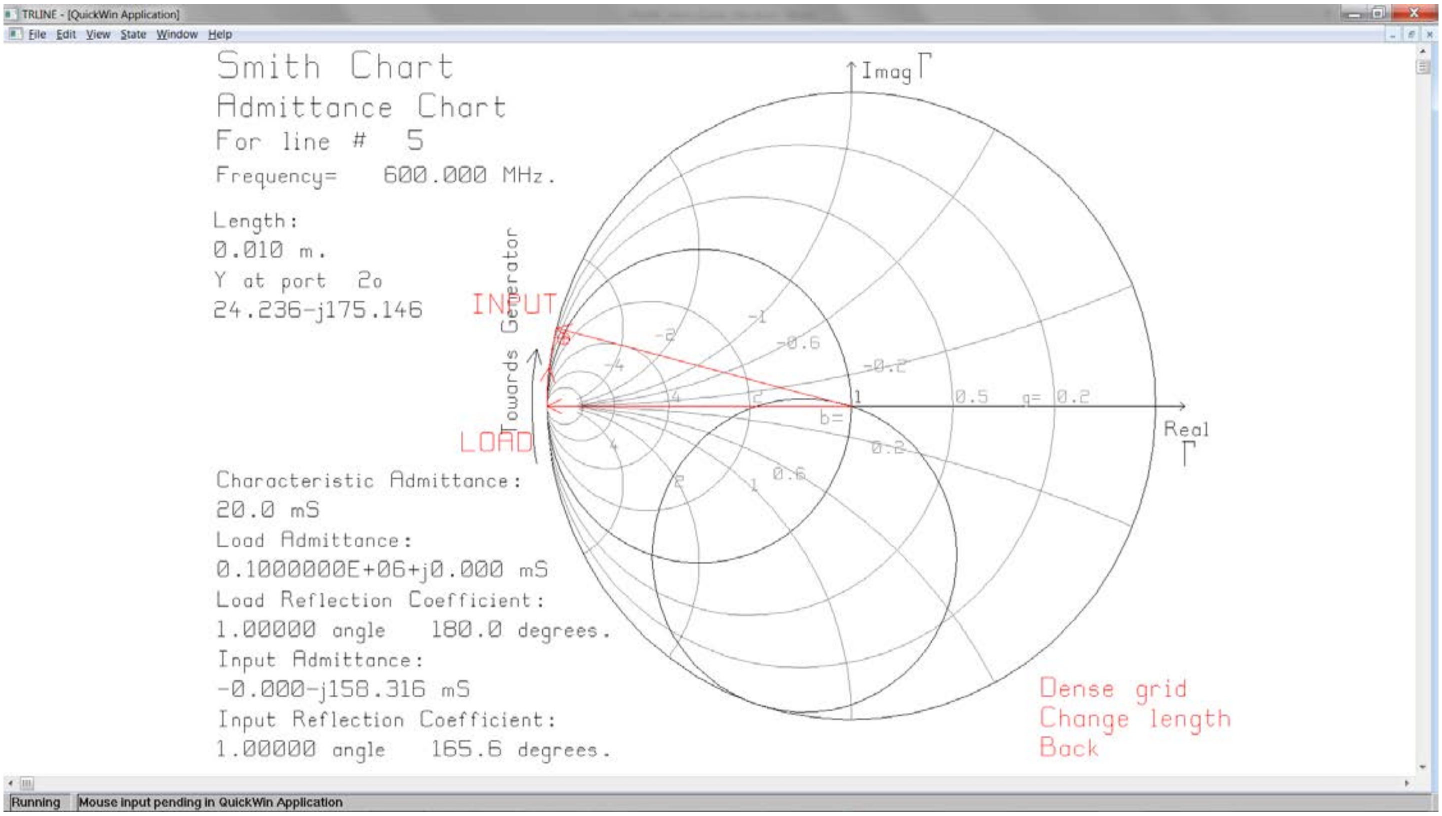
Length:
0.220 m.
Y at port 4i
24.237-j16.829

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle 180.0 degrees.
Input Admittance:
-0.000+j49.878 mS
Input Reflection Coefficient:
1.00000 angle -136.3 degrees.

Running
Mouse input pending in QuickWin Application

Fig. 3.26 A stub length of 0.220 m puts the input admittance to line #4 close to the rotated g=1 circle.

Fig. 3.26 shows the Smith Chart for stub #3, with the input admittance to line #4 (port 4i) shown with the target symbol. The length of the stub has been adjusted to put the admittance at port 4i as close as possible to the rotated g=1 circle. This is the admittance that will be matched with the double-stub matching circuit. Adjusting stub #2 and stub #1 for this load proceeds as described above for the double-stub matching circuit. The first step is to move the admittance onto the g=1 circle by adjusting stub #2.



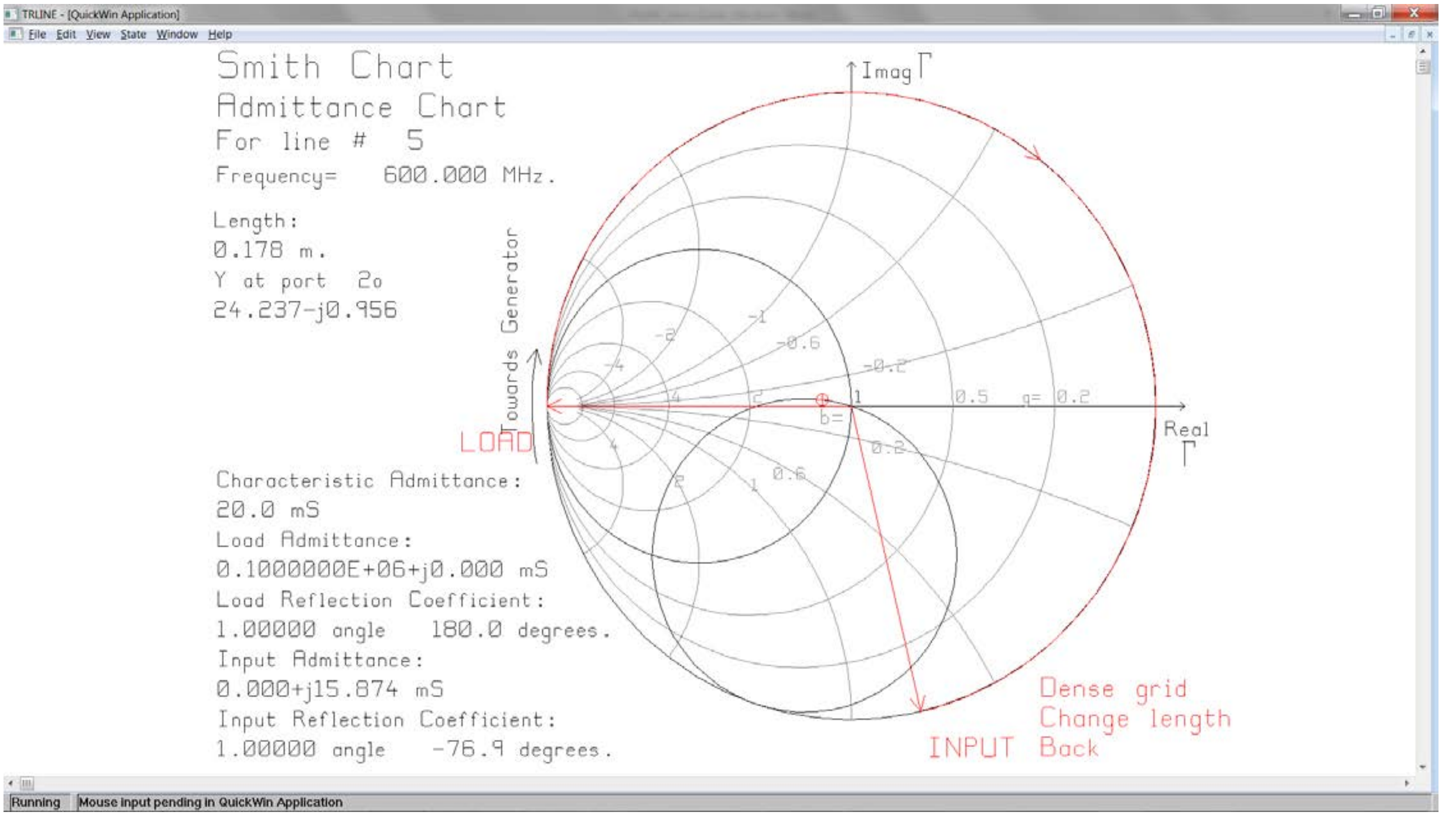
```
Smith Chart
Admittance Chart
For line #   5
Frequency=   600.000 MHz.

Length:
0.010 m.
Y at port  2o
24.236-j175.146

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
-0.000-j158.316 mS
Input Reflection Coefficient:
1.00000 angle   165.6 degrees.
```

Fig. 3.27 Monitor the admittance at port 2o and draw the Smith Chart for stub #2, which is line #5.

To adjust the length of stub #2 (line #5) monitor the admittance at port #2o, which is the output port of the line joining stub #1 to stub #2. We want to adjust the length of stub #2 to put this admittance onto the rotated g=1 circle. Fig. 3.27 shows the admittance at port #2o as the target symbol at left in the Smith Chart. It is very close to the g=1 circle.



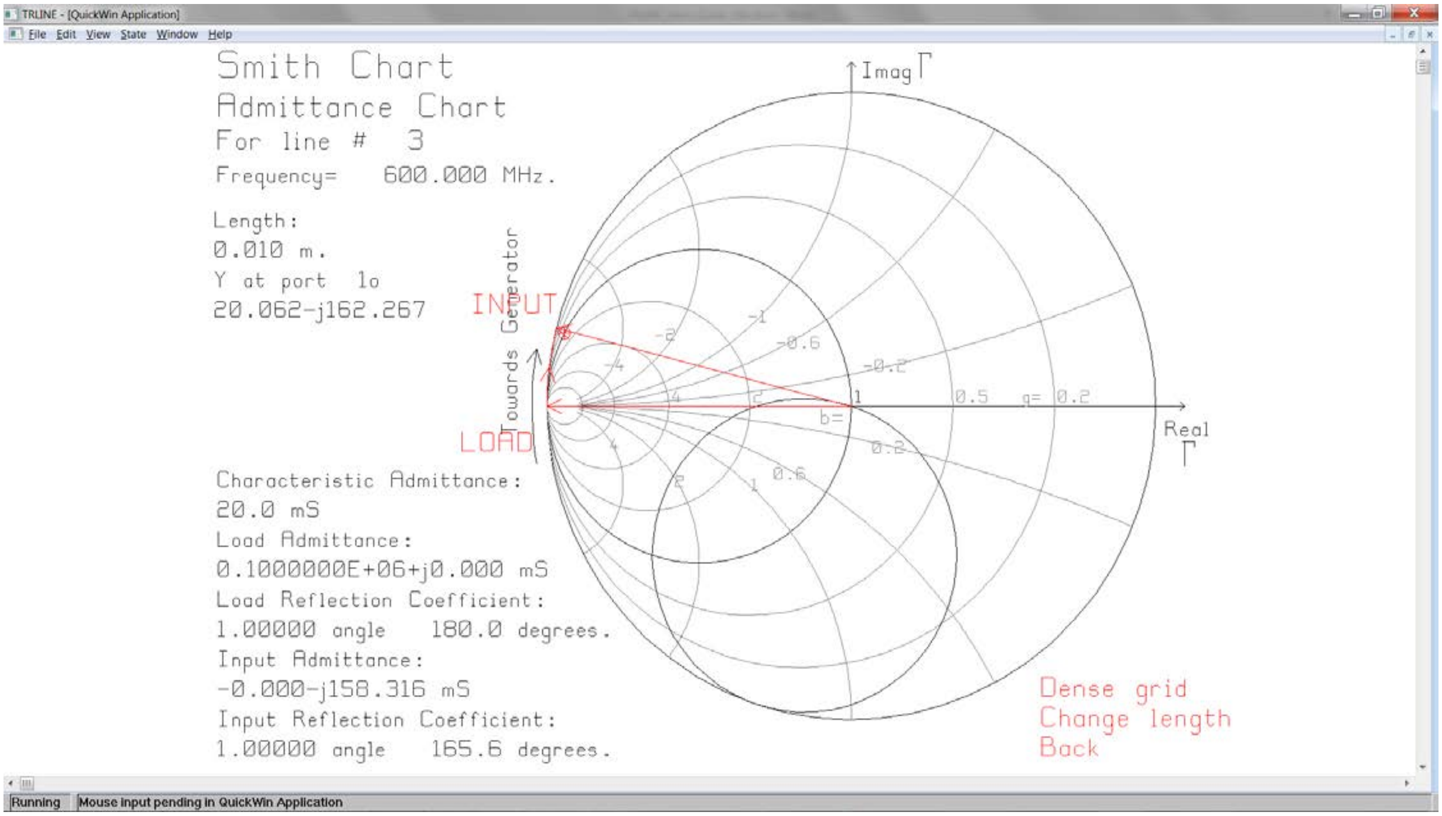
Smith Chart
Admittance Chart
For line # 5
Frequency= 600.000 MHz.

Length:
0.178 m.
Y at port 2o
24.237-j0.956

Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle 180.0 degrees.
Input Admittance:
0.000+j15.874 mS
Input Reflection Coefficient:
1.00000 angle -76.9 degrees.

Fig. 3.28 Change the length of stub #2 to put the admittance onto the rotated g=1 circle.

Adjust the length of stub #2 (line #5) to move the admittance at port #2o onto the rotated g=1 circle. Fig. 3.28 shows that with the stub length adjusted to 0.178 m, the admittance at port #2o is on the rotated g=1 circle. Note that although we start with the admittance close to the g=1 circle itself in Fig. 3.27, no length for stub #2 moved the admittance to the origin for the desired match. The best we can do is move close to the origin, Fig. 3.28, and then use stub #1 to achieve the match.

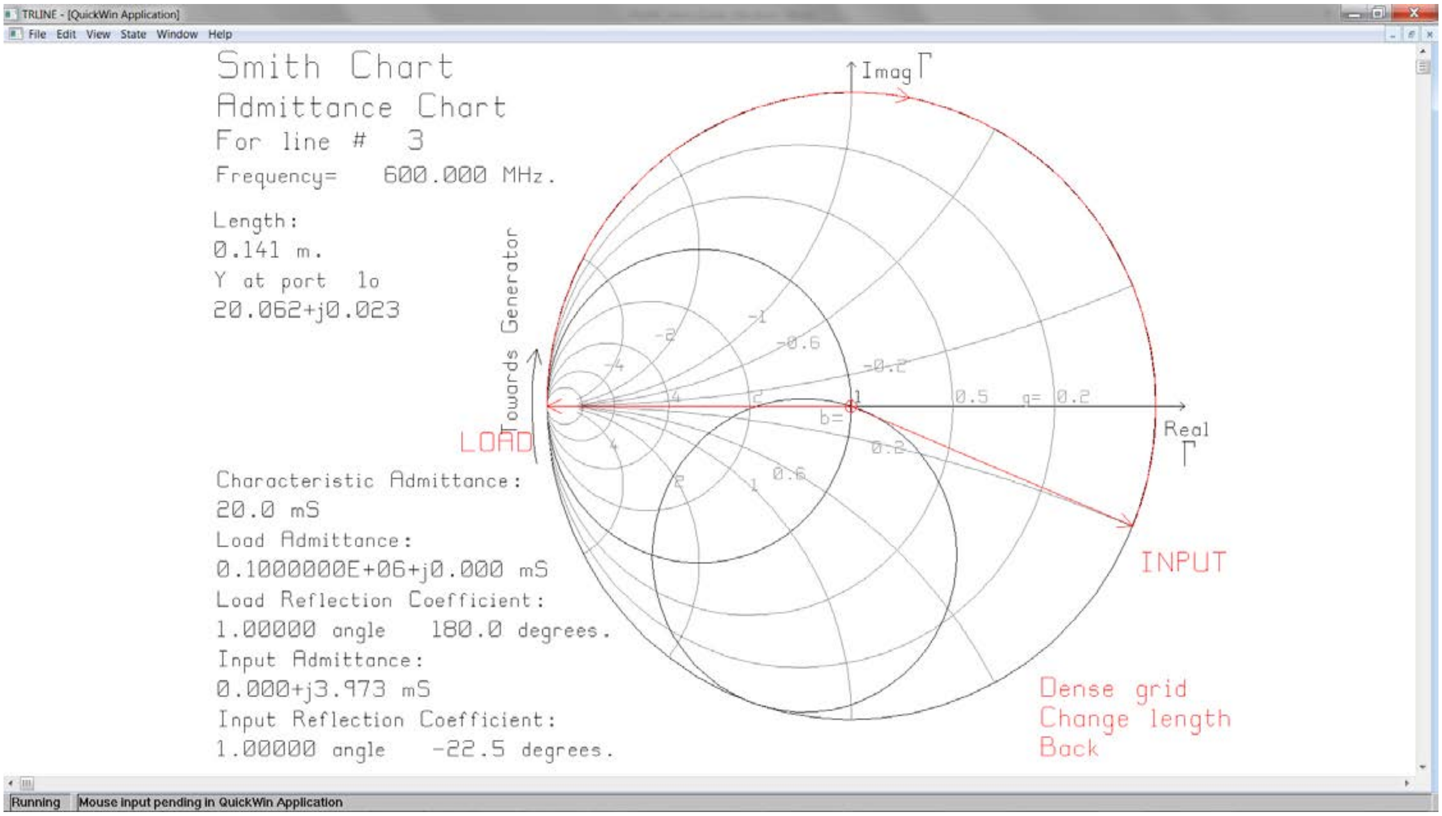


```
Smith Chart
Admittance Chart
For line #  3
Frequency=   600.000 MHz.
Length:
0.010 m.
Y at port  1o
20.062-j162.267
Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle   180.0 degrees.
Input Admittance:
-0.000-j158.316 mS
Input Reflection Coefficient:
1.00000 angle   165.6 degrees.
```

Running
Mouse input pending in QuickWin Application

Fig. 3.29 Monitor port #1o to adjust stub #1, which is line #3.

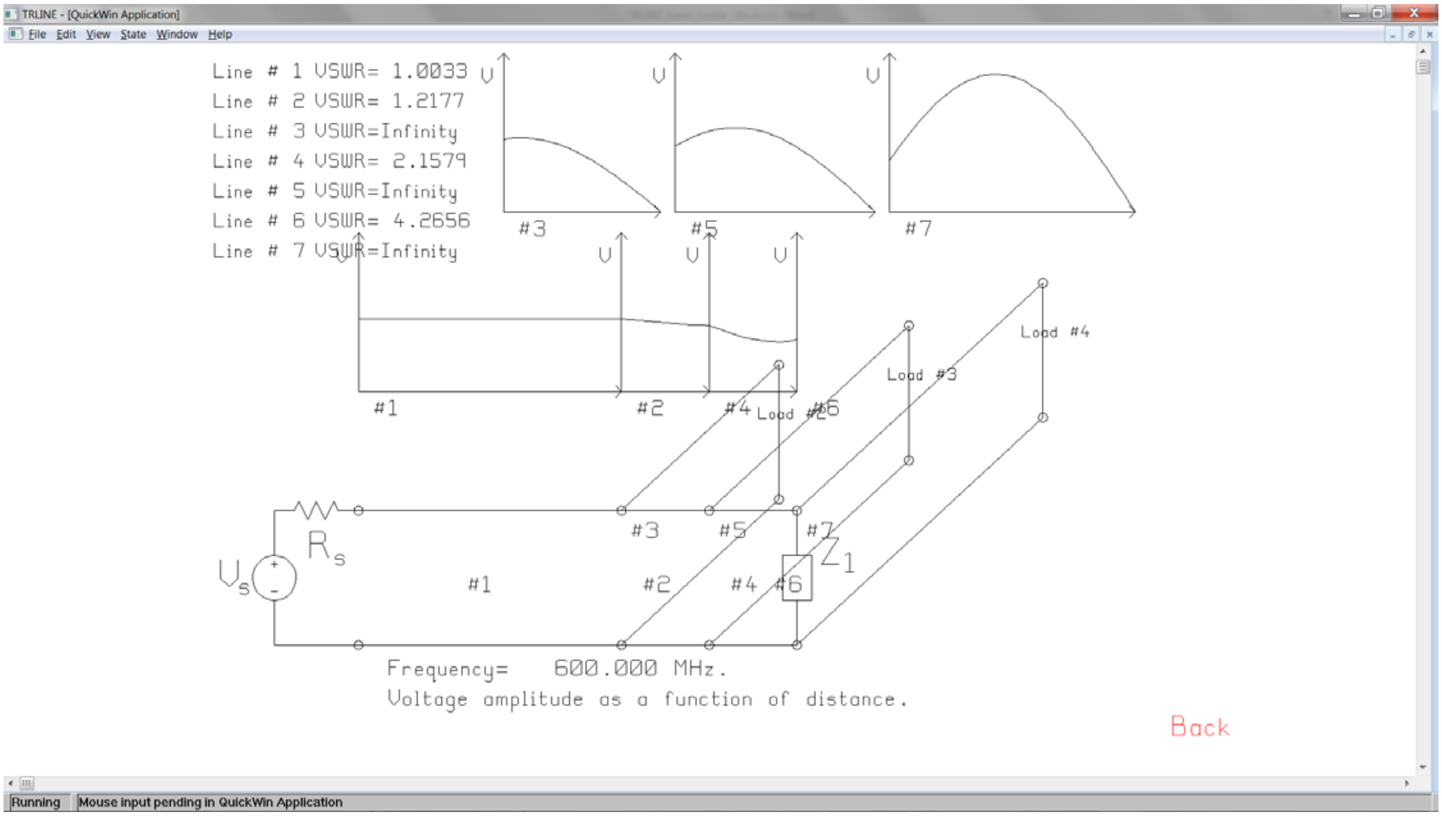
Fig. 3.29 shows the starting point for adjusting stub #1 (line #3). Monitor the admittance at port 1o, the input port to the matching circuit, shown by the target symbol at left in Fig. 3.29. Then change the length of stub #1 to move the admittance around the g=1 circle to the origin.



```
Smith Chart
Admittance Chart
For line #  3
Frequency=   600.000 MHz.
Length:
0.141 m.
Y at port  1o
20.062+j0.023
Characteristic Admittance:
20.0 mS
Load Admittance:
0.1000000E+06+j0.000 mS
Load Reflection Coefficient:
1.00000 angle  180.0 degrees.
Input Admittance:
0.000+j3.973 mS
Input Reflection Coefficient:
1.00000 angle   -22.5 degrees.
```

Fig. 3.30 Adjust the length of line #3 to put the admittance at the center of the Smith Chart.

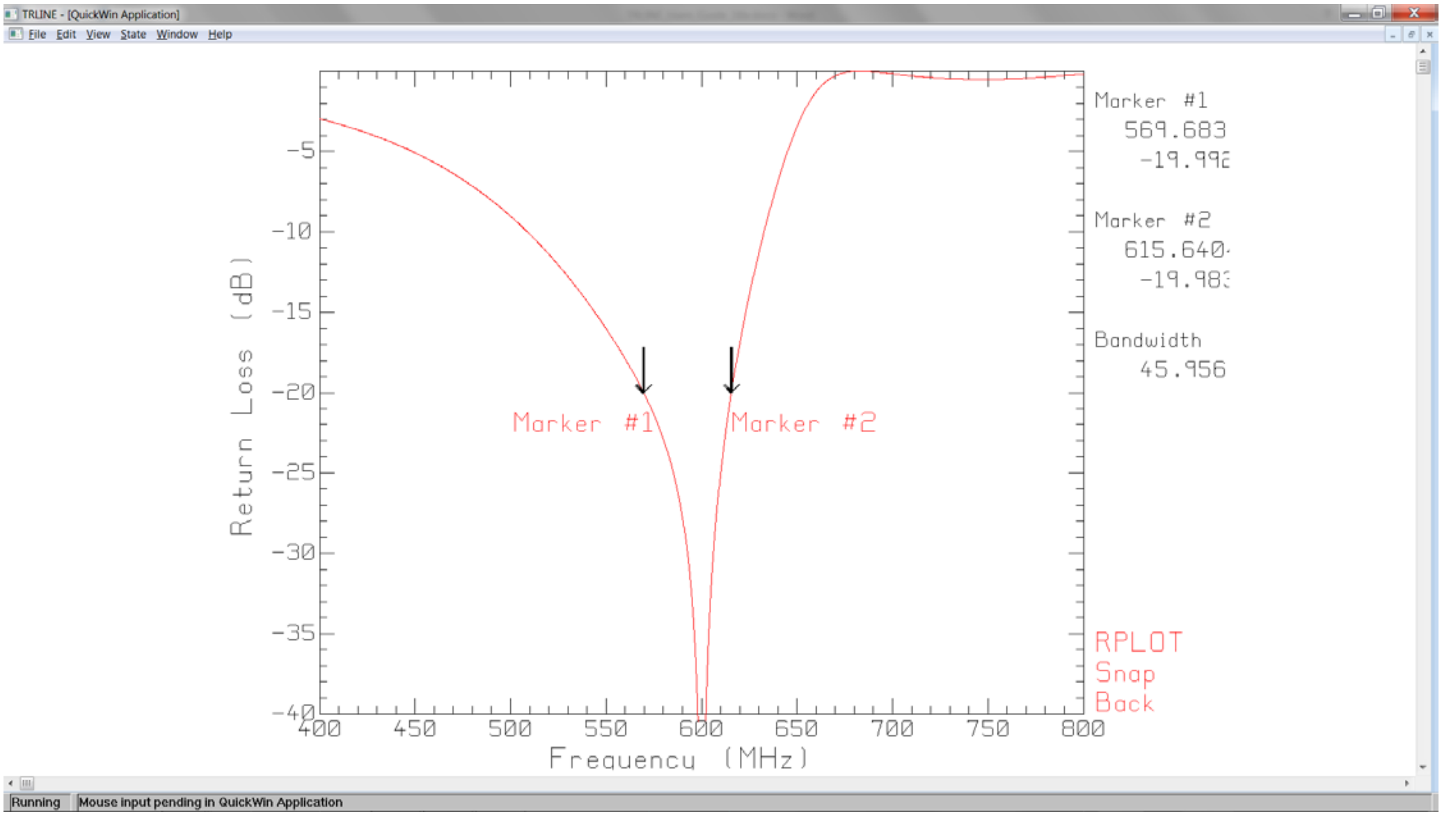
In Fig. 3.30, the length of stub #1 has been set to 0.141 m, and the admittance at port #1o is a match to the 20 mS transmission line.



```
Line # 1 VSWR= 1.0033
Line # 2 VSWR= 1.2177
Line # 3 VSWR=Infinity
Line # 4 VSWR= 2.1579
Line # 5 VSWR=Infinity
Line # 6 VSWR= 4.2656
Line # 7 VSWR=Infinity
Frequency=   600.000 MHz.
Voltage amplitude as a function of distance.
```

Fig 3.31 The triple stub matching circuit achieves a good match on line #1.

Fig. 3.31 shows the voltage waveforms on all the transmission lines. Line #1 is the input line and has a VSWR of 1.0033, a good match.



Marker #1
569.683
-19.99

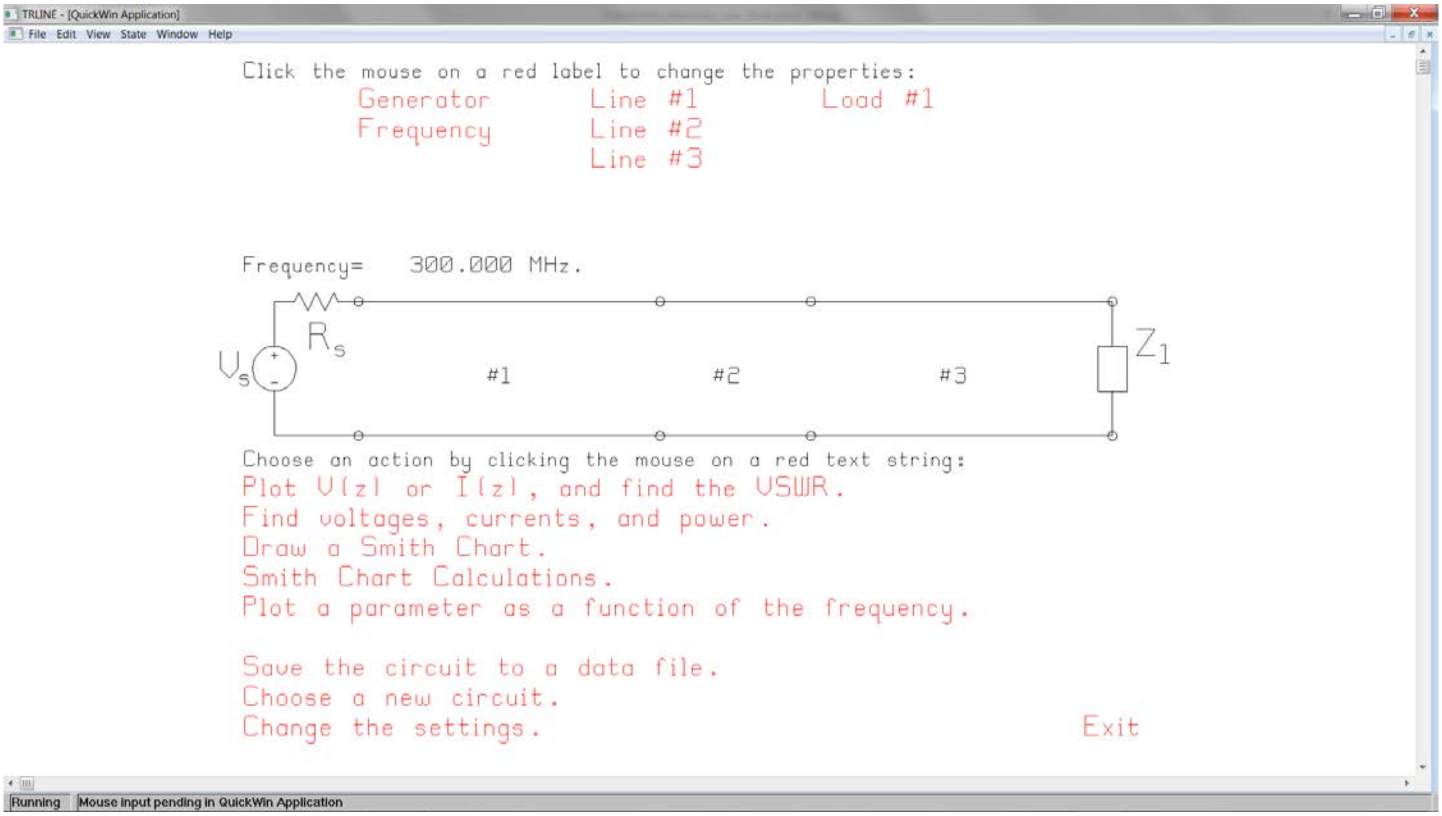
Marker #2
615.640
-19.98

Bandwidth
45.956

Running | Mouse input pending in QuickWin Application

Fig. 3.32 A bandwidth of 45.96 MHz is obtained for a return loss of 20 dB or better.

Fig. 3.32 shows that for a return loss of 20 dB or better, the bandwidth of the match is 45.96 MHz.



Click the mouse on a red label to change the properties:

Frequency= 300.000 MHz.

Choose an action by clicking the mouse on a red text string:

Fig. 4.1 The quarter-wave transformer circuit template.

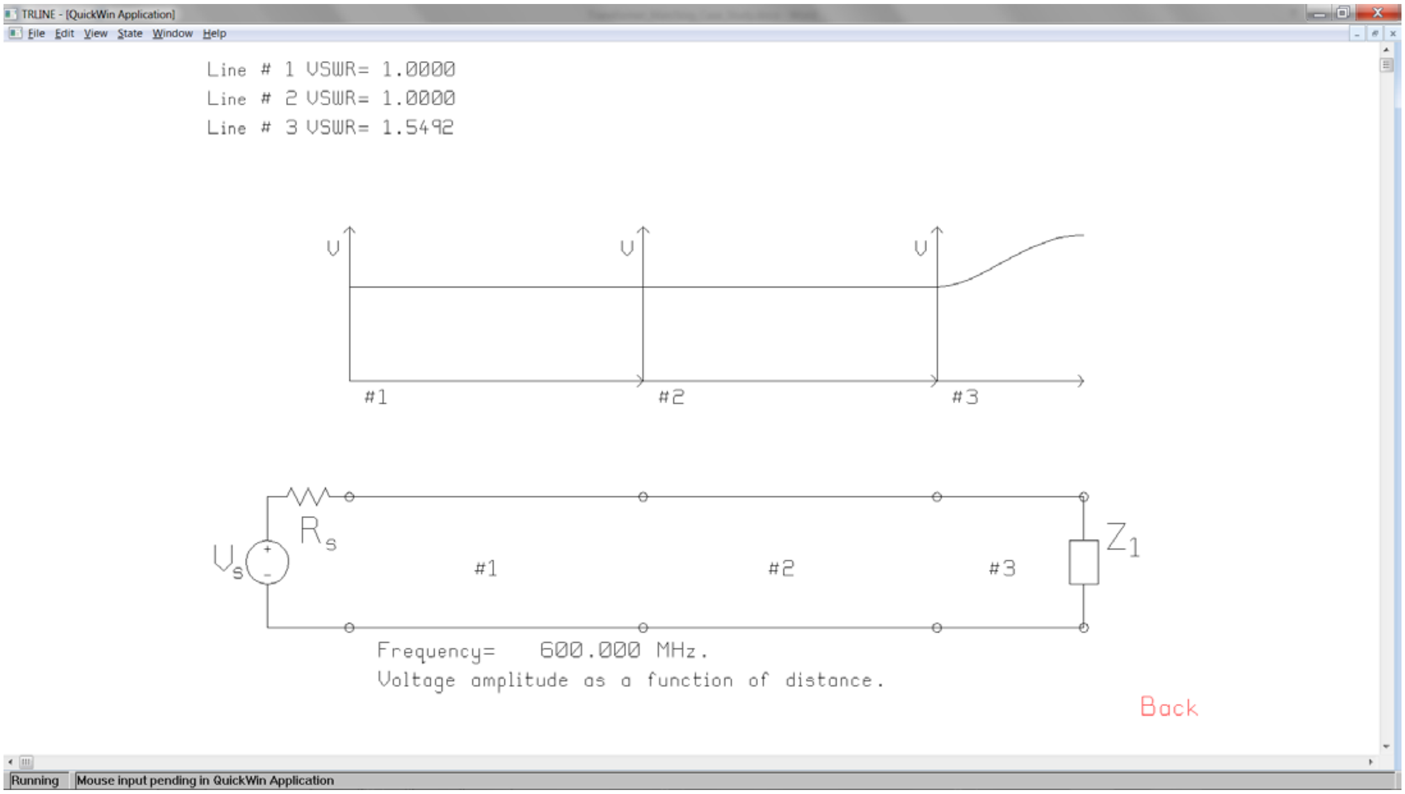
4. Transformer Matching for Real Loads

TRLINE offers circuit templates for two, three, four and five transmission lines in series. These can be used to demonstrate quarter-wave transformers.

4.1. Simple Quarter-Wave Transformer

Fig. 4.1 shows that the circuit template called quarter-wave transformer consists of three transmission lines in series. The parameters are set up to match line #1, a 50-ohm line, to a 100 ohm load comprising line #3 with characteristic resistance 100 ohms, and the load Z_1 of 100 ohms, at 300 MHz. Click “Plot V(z)” and then “Plot the voltage amplitude on all the lines” to demonstrate the match.

Suppose we want to match a 50-ohm line to a load of Z_1=120+j0 ohms, at 600 MHz. The wavelength is 0.5 m and the quarter wave transformer length is 0.125 m. The required characteristic impedance for the transformer is $\sqrt{50x120}$ =77.459 ohms. All the lines have speed of travel 300 meters per microsecond, so set all three transmission lines to this speed of travel.



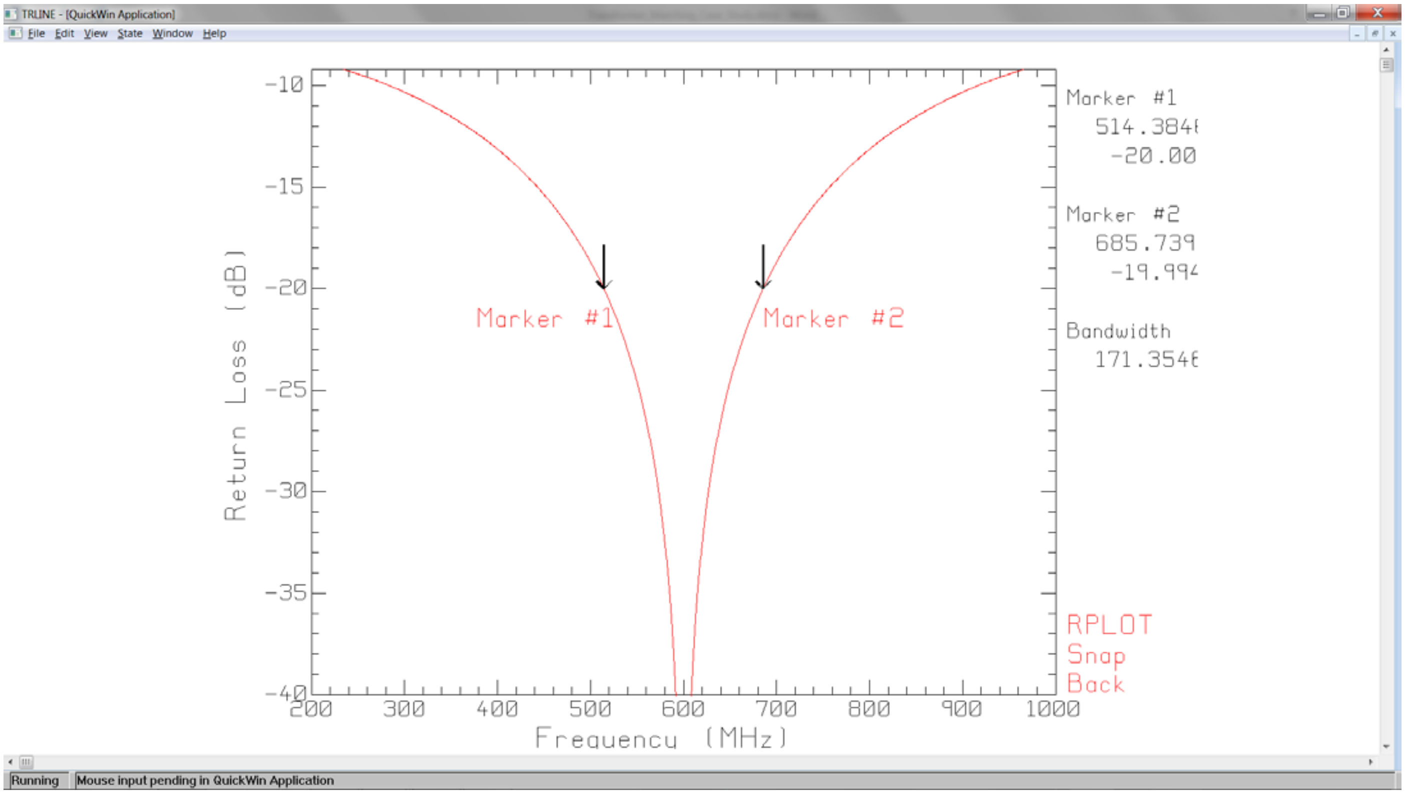
```
Line # 1 VSWR= 1.0000
Line # 2 VSWR= 1.0000
Line # 3 VSWR= 1.5492
```

```
Frequency=   600.000 MHz.
Voltage amplitude as a function of distance.
```

```
Running    Mouse input pending in QuickWin Application
```

Fig. 4.2 A quarter-wave transformer to match a 50 ohm line to a 120 ohm load.

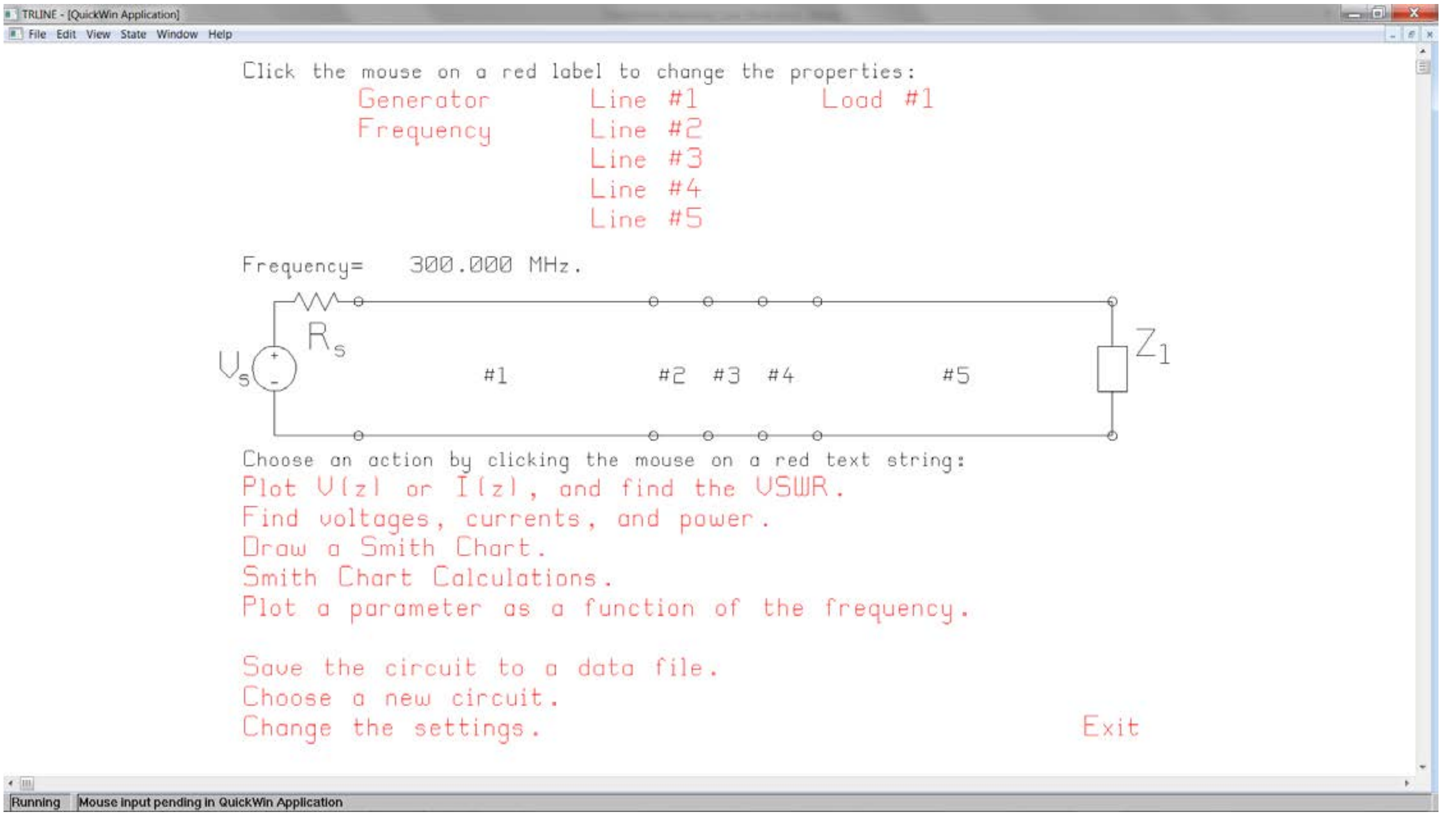
For this example, use lines #1 and #2 as input lines and set their characteristic impedances to 50 ohms. Set their lengths to 0.25 m. Line #3 is the transformer so set its length to 0.125 m and its characteristic impedance to 77.459 ohms. Set the load to 120 ohms. Set the frequency to 600 MHz. Then click “Plot V(z)” and then “Plot the voltage amplitude on all the lines” to demonstrate the match as in Fig. 4.2. We see that the voltage is constant with position on lines #1 and #2, with a VSWR of 1.0000.



```
Marker #1
  514.384
   -20.00
Marker #2
  685.739
   -19.99
Bandwidth
  171.354
```

Fig. 4.3 Use the frequency-sweep function to find the bandwidth as 171.35 MHz.

To find the bandwidth of the match for a return loss of 20 dB or better, click on “Plot a parameter as a function of frequency” then “Specify the range” and set the start and stop frequency to 200 and 1000 MHz respectively. Then click on “Calculate the frequency response” to get the return loss. Use the snap function to snap the markers to -20 dB to get Fig. 4.3. The bandwidth is 171.35 MHz.



```
Click the mouse on a red label to change the properties:
        Generator       Line #1        Load #1
        Frequency       Line #2
                        Line #3
                        Line #4
                        Line #5

Frequency=   300.000 MHz.

Choose an action by clicking the mouse on a red text string:
Plot V(z) or I(z), and find the VSWR.
Find voltages, currents, and power.
Draw a Smith Chart.
Smith Chart Calculations.
Plot a parameter as a function of the frequency.

Save the circuit to a data file.
Choose a new circuit.
Change the settings.                              Exit
```

Fig. 4.4 The circuit template called three-step quarter wave transformer.

4.2. Three-Step Quarter Wave Transformer

To improve the bandwidth of the match, we can use a multi-step quarter wave transformer. The circuit template called three-step quarter wave transformer, Fig. 4.4, consists of five transmission lines in series. The component values demonstrate matching a 50 ohm line to a 100 ohm load, with a three-step transformer consisting of lines #2, 3 and 4. Let's use the circuit template to demonstrate a four step transformer to match a 50 ohm line to a 120 ohm load at 600 MHz.

The transformer can be designed using the method in [2]. Evaluate coefficient A with $N = 4$ and $Z_L = 120$ ohms,

$$A = 2^{-N}\frac{Z_L - Z_0}{Z_L + Z_0} = 2^{-4}\frac{120-50}{120+50} = 2^{-4}\frac{70}{170} = 0.025735$$

The binomial coefficients are given by

$$C_n^N = \frac{N!}{(N-n)!n!}:$$

and are

$$C_0^4 = \frac{4!}{(4-0)!0!} = \frac{4!}{4!} = 1$$

$$C_1^4 = \frac{4!}{(4-1)!1!} = \frac{24}{6} = 4$$

$$C_2^4 = \frac{4!}{(4-2)!2!} = \frac{2x3x4}{2x2} = 3x2 = 6$$

$$C_3^4 = \frac{4!}{(4-3)!3!} = \frac{2x3x4}{1x2x3} = 4$$

$$C_4^4 = \frac{4!}{(4-4)!4!} = 1$$

The characteristic impedance values of the lines are found with

$$\ln\frac{Z_{n+1}}{Z_n} \approx 2^{-N} C_n^N \ln\frac{Z_L}{Z_0}$$

hence

$$\ln\frac{Z_1}{Z_0} \approx 2^{-N} C_0^N \ln\frac{Z_L}{Z_0} = 2^{-4} x1x \ln\frac{120}{50} = 0.054716$$

So

$$Z_1 = Z_0 e^{2^{-N} C_0^N \ln Z_L / Z_0} = 50e^{0.054716} 52.812 \text{ ohms}$$

The characteristic impedances of the remaining sections are calculated with the same formula. Thus

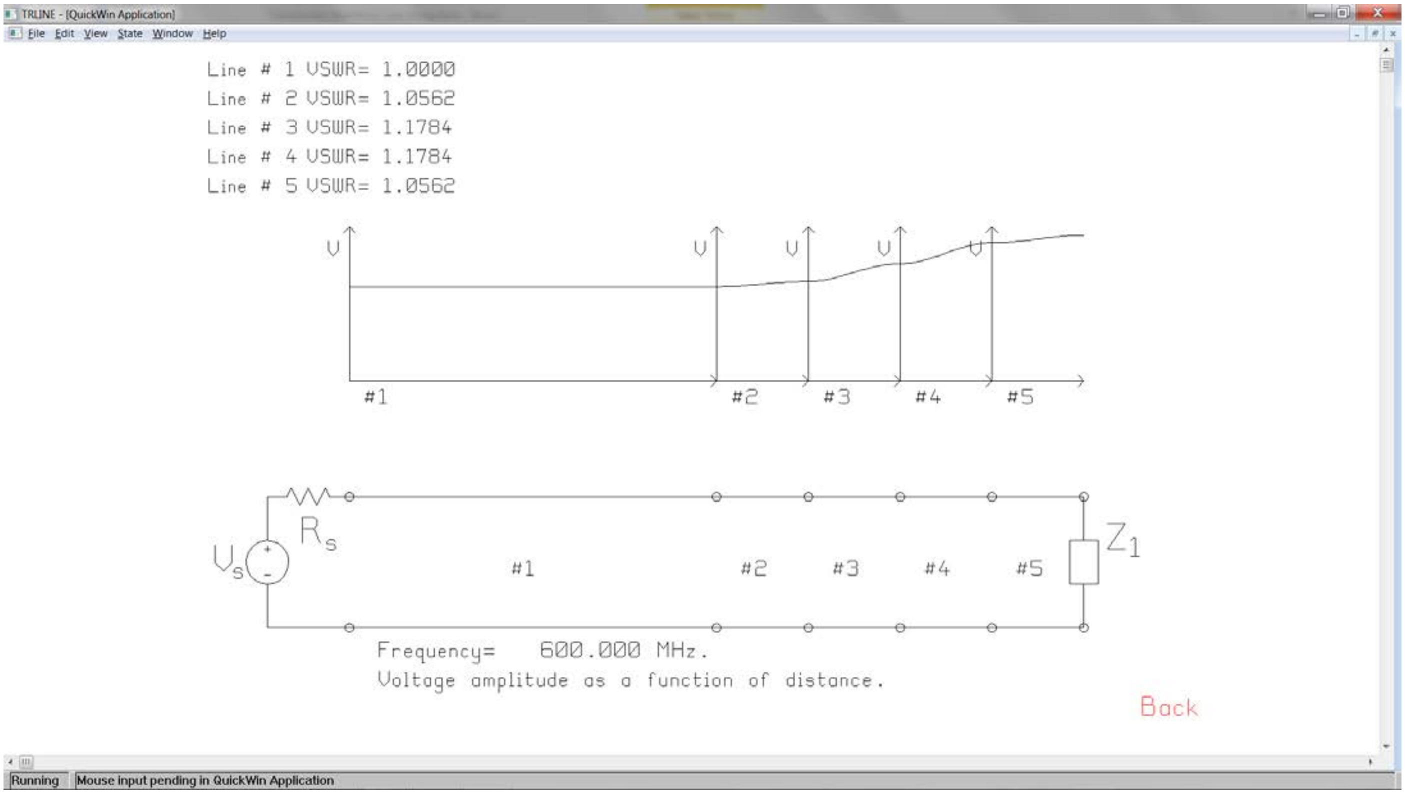
$$Z_2 = 65.733 \text{ ohms}$$

$$Z_3 = 91.278 \text{ ohms}$$

and

$$Z_4 = 113.610 \text{ ohms}$$

Enter these values for lines #2, 3, 4 and 5 in Fig. 4.4. Set the frequency to 600 MHz. The input line length is 0.25 m, and the four transformer sections have length 0.125 m.

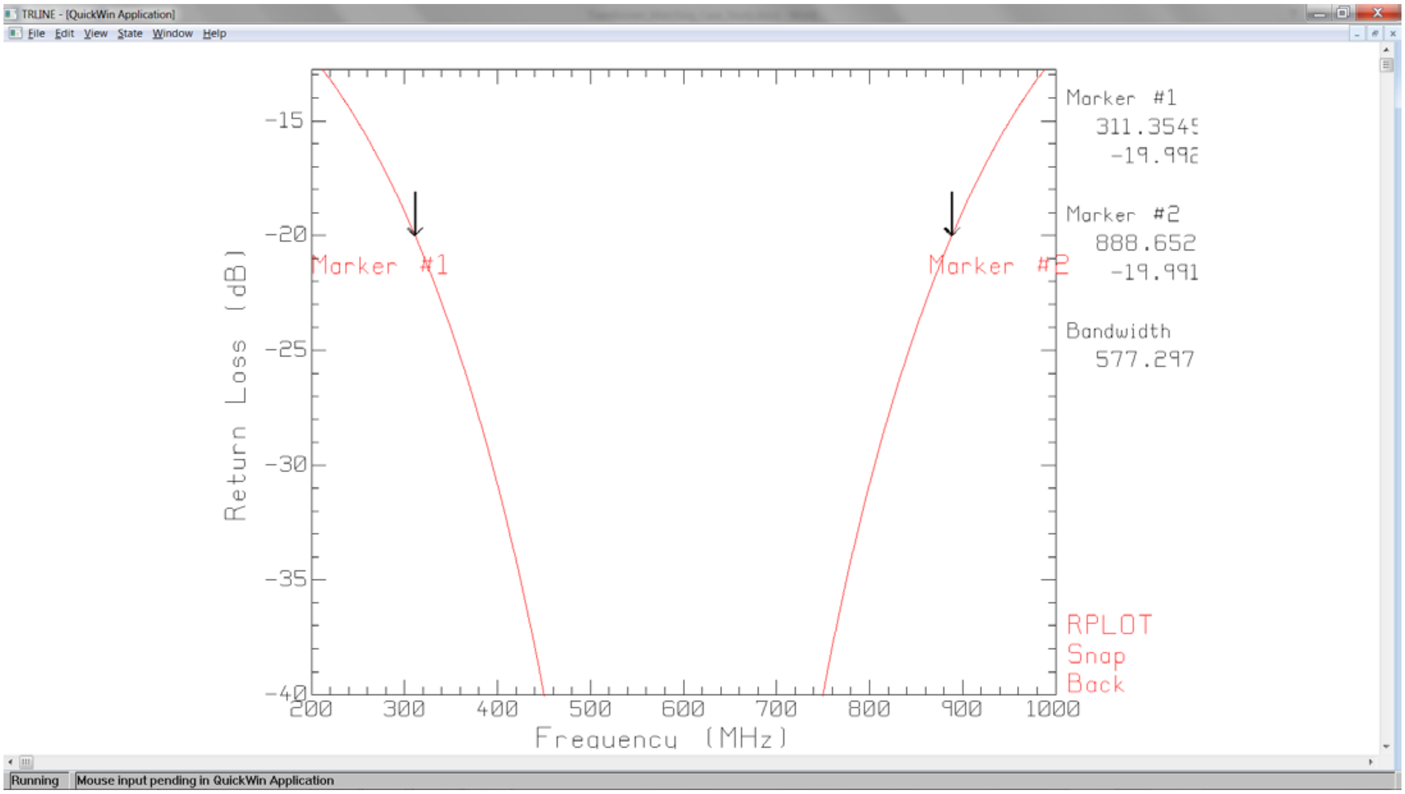


```
Line # 1 VSWR= 1.0000
Line # 2 VSWR= 1.0562
Line # 3 VSWR= 1.1784
Line # 4 VSWR= 1.1784
Line # 5 VSWR= 1.0562
```

```
Frequency=   600.000 MHz.
Voltage amplitude as a function of distance.
```

Fig. 4.5 The four-section quarter wave transformer obtains a perfect match at 600 MHz.

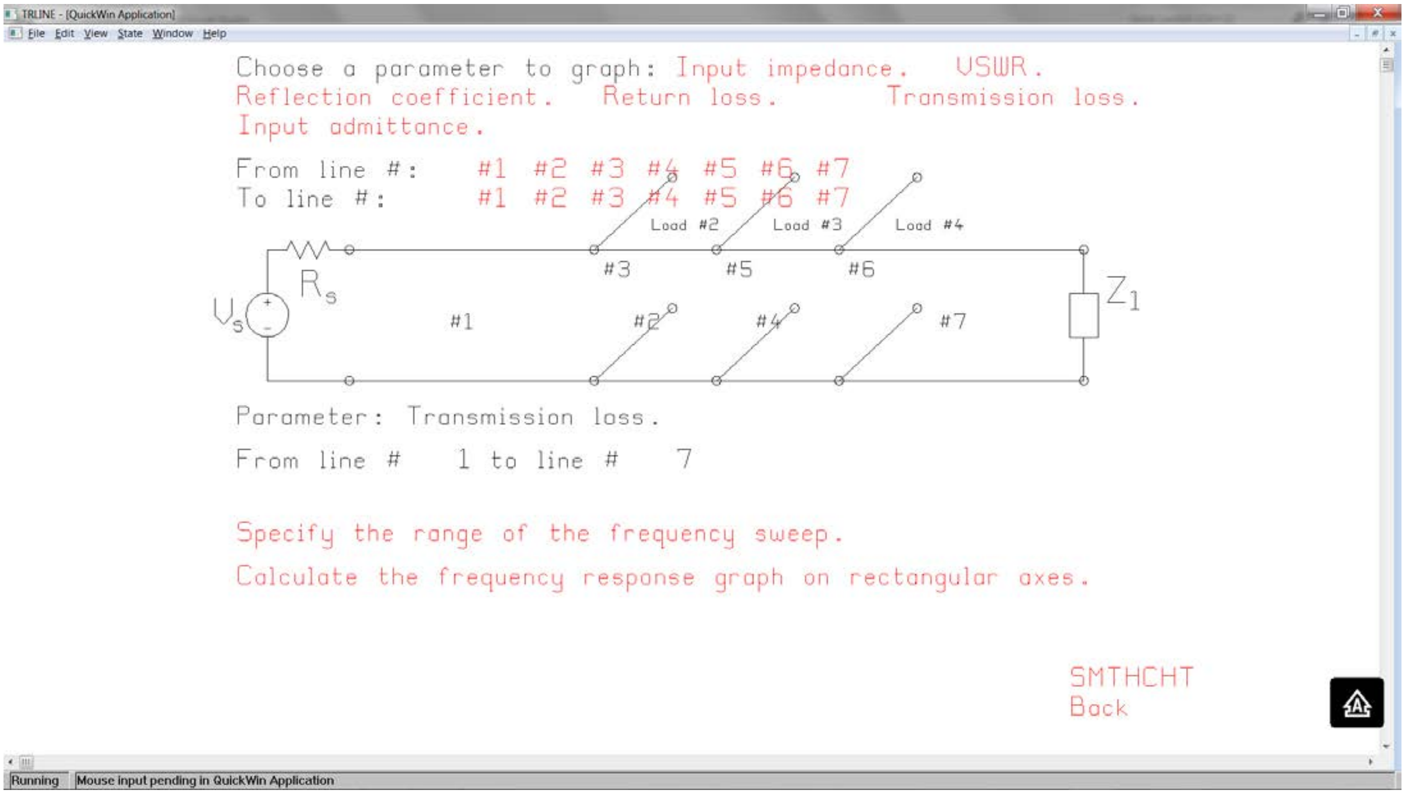
Fig. 4.5 shows the voltage on each transmission line at 600 MHz and demonstrates that the transformer matches the 50 ohm line to the 120 ohm load perfectly.



```
Marker #1
  311.3545
   -19.992
Marker #2
  888.652
   -19.991
Bandwidth
  577.297
```

Fig. 4.6 The bandwidth of the four-step quarter wave transformer.

Fig. 4.6 shows the return loss of the four-step quarter wave transformer. The bandwidth for a return loss of 20 dB or better is 577.297 MHz.



```
Choose a parameter to graph: Input impedance.  VSWR.
Reflection coefficient.   Return loss.      Transmission loss.
Input admittance.

From line #:     #1  #2  #3  #4  #5  #6  #7
To line #:       #1  #2  #3  #4  #5  #6  #7

Parameter: Transmission loss.

From line #    1 to line #    7

Specify the range of the frequency sweep.

Calculate the frequency response graph on rectangular axes.
```

Fig. 5.1 The low-pass filter circuit.

5. Filters

The TRLINE program can be used to demonstrate filters constructed with shunt stubs. The built-in circuits show a low pass filter and a bandstop filter, as described in the following.

5.1.Chebyshev Low-Pass Filter

Fig. 5.1 shows TRLINE's low-pass filter circuit comprised of four transmission lines in series with three shunt stubs. The circuit comes set up to demonstrate Pozer's low-pass filter in Example 8.5 of Reference [2]. The problem is to design a Chebyshev or equal-ripple low-pass filter with a ripple of 3 dB, a cutoff frequency of 4 GHz, and N=3 elements. The impedance of the transmission lines and load is 50 ohms.

In Fig. 5.1, line #1 is the input line connecting the generator to the filter, and line #7 is the output line, both of characteristic resistance R_c =50 ohms. The load is Z_1 =50 ohms. The filter consists of series lines #2 and #4, of characteristic resistance R_{c2} and R_{c4} respectively, and three open-circuited stubs, lines #3, #5 and #6, of characteristic resistance R_{c3}, R_{c5} and R_{c6} respectively. Lines #2, #3, #4, #5 and #6 all have length one-eighth wavelength at the cutoff frequency. To design the filter we must specify the characteristic resistance of the five lines making up the filter: R_{c2} , R_{c3}, R_{c4} R_{c5} and R_{c6}.

Pozar [2] explains the design in detail with instructive circuit diagrams. Table 1 summarizes the steps in Pozar's design. A lumped-element low-pass prototype consists of a series inductance, L_1, a shunt capacitance C_1, and another series inductance L_2, terminated with a matched load, R_L . The prototype is designed using element values taken from Pozar's Table 8.4 [2] for a Chebyshev filter with a 3 dB ripple. The prototype has a normalized impedance of 1 ohm and a normalized cutoff frequency of ω =1 rad/sec. The second step is to replace the L and C elements by short-circuited and open-circuited stubs of length one-eighth wavelength at the cutoff frequency. The characteristic impedance values of the "equivalent" stubs R_{ce1}, R_{ce2}, and R_{ce3} are derived from the *L* and *C* values as in Table 1. The third step is to add a "unit element" transmission line line to each end of the filter of length one-eighth wavelength, and then use one of Kuroda's Identities to replace the line and series short-circuited stub with a shunt open-circuited stub and series line, of appropriate characteristic impedance as given in column 4 of Table 1. Thus, each inductor in the prototype circuit is replaced by a shunt open-circuited stub of characteristic resistance R_{csn} and a series line of characteristic impedance R_{cL1}. The final step is to scale the impedance to 50 ohms by multiplying all the characteristic impedances by 50 ohms. The last column of the table gives the characteristic impedance of each of the five transmission lines making up the filter in Fig. 5.1.

Table 1 Design of a low-pass filter [2].

Component	Value	Replace by equivalent stub of characteristic resistance R_{cen}	Equivalent Shunt Stub Stub $R_{csn} = 1+\frac{1}{R_{cen}}$ Line $R_{cLn} = R_{cen} + 1$	Scaled Impedance for Fig. 5.1
Series L_1	3.3487	Series short-circuited stub with $R_{ce1} = L_1$ =3.3487	$R_{cs1} = 1+\frac{1}{3.3487}$ =1.2986 $R_{cL1} = R_{ce1} + 1$ =4.3487	Stub $R_{c3} = 64.9$ ohms Line $R_{c2} = 217.5$ ohms
Shunt C_1	0.7117	Shunt open-circuited stub with R_{ce2} =1/C_1=1.405		$R_{c5} = 70.3$ ohms
Series L_2	3.3487	Series short-circuited stub with	$R_{cs3} = 1+\frac{1}{3.3487}$ =1.2986	Stub $R_{c6} = 64.9$ ohms

		$R_{ce3} = L_2$ =3.3487	$R_{cL3} = R_{ce3} + 1$=4.3487	Line $R_{c4} = 217.5$ ohms
load R_L	1.0000	R_L =1 for normalized impedances		50 ohms

The line lengths for the filter are one-eighth wavelength at the cutoff frequency of 4 GHz. At a speed of travel of 30 cm/ns, the wavelength is 7.5 cm and one-eighth wavelength is 0.9375 cm, so lines #2, 3, 4, 5 and 6 in the circuit of Fig. 5.1 are set to this length. The series lines in the filter, lines #2 and 4, are set to characteristic impedance 217.5 ohms. Stub #1 is line #3 and is set to 64.9 ohms; stub #2 is line #5 and is set to 70.3 ohms, and stub #3 is line #6 and is set to 64.9 ohms. The input line, #1, and the output line, #7, have arbitrary lengths, set to 1.875 cm for this example, and characteristic resistance 50 ohms. The load, Z_1 in Fig. 5.1, is set to 50 ohms for the transmission loss calculation.

5.2. Transmission Loss

The TRLINE program can calculates the transmission loss as a function of frequency. Fig. 5.1 shows the frequency sweep menu where the user has selected the transmission loss as the parameter. TRLINE calculates the transmission loss from “input” line *m* to “output” line *n*. The travelling wave complex amplitudes on the input line, #*m*, are V_m^+ and V_m^-. The output line, #*n*, should be terminated with a matched load. The travelling wave amplitudes are V_m^+ and V_m^-=0. The transmission loss from line *m* to line *n* is defined as

$$TL = 20\log\frac{|V_m^+|}{|V_n^+|}$$

For the low pass filter, use the “From line #” button in Fig. 5.1 to select line #1 coming from the generator as the input line. Use “To line #” to select line #7 as the output line leading to the matched load. Then click on “Calculate the frequency response”. TRLINE then solves the circuit at each frequency in the sweep, and uses the travelling-wave amplitudes on lines #1 and #7 to evaluate the transmission loss as

$$TL = 20\log\frac{|V_7^+|}{|V_1^+|}$$

TRLINE graphs the TL as in Fig. 5.1.

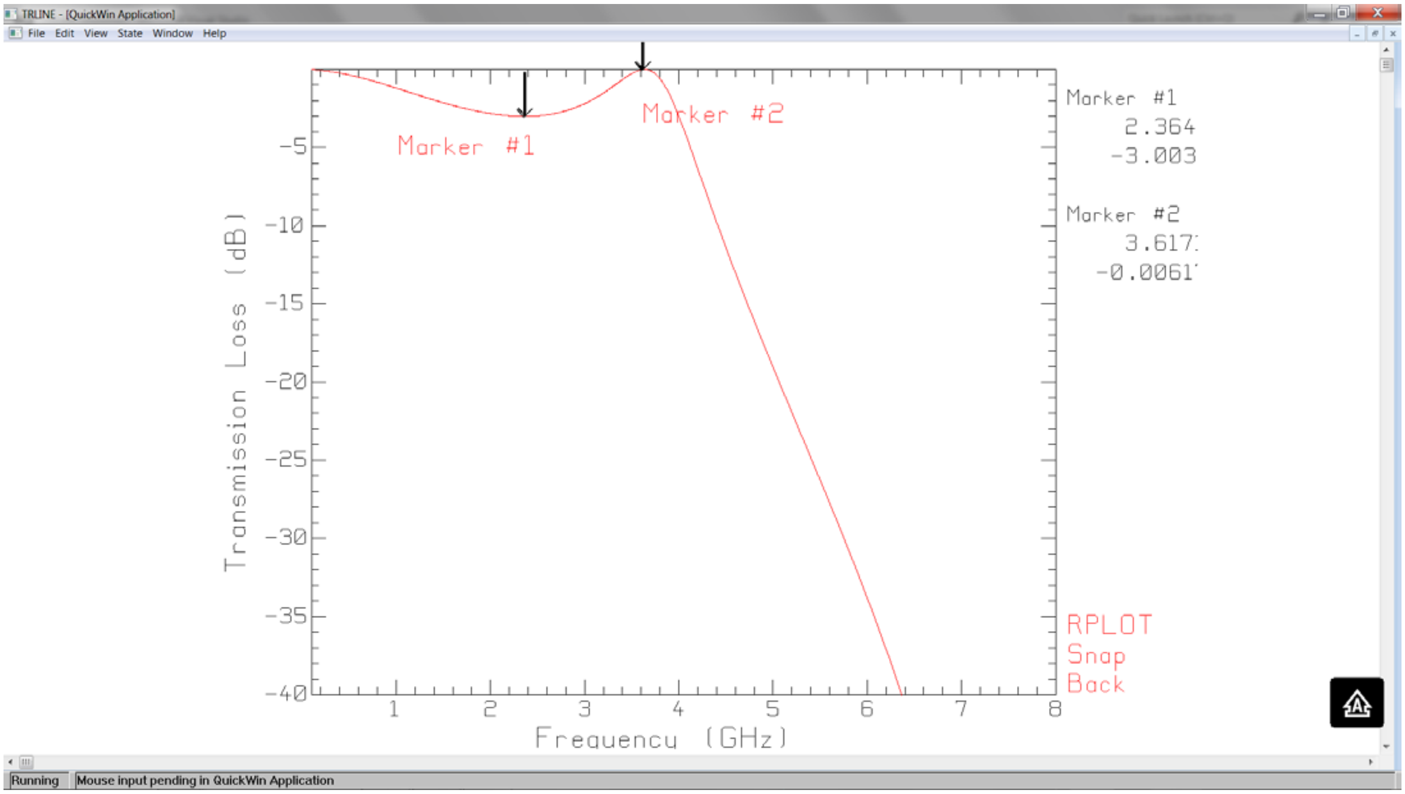
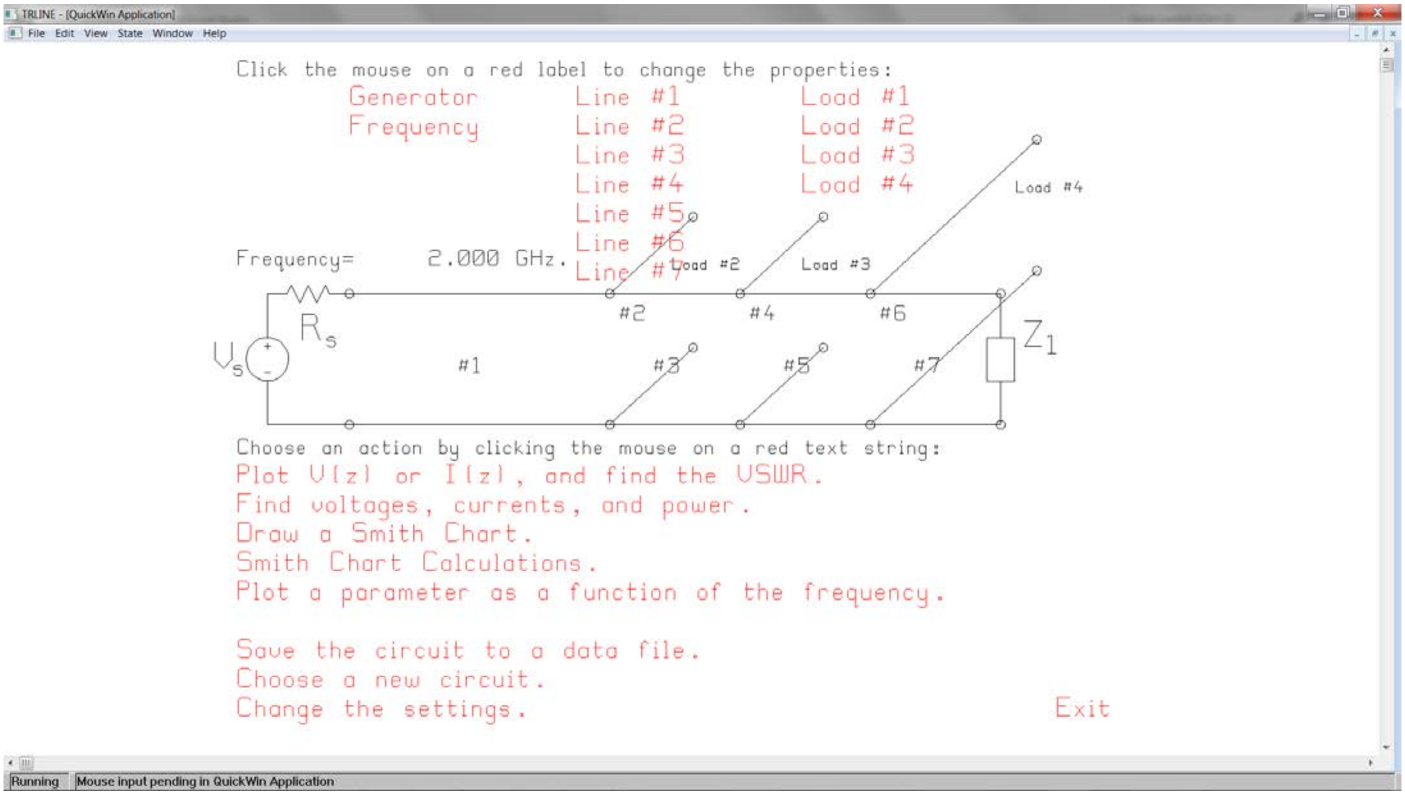


Fig. 5.2 The transmission loss of the low pass filter.

Fig. 5.2 shows the transmission loss as a function of frequency from 0.1 GHz to 8 GHz. The figure shows a low-pass filter with a ripple of 3 dB and a cutoff frequency of 4 GHz, as expected. At the cutoff frequency the transmission loss is 3 dB. In Fig 5.2 the markers have been set to demonstrate the 3 dB ripple.



Click the mouse on a red label to change the properties:

Choose an action by clicking the mouse on a red text string:
Plot V(z) or I(z), and find the VSWR.
Find voltages, currents, and power.
Draw a Smith Chart.
Smith Chart Calculations.
Plot a parameter as a function of the frequency.

Save the circuit to a data file.
Choose a new circuit.
Change the settings.

Fig. 5.3 Circuit template for the bandstop filter.

5.3. Bandstop Filter

Pozar [2] explains the design of a Chebyshev bandstop filter. In Example 8.8 [2] he presents the design of a Chebyshev bandstop filter with N=3, a center frequency of 2 GHz, a bandwidth of 15%, a ripple of 0.5 dB, and an impedance of 50 ohms. Fig. 5.3 shows the circuit template. Line #1 is the input and line #7 is the output, and these lines have characteristic impedance 50 ohms. The load is $Z_1 = 50$ ohms. Lines #2, 3, 4, 5 and 6 comprise the filter. All of these lines are a quarter wavelength in length at 2 GHz. The series lines, #3 and 5, have characteristic impedance 50 ohms. The stubs are terminated in open circuits. The low-pass prototype circuit elements are taken from Pozar's Table 8.3 [2] and are $g_1 = 1.5963$, $g_2 = 1.0967$, and $g_3 = 1.5963$. The characteristic impedance of the stubs are then calculated using

$$Z_{0n} = \frac{4Z_0}{\pi g_n \Delta}$$

where $Z_0 = 50$ ohms, the fractional bandwidth is $\Delta = 0.15$. Thus for stub #1, $Z_{01} = 265.9$ ohms, and this is line #2 in Fig. 5.3. For stub #2, $Z_{02} = 387.0$ ohms, and this is line #4, and for stub #3, $Z_{03} = 265.9$ ohms, and this is line #3. These values are used in the "bandstop filter" circuit template in the entry menu of Fig. 2.1.

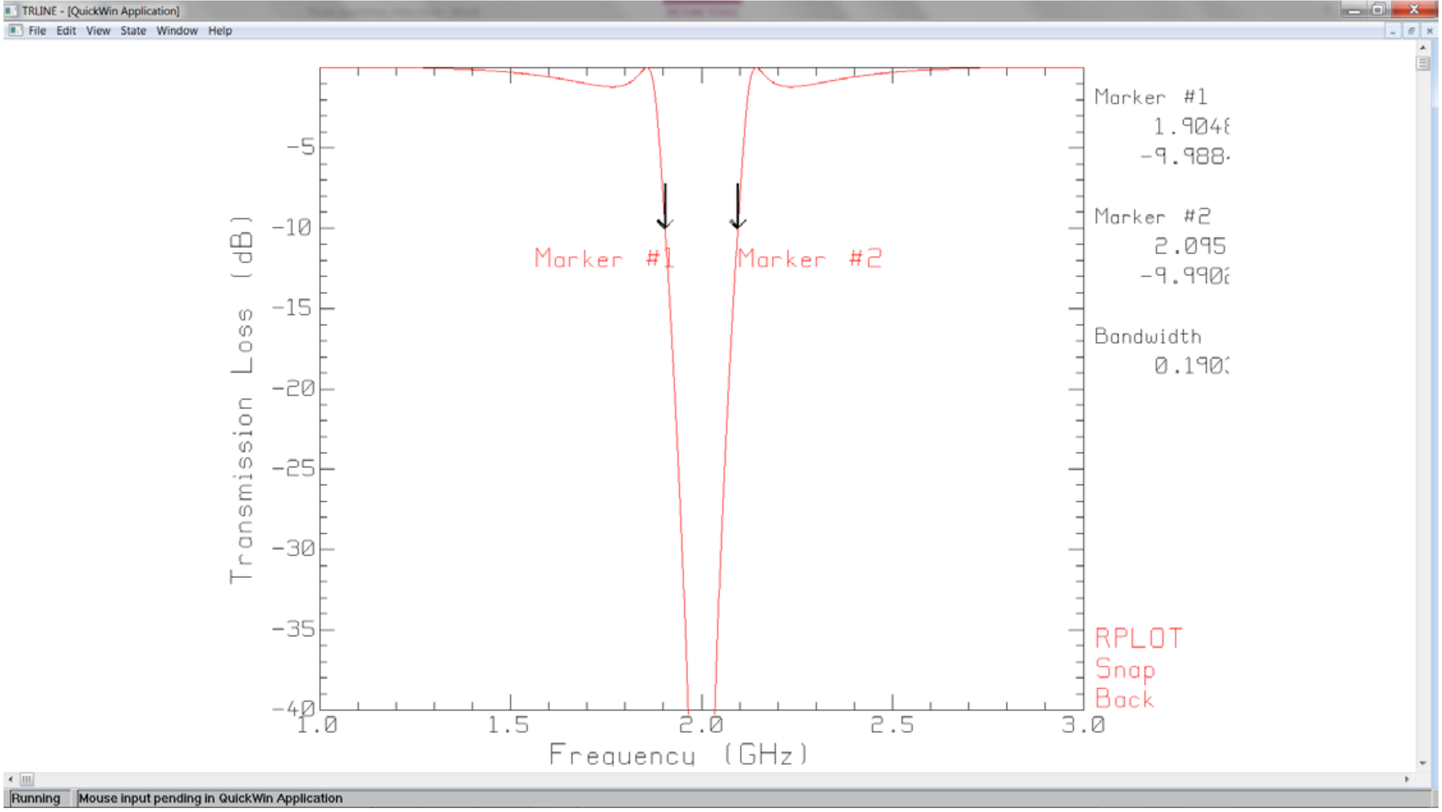
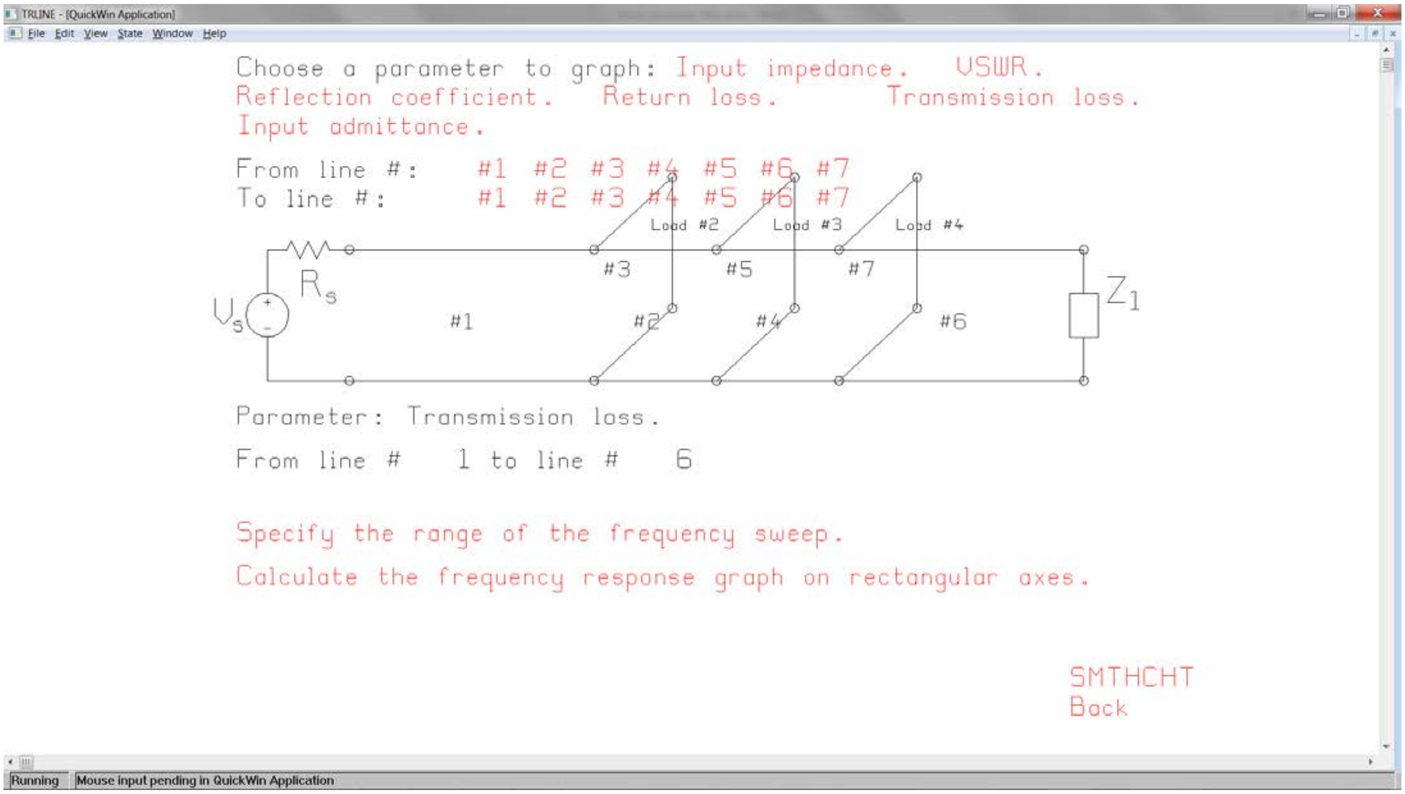


Fig. 5.4 Transmission loss of the bandstop filter.

Fig. 5.4 shows the transmission loss of the bandstop filter, from the input line (#1) to the output line (#7). We see that the filter is centered at 2 GHz as expected. For a transmission loss of -0.5 dB, the bandwidth is 0.260, which is approximately the expected 15% bandwidth. The figure shows that the bandwidth for a transmission loss of -10 dB is 0.190 GHz.



Choose a parameter to graph: Input impedance. VSWR.
Reflection coefficient. Return loss. Transmission loss.
Input admittance.

From line #: #1 #2 #3 #4 #5 #6 #7
To line #: #1 #2 #3 #4 #5 #6 #7

Parameter: Transmission loss.

From line # 1 to line # 6

Specify the range of the frequency sweep.

Calculate the frequency response graph on rectangular axes.

SMTHCHT
Back

Mouse input pending in QuickWin Application

Fig. 5.5 The N=3 bandpass filter uses short circuited stubs.

5.4.Bandpass Filter with N=3

We can make a bandpass filter by terminating the quarter-wave stubs with short circuits. At the center frequency the input impedance of a quarter-wave stub terminated by a short circuit is an open circuit, so the stubs do nothing and the signal passes through the filter with no attenuation. To demonstrate the bandpass filter, design a filter with N=3, a center frequency of 2 GHz, a bandwidth of 15%, a ripple of 0.5 dB, and an impedance of 50 ohms. The low-pass prototype has elements from Pozar's Table 8.3 [2]: $g_1 = 1.5963$, $g_2 = 1.0967$, and $g_3 = 1.5963$. For the bandpass filter, Pozar gives the characteristic impedances of the stubs as

$$Z_{0n} = \frac{\pi Z_0 \Delta}{4 g_n}$$

where $Z_0 = 50$ ohms, and the fractional bandwidth is $\Delta = 0.15$. For stub #1, $Z_{01} = 3.690$ ohms; for stub #2, $Z_{02} = 5.731$ ohms; and for stub #3, $Z_{03} = 3.690$ ohms.

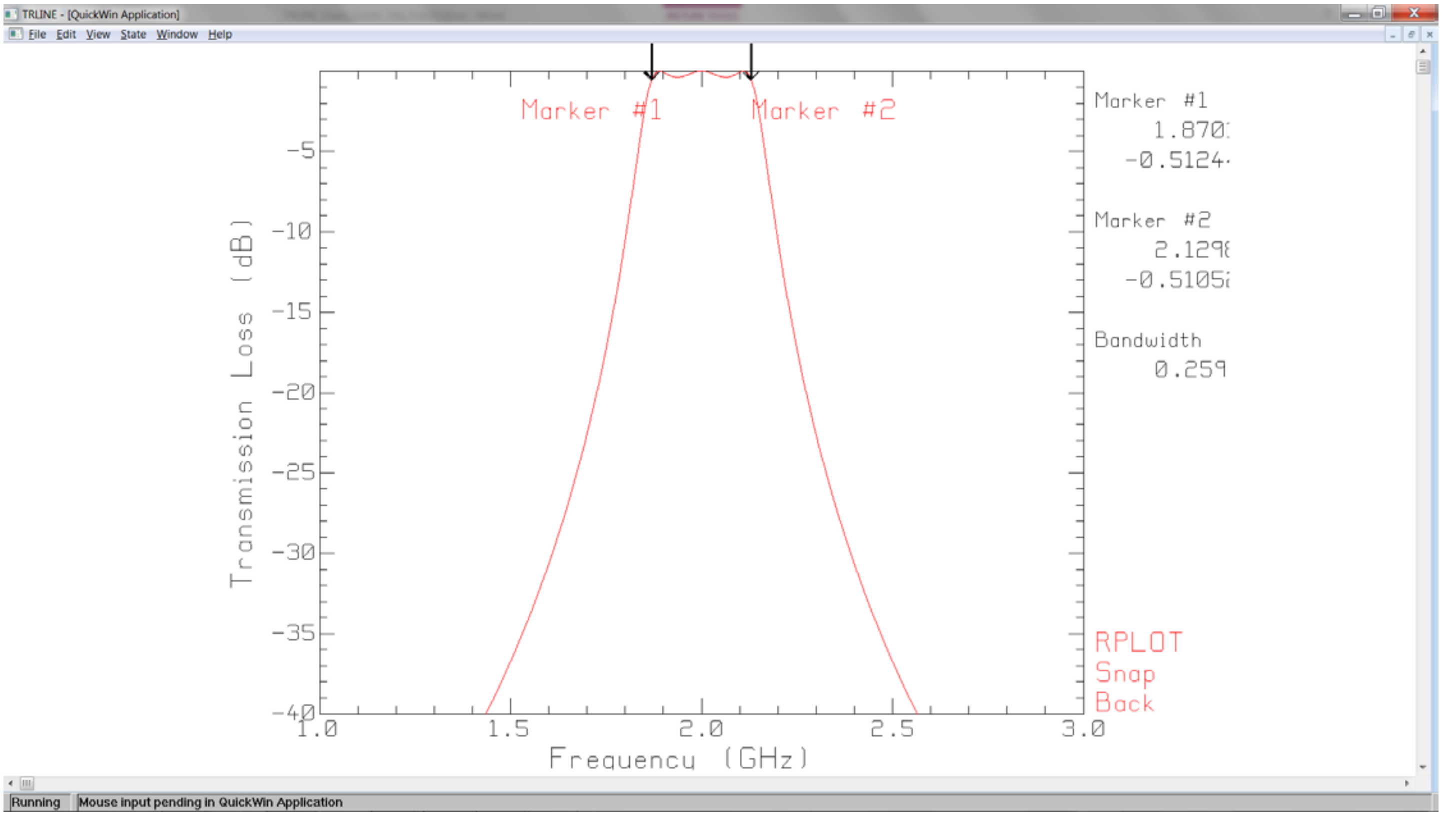
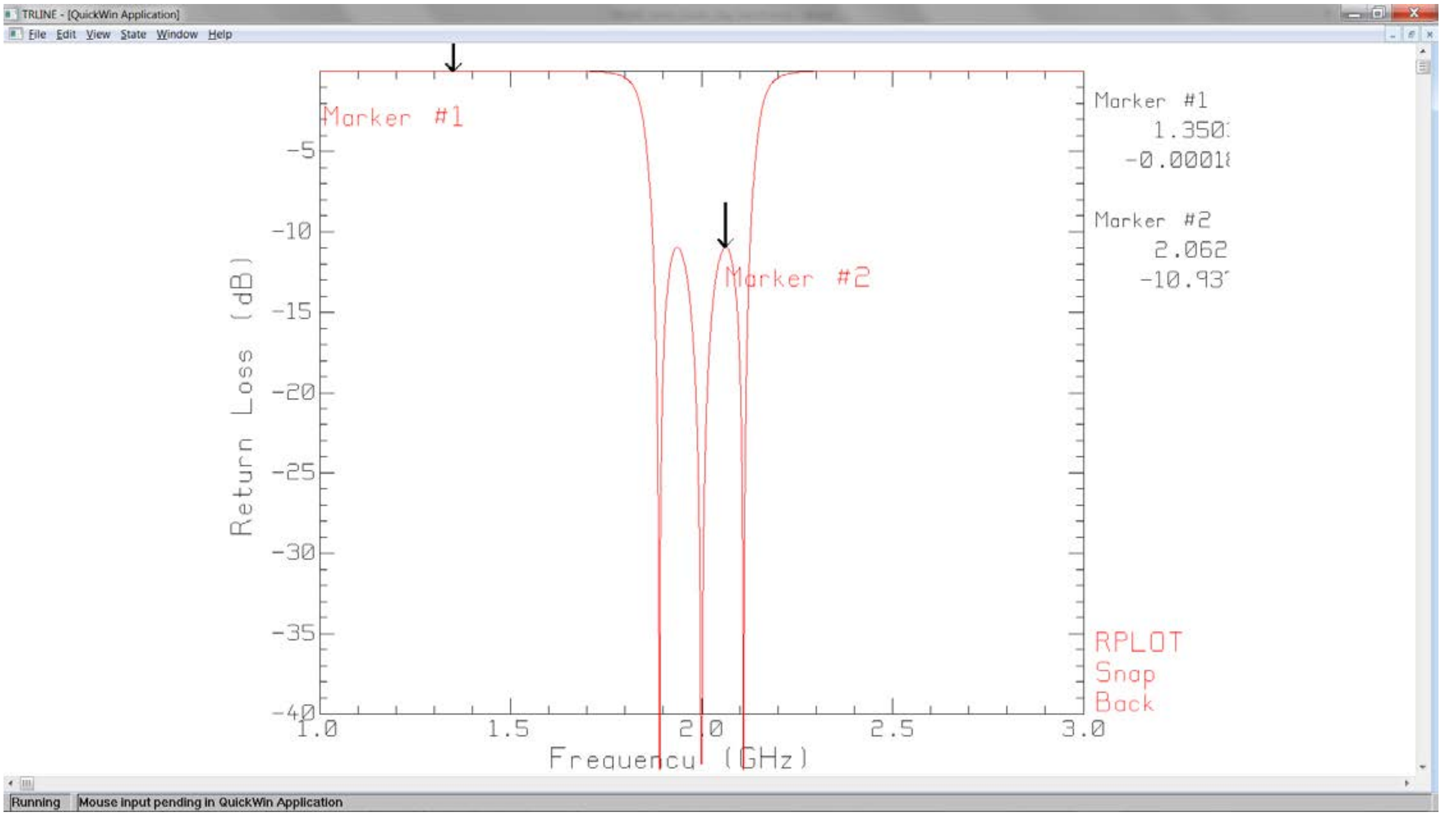


Fig. 5.6 Transmission loss of the bandpass filter.

Fig. 5.6 shows the transmission loss of the Chebyshev filter. It is centered on 2 GHz as expected. The markers are set to show the bandwidth of 0.259 GHz for a transmission loss of 0.5 dB, which corresponds approximately to the expected 15% bandwidth.

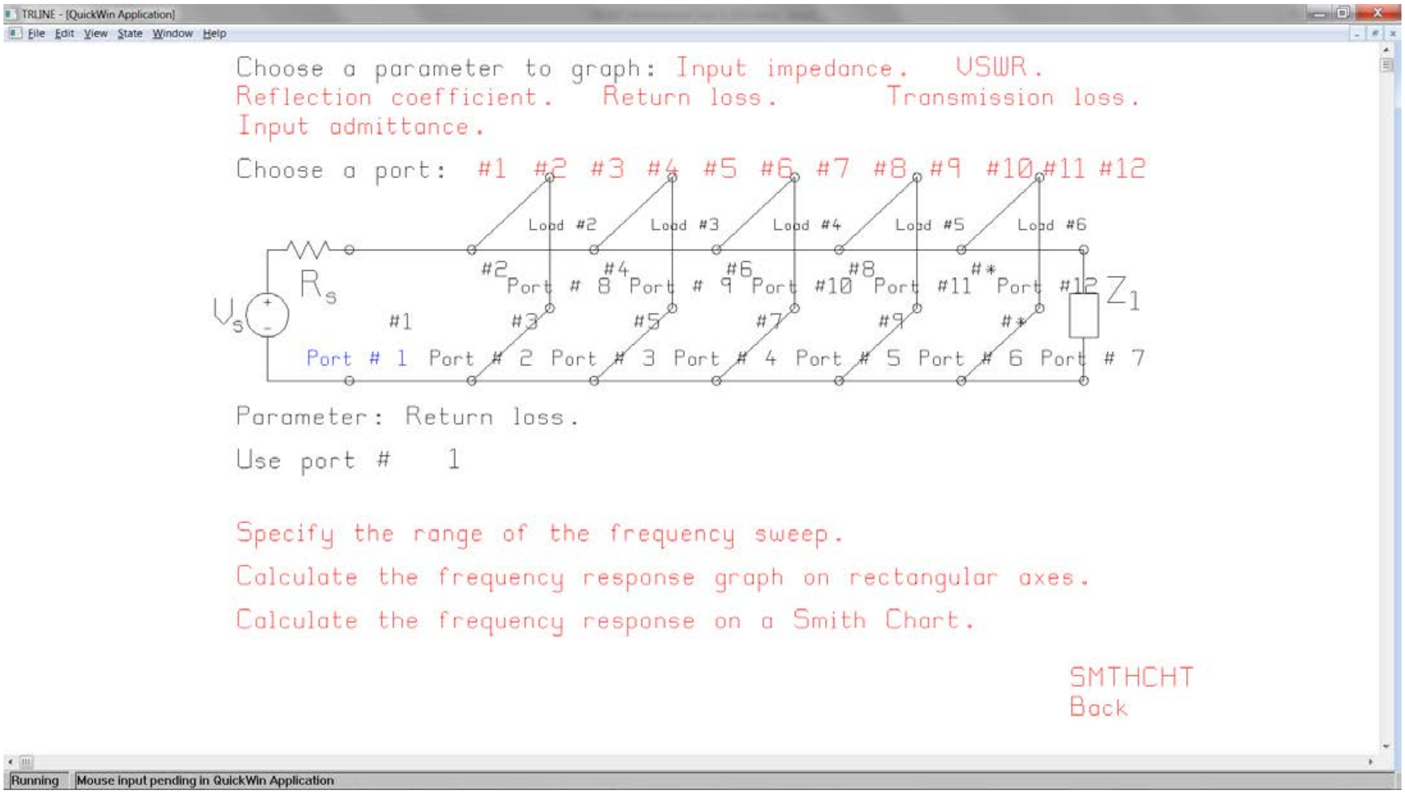


Running

Mouse input pending in QuickWin Application

Fig. 5.7 Return loss of the bandpass filter.

Fig. 5.7 shows the return loss of the Chebyshev filter. The peaks in the pass band are at -10.9 dB return loss.



Choose a parameter to graph: Input impedance. VSWR. Reflection coefficient. Return loss. Transmission loss. Input admittance.

Choose a port: #1 #2 #3 #4 #5 #6 #7 #8 #9 #10 #11 #12

Parameter: Return loss.

Use port # 1

Specify the range of the frequency sweep.

Calculate the frequency response graph on rectangular axes.

Calculate the frequency response on a Smith Chart.

Running

Mouse input pending in QuickWin Application

Fig. 5.8 Bandpass filter with N=5.

5.5. Bandpass Filter with N=5

We can make a bandpass filter using N=5 with the circuit template of Fig. 5.8. This template has six transmission lines in series, and five stubs. To design a bandpass filter with N=5, a 3 dB ripple, a center frequency of 4 GHz, and a 15% bandwidth, use Table 8.3 in [2] to get the component values for the low pass prototype, listed in Table 5.5. Then calculate the characteristic impedance for each stub using [2]

$$Z_{0n} = \frac{\pi Z_0 \Delta}{4 g_n}$$

with $\Delta = 0.15$ and $Z_0 = 50$ ohms. Enter these values for the stub characteristic impedances into TRLINE, and then use the frequency sweep menu to compute the transmission loss and the return loss.

Tale 5.5 Component values for the N=5 bandpass filter.

Element	Value	Characteristic Impedance
g_1	3.4817	1.692
g_2	0.7618	7.732
g_3	4.5381	1.298
g_4	0.7618	7.732
g_5	3.4817	1.692

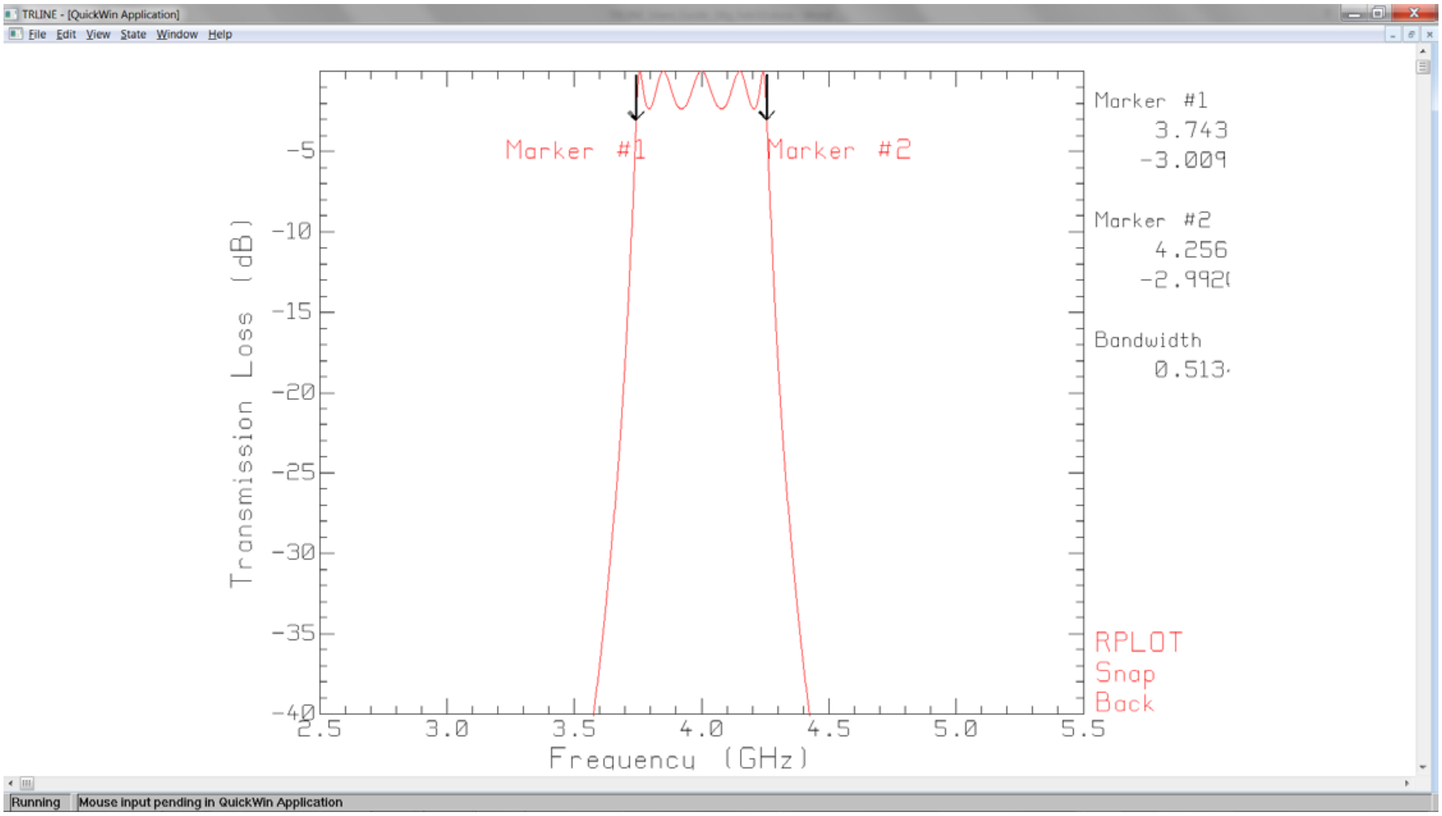


Fig. 5.9 Transmission loss of the N=5 filter for a 3 dB ripple.

Fig. 5.9 shows the transmission loss of the N=5 filter. The filter is centered at 4 GHz. The ripple is approximately 3 dB, and the bandwidth for a return loss of 3 dB is 0.513 GHz.

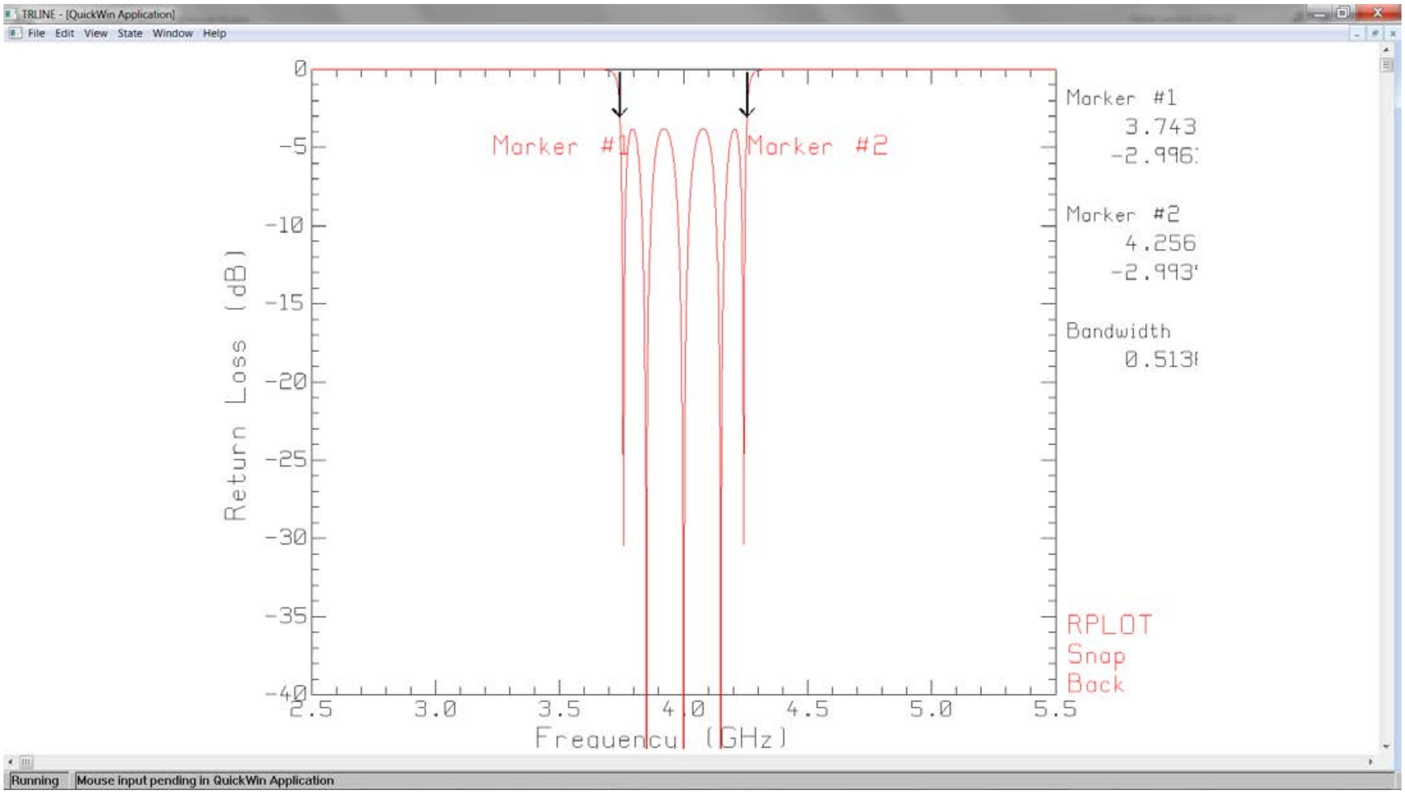


Fig. 5.10 Return loss for the N=5 filter.

Fig. 5. 10 shows the return loss of the N=5 filter. We have five sharp minima in the return loss, separated by four peaks of equal magnitude, as expected from a Chebyshev bandpass filter.

6. Conclusion

Program TRLINE's circuit templates make it easy for the student to study typical circuits encountered in a "fields and waves" course or in a "microwave circuits" course. TRLINE illustrates the basic behavior of transmission lines well. TRLINE provides a computational "laboratory" for students to test their solutions to pencil-and-paper homework problems involving series transmission lines, transformer matching, stub matching, and branching circuits. TRLINE's frequency sweeping capabilities make it possible to study the bandwidth of these circuits. TRLINE provides circuit templates for more advanced topics such as power splitters, band pass and bands top filters.

Reference

[1] C.W. Trueman, "Interactive Transmission Line Computer Program for Undergraduate Teaching," IEEE Trans. on Education, Vol. 43, No. 1, pp. 1-14, February 2000.
[2] P. Pozar, "Microwave Engineering", 3rd edition, Wiley 2004.