Appendix A

Voltage Stability Toolbox (VST)

A.1 Introduction

Voltage Stability Toolbox (VST) has been developed to investigate stability and bifurcation issues in power systems. The VST integrates the symbolic and numeric computations with a graphical menu-driven interface based on MATLAB and its Extended Symbolic Toolbox. It implements symbolic computations to build exact load flow equations and Jacobian matrices including 2^{nd} –order derivatives, required to implement numerical computations such as Newton-Raphson (NR) and Newton-Raphson-Seydel (NRS) for bifurcation analysis. The numerical calculations of solutions for power system equations are performed and controlled via a graphical user interface (GUI). The GUI makes the complex theoretical backgrounds readily accessible to power system engineers who use them to solve practical problems. It has proved to be a useful tool for education and research in the area of power system stability analysis. Even a user not well versed in the mathematics of bifurcation analysis can easily experiment with standard test systems or construct one of his/her own. An experienced user can exploit MATLAB's open architecture to implement and experiment with alternative computational algorithms. Fig. A.1 shows a schematic of the VST.

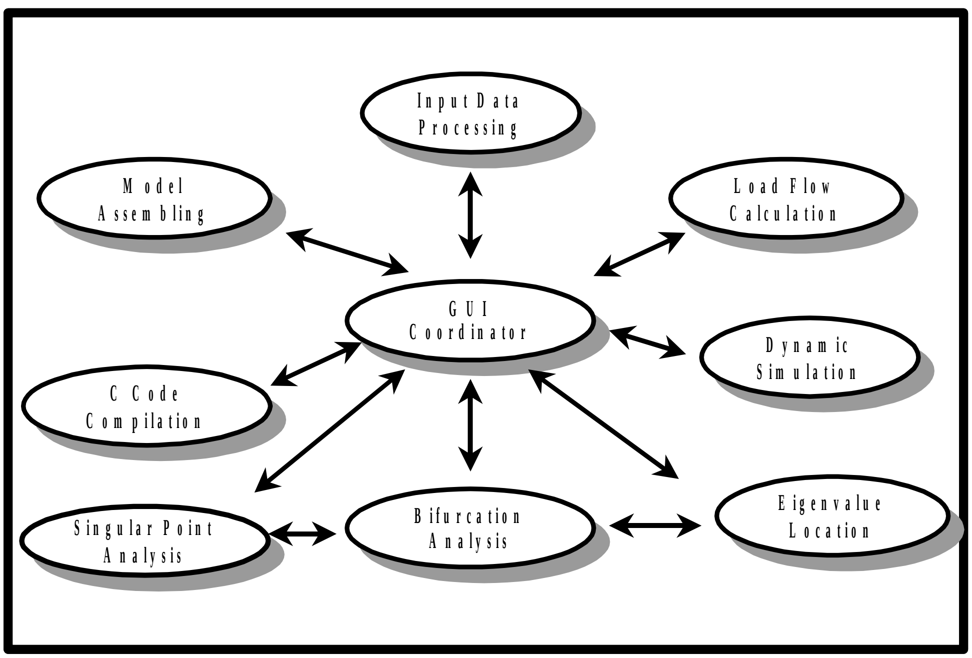

Fig. A.1 The schematic of VST

The following analysis can be performed with the VST, as can be seen in Fig. A.2:

- Load flow analysis
- Time domain simulations
- Static bifurcation analysis
- Dynamic bifurcation analysis
- Singularity analysis
- Eigenvalue analysis

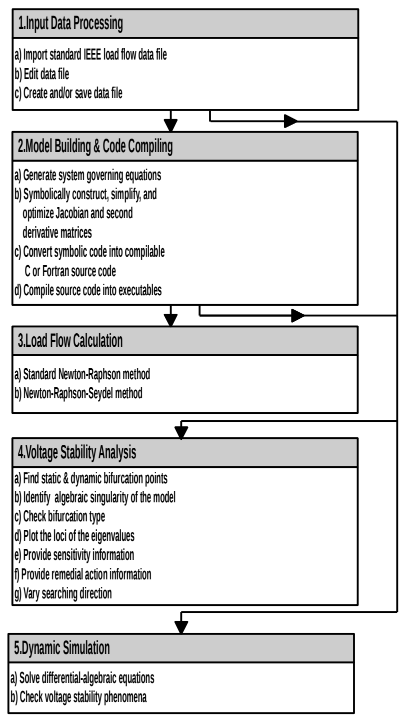

Fig. A.2 Flowchart of VST

A.2 Graphical User Interface of Voltage Stability Toolbox

This section provides brief information on the GUI of the PC version of the VST.

A.2.1 General Information on the Menu Items:

The main window of the VST has the following categories as shown in Fig. A.3:

1. General window menu items: File, Edit, Tools, Windows and Help
2. VST menu items: Model, Analysis, Edit and Help

Model

This menu provides options for data importing, loading the data into MATLAB's workspace, building network equations in either C-form or Maple-form, and compiling the C source.

Analysis

This menu contains several analyses such as load flow, time domain simulation, static and dynamic bifurcation analysis, singular point analysis, etc.

Edit

This menu provides an option to edit the system data such as bus and transmission line data.

Help

This menu item provides information on how to simulate the test systems in the VST.

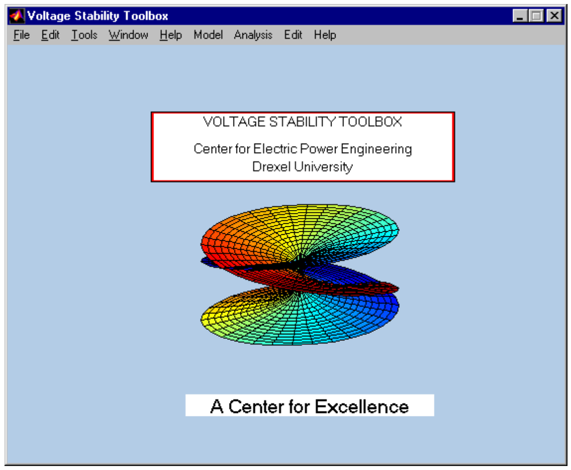

Fig. A.3 The VST main window

A.2.2 VST Pull-Down Menus

This section provides information on each of the main window menu items. Following is a list and general description of the pull-down menus for the four categories.

A.2.2.1 Model Pull-Down Menu

This section describes the options available on the Model pull-down menu, as shown in Fig. A.4.

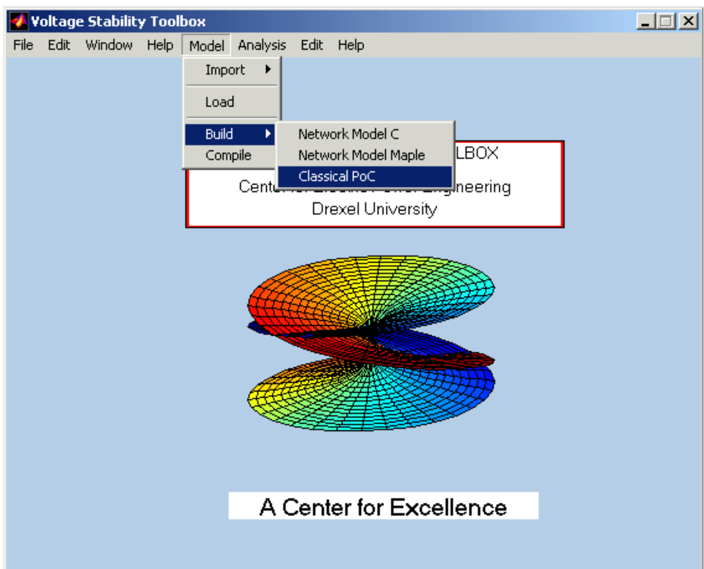

Fig. A.4 The Model pull-down menu

Import

IEEE Static: It imports the standard IEEE data format and converts it to a VST data format.

Load

It allows the user to load the system data into MATLAB's workspace.

Build

Network Model C: It constructs the classical power system equations and the Jacobian matrix in C-form.

Network Model Maple: It constructs the classical power system equations in Maple-form.

Classical PoC: It constructs the classical power system equations and the Jacobian matrix including 2^{nd} -order derivatives and converts the symbolic equations into computationally optimal C source code.

Compile

It compiles the C source as a MEX function callable from MATLAB.

A.2.2.2 Analysis Pull-Down Menu

This section describes the options available on the Analysis pull-down menu, as shown in Fig. A.5.

Load Flow

It implements the Newton-Raphson algorithm for power flow studies.

Simulation

It implements the time-domain simulation for differential-algebraic classical power system model.

Static Bifurcation

It implements a two-stage algorithm consisting of the Newton-Raphson (NR) and Newton-Raphson-Seydel (NRS) methods to compute the equilibria up to the saddle node bifurcation point.

Dynamic Bifurcation Analysis

Zoom around nose point: It implements a two-stage algorithm (NR→NRS) to compute the system equilibria and their corresponding bifurcations, including Hopf and singularity induced bifurcations, and characterizes the stability features of the system equilibria along the nose curve.

Zoom lower part: It implements a three-stage algorithm (NR→NRS→NR) to compute the system equilibria and their corresponding bifurcations, including Hopf and singularity induced bifurcations, and characterizes the stability features of the system equilibria along the nose curve.

Eigenvalue of system matrix

It plots the eigenvalues of the system matrix of $\dot{x} = [A_{SYS}]x$.

Sensitivity around the saddle node bifurcation

It plots the absolute values of the components of the right and left eigenvectors corresponding to the zero eigenvalue of the load flow Jacobian matrix evaluated at the saddle node bifurcation point.

Singular Point Analysis

It implements the NR and NRS algorithms starting at an upper equilibrium point of the nose curve at a fixed parameter to compute the singular points of the DAE model as shown in Fig. A.6.

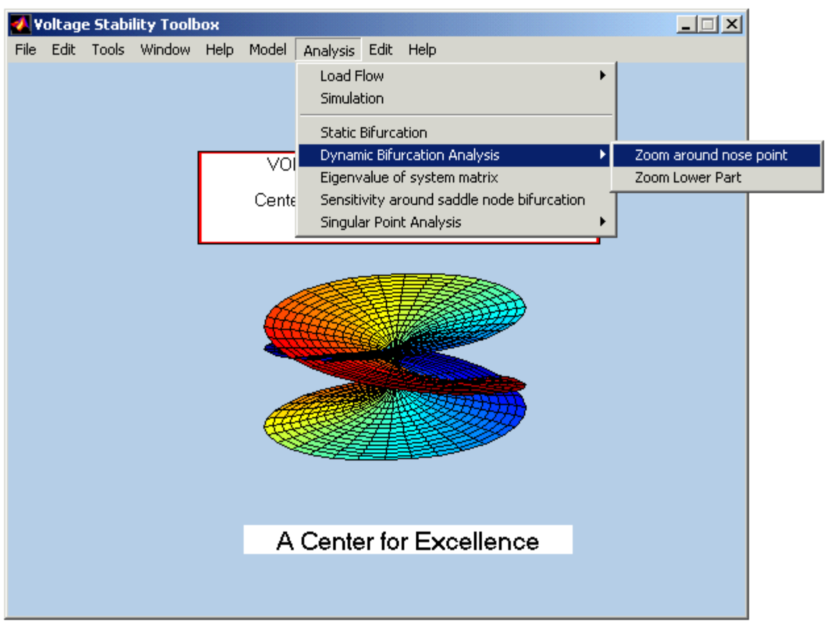

Fig. A.5 The Analysis pull-down menu

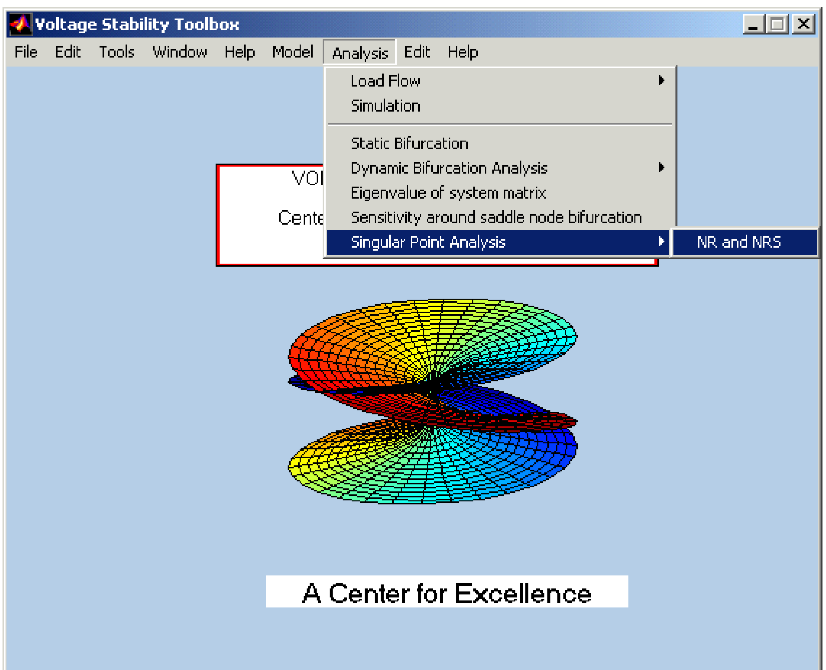

Fig. A.6 The Singular Point Analysis menu item

A.2.2.3 Edit Pull-Down Menu

Edit VST Data

This option allows to the user to view and modify the selected system data, including the bus injections, transmission line parameters, and generator parameters as shown in Fig. A.7.

A.2.2.4 Help Pull-Down menu

Help

This menu provides help windows showing how to run the analysis in the VST as shown in Figs. A.8 and A.9

About

This item provides information about the VST 2.0 as shown in Fig. A.10.

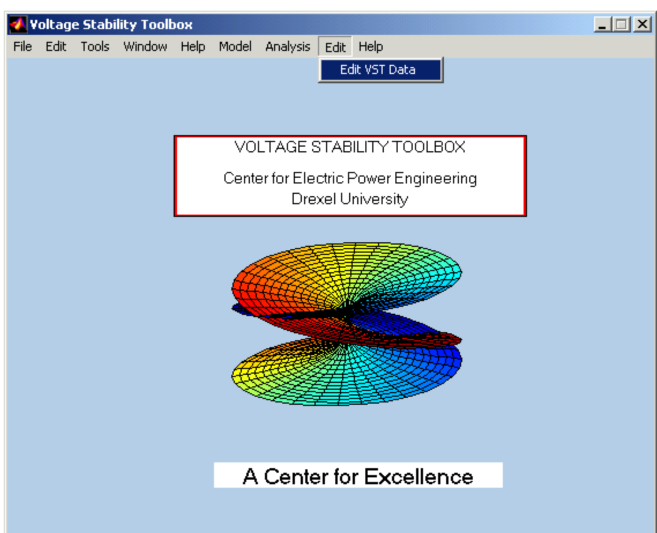

Fig. A.7 The Edit pull-down menu

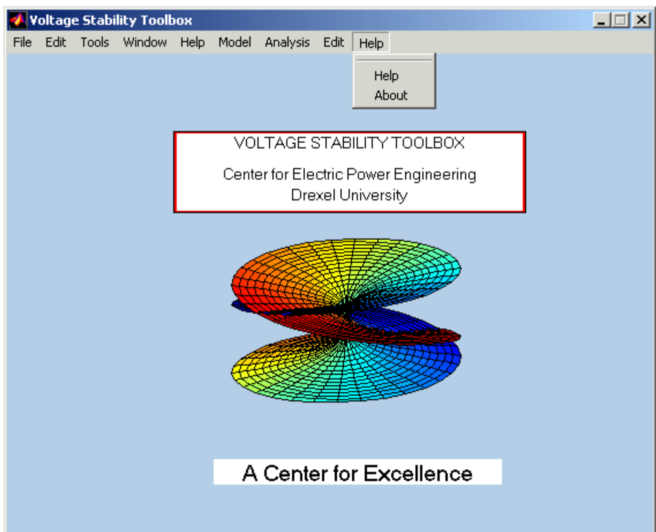

Fig. A.8 The Help pull-down menu

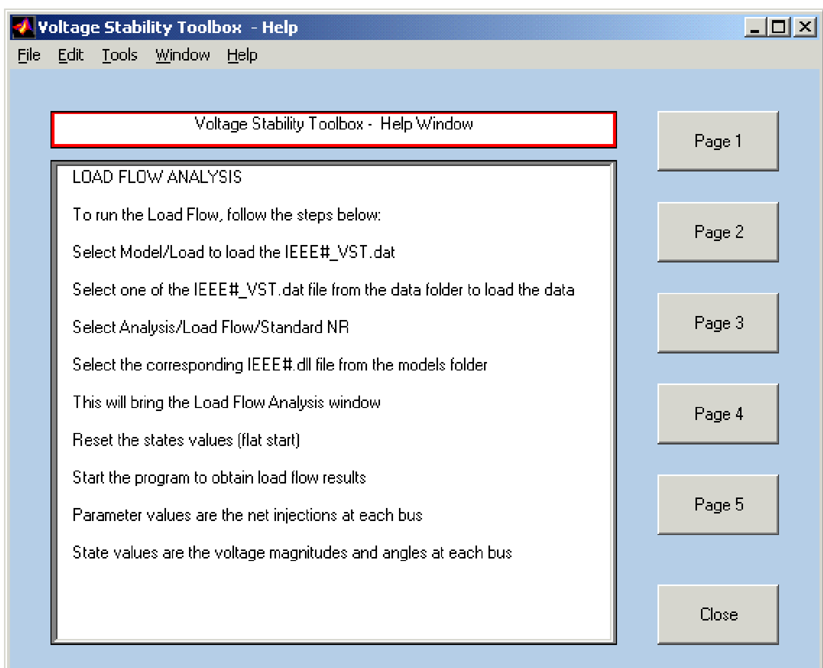

Fig. A.9 An example of help window

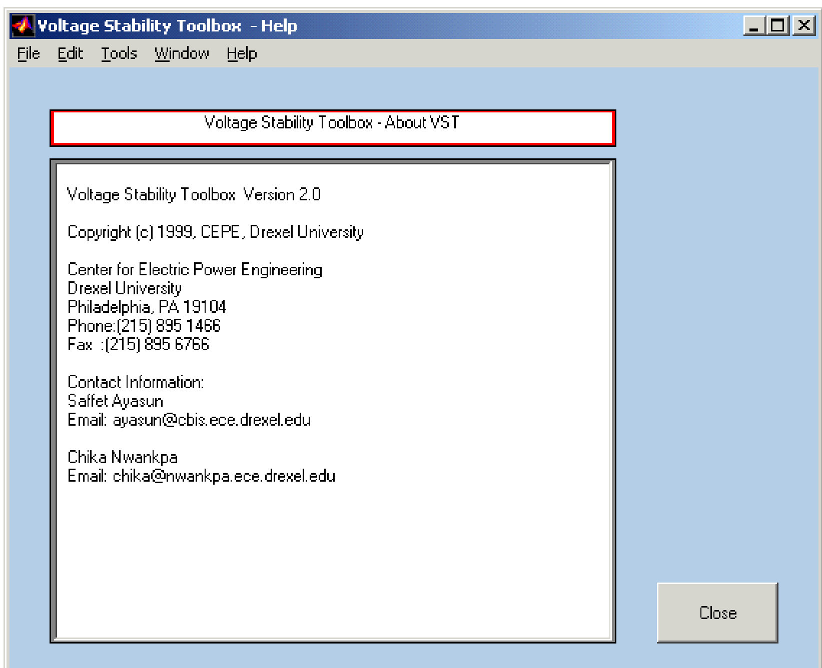

Fig. A.10 The Help window about VST

A.3 How to Use Voltage Stability Toolbox

This section describes how to use voltage stability toolbox by going through a 5-bus power system example whose one line diagram and data are given in Appendix B.

Importing the Data

To convert the IEEE standard data format to the VST data format, follow the steps below:

- Select Import-IEEE Static (i.e., IEEE5a) from the Model menu in the main window.
- This will activate the dialog box shown in Fig. A.11.
- Select one of the IEEE standard test systems.
- This will activate the Save dialog box shown in Fig. A.12.
- Save the data as system-name_VST.dat (i.e., IEEE5a_VST.dat).

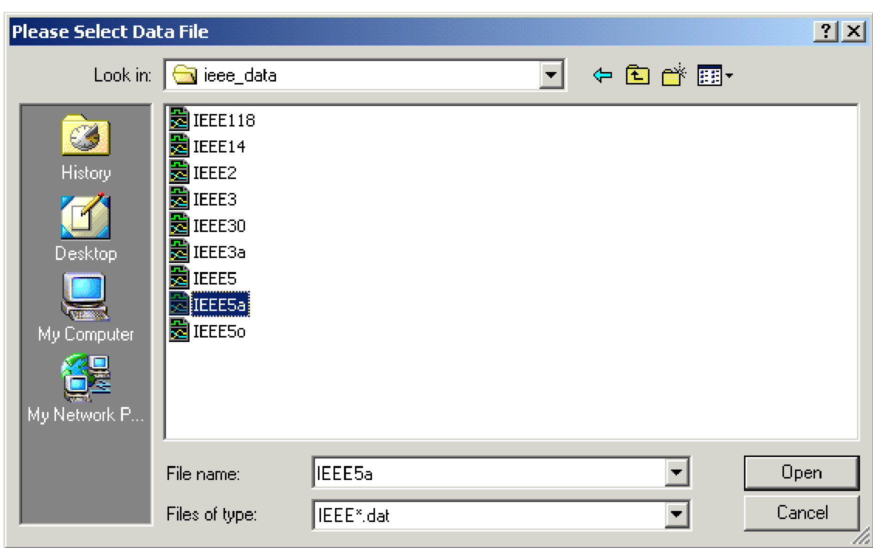

Fig. A.11 The Import dialog box

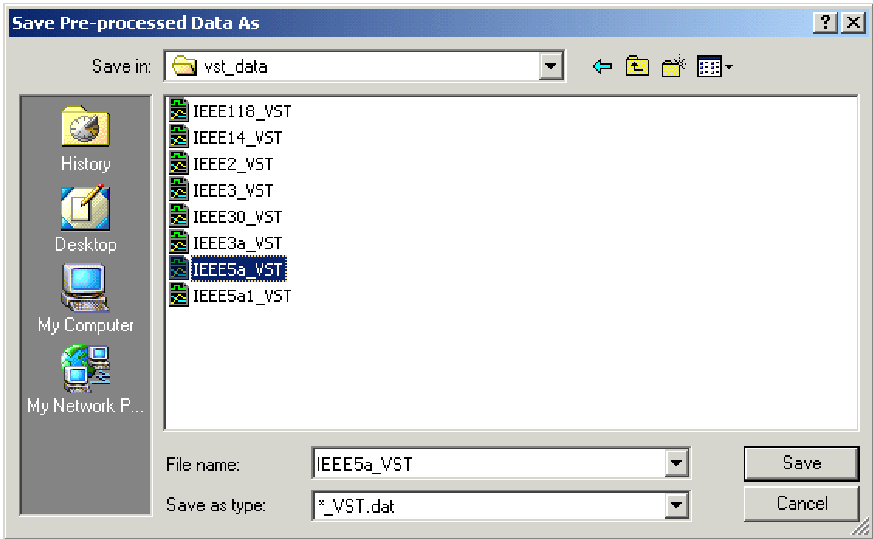

Fig. A.12 The Save dialog box

Loading the System Data

To load the system data into MATLAB's workspace, please follow the steps below:

- Select Load from the Model menu in the main window.
- This will activate a dialog box shown in Fig. A.13.
- Select one of the VST.dat files (i.e., IEEE5a_VST.dat).

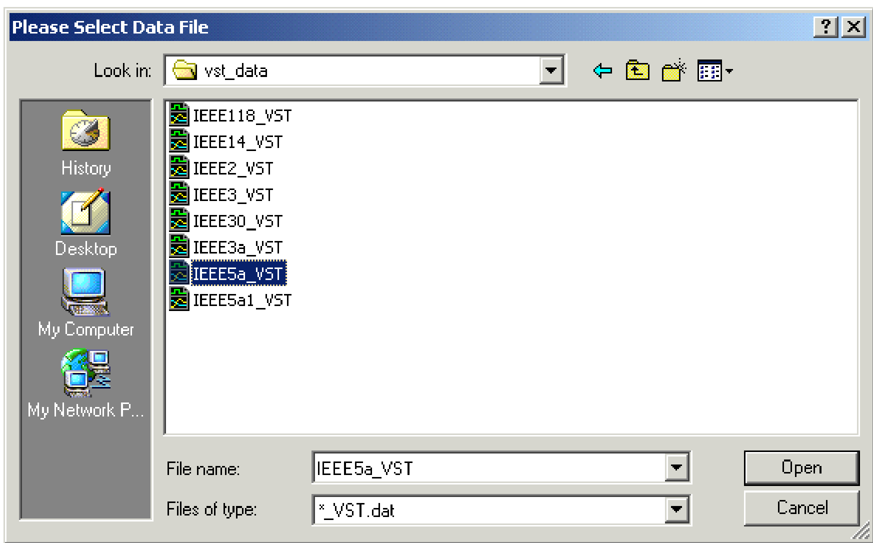

Fig. A.13 The Load dialog box

Building the System Equations for Load Flow and Bifurcation Analysis

To construct the symbolic equations and the Jacobian matrix in C code form, please follow the steps below:

- Load the system data if it is not previously loaded.

- Select Build-Classical PoC from the Model menu in the main window.
- This will activate the dialog box shown in Fig. A.14.
- Save the C code as system_name.c file (i.e., IEEE5a.c).
- Select Build-Network Model C from the Model menu in the main window to build the power flow equations and the 1st –order Jacobian matrix in C-form. The resulting file name is model.c.
- Select Build-Network Model Maple from the Model menu in the main window to build the power flow equations in Maple-form. The resulting file name is model.src.

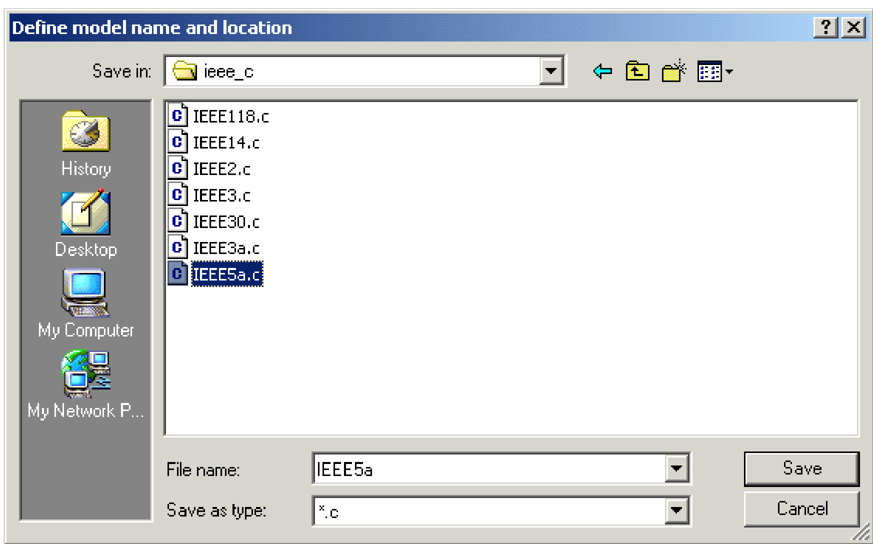

Fig. A.14 The Build dialog box

Compiling the C Source

To compile the C source as MEX function callable from MATLAB, please follow the steps below:

- Select Compile from the Model menu in the main window.
- This will activate the dialog box shown in Fig. A.15.
- Select the C source file (i.e., IEEE5a.c).
- This will compile the C source into an executable file (for example, IEEE5a.dll for PC or IEEE5a.mexsol for Sun Unix environment).

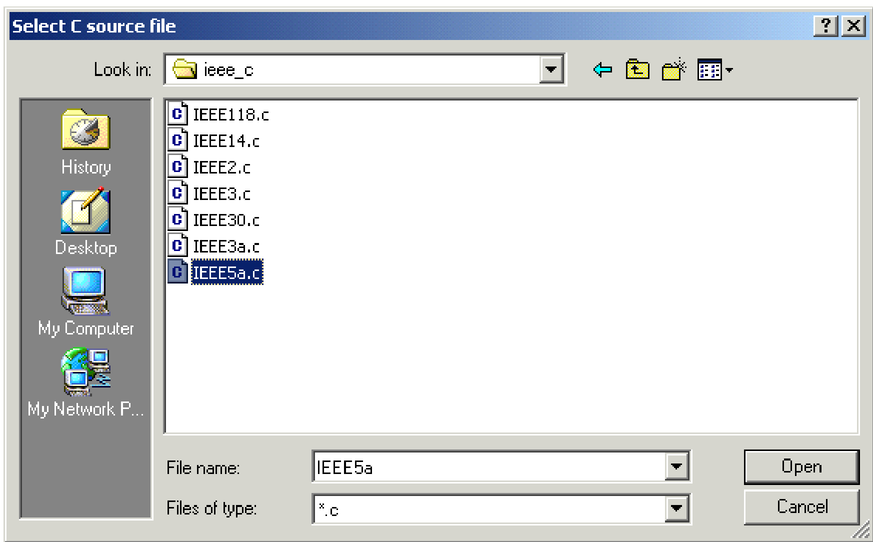

Fig. A.15 The Compile dialog box

Load Flow Analysis

The load flow analysis implements the Newton-Raphson (NR) algorithm to compute the load flow solutions at a given set of bus injections. The Load Flow Analysis window as shown in Fig. A.16 allows the user to set control variables of the NR algorithm such as maximum number of iteration, error tolerances and to specify the bus injections

(Parameter Values) and the initial conditions of load flow variables (State Values) through the editable fields. The results are displayed in the same window. The resulting voltage magnitudes are in pu and angles are in radians. In order to perform the load flow analysis, please follow the steps below:

- Load the system data if it is not previously loaded (i.e., IEEE5a_VST.dat).
- Select Load Flow-Standard NR from the Analysis menu in the main window.
- This will activate the dialog box shown in Fig. A.17.
- Select the corresponding MEX file (i.e., IEEE5a.dll for PC or IEEE5a.mexsol for Unix).
- This will activate the Load Flow Analysis window as shown in Fig. A.16.
- Set the load flow control variables such tolerance, max_iterations, and parameter values, etc.
- Push the Reset button for a flat start. The Reset button sets the voltage magnitudes to 1.0 pu and the angles to 0 radian as being the initial conditions of the NR algorithm. The user can also set initial conditions to any value through the editable fields named State Values rather than having a flat start.
- Push the Start button to run the program
- The load flow results will be displayed in the field named States Values.

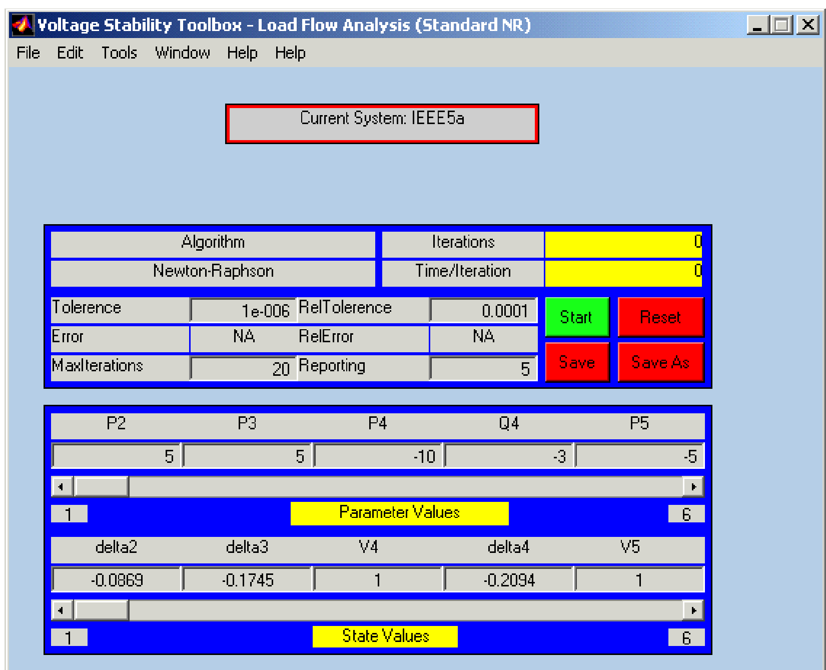

Fig. A.16 The Load Flow Analysis window

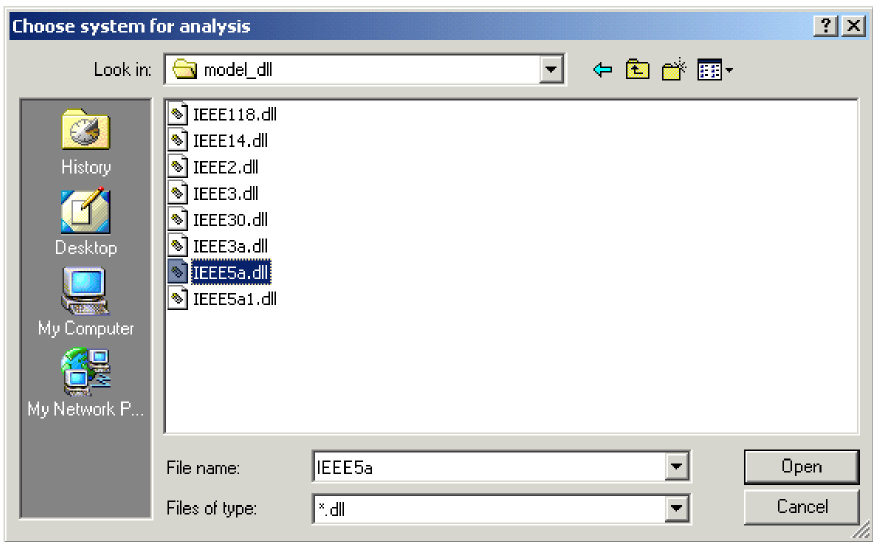

Fig. A.17 The Analysis dialog box

Static Bifurcation Analysis

The static bifurcation program implements a two-stage (NR→NRS) algorithm to compute the system equilibria as the injections at a bus or at a group of buses vary. The results are displayed as a nose curve. The program identifies the tip of the nose curve as the saddle node bifurcation point. The Static Bifurcation Analysis window allows the users to specify load flow control variables. In order to perform the static bifurcation analysis, please follow the steps below:

- Load the system data if it is not previously loaded (i.e., IEEE5a_VST.dat).
- Select Static Bifurcation from the Analysis menu in the main window.
- This will activate the dialog box shown in Fig. A.17.
- Select the corresponding MEX file (IEEE5a.dll for PC or IEEE5a.mexsol for Unix).
- This will activate the Static Bifurcation Analysis window shown in Fig. A.18.
- Reset the state value for a flat start.
- Set the control variables of the algorithm such as tolerance and max_iterations.
- Select the Search Direction option under the Parameter Values. That will set all the field values to zero.
- Select a bus or a group of buses whose real and/or reactive power injections are to be varied by changing the corresponding field values to a positive or negative number. For example, if you want to increase real power injections at the buses 2 and 3 at the same rate, set the field values of P_2 and P_3 to 1 (or any positive number). The real and reactive power injections at the load buses can also be varied similarly. For example, if you want to increase the real and reactive demand at bus 4 while keeping the power factor constant, set the field values of P_4 and Q_4 to –1 and –0.3 respectively.
- Push the Start button to run the program.

- The resulting nose curve is depicted in Fig. A.19. Any of the bus voltages or phase angles can be plotted by using sliders in that window.

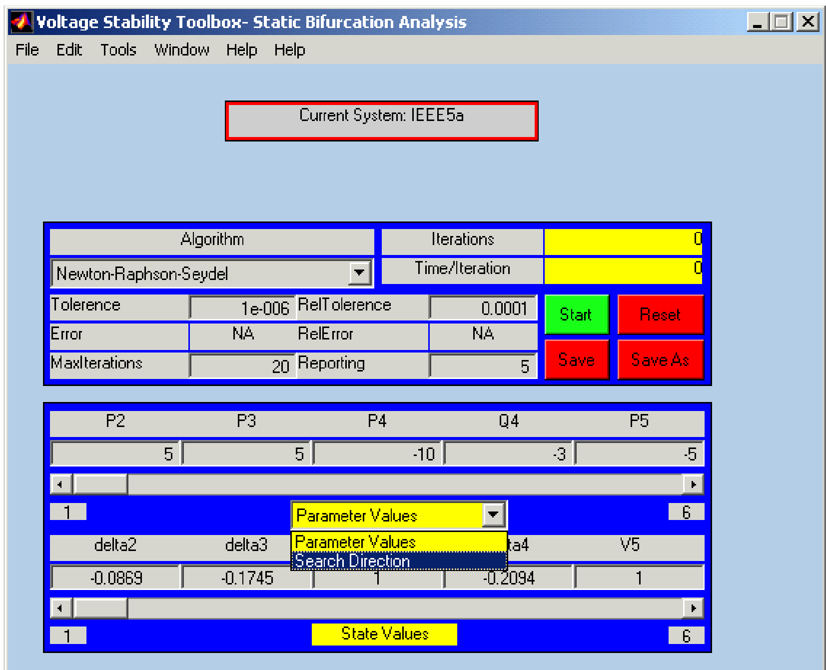

Fig. A.18 The Static Bifurcation Analysis window

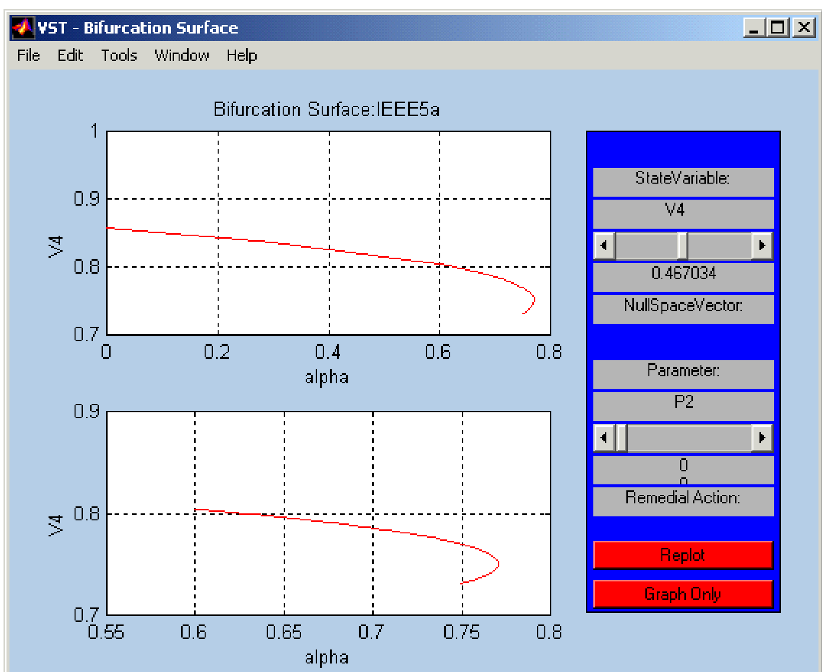

Fig. A.19 A typical result of the static bifurcation analysis

Dynamic Bifurcation Analysis

The dynamic bifurcation analysis has two options:

1. Zoom around the nose point
2. Zoom lower part

Both of them compute the system equilibria as the selected bus injections vary. The first one computes only the upper part of the nose curve including the tip of the nose. The second one goes around the tip of the nose to identify the lower part of the nose curve. Both programs also provide the stability properties of the equilibria along the nose curve. In order to compute the complete nose curve, please follow the steps below:

- Load the system data if it is not previously loaded (i.e., IEEE5a_VST.dat).
- Select Dynamic Bifurcation Analysis-Zoom Lower Part from the Analysis menu in the main window.
- This will activate the dialog box shown in Fig. A.17.
- Select the corresponding MEX file (IEEE5a.dll for PC or IEEE5a.mexsol for Unix).
- This will activate the Dynamic Bifurcation Analysis window shown in Fig. A.20.
- Reset the state value for a flat start.
- Set the control variables of the algorithm such as tolerance, max_iterations, NR_Steps, and NRS_Steps, etc.
- Select the Search Direction option under the Parameter Values. That will set all the field values to zero.

- Select a bus or a group of buses whose real and/or reactive power injections are to be varied by changing the corresponding field values to a positive or negative number (please see the Static Bifurcation Analysis section for details).
- Push the Start button to run the program.
- The resulting bifurcation surface is depicted in Fig. A.21. Any of the bus voltages or phase angles can be plotted by using sliders in that window. The green color represents the small-signal stable equilibrium points while the red color represents the unstable equilibrium points.

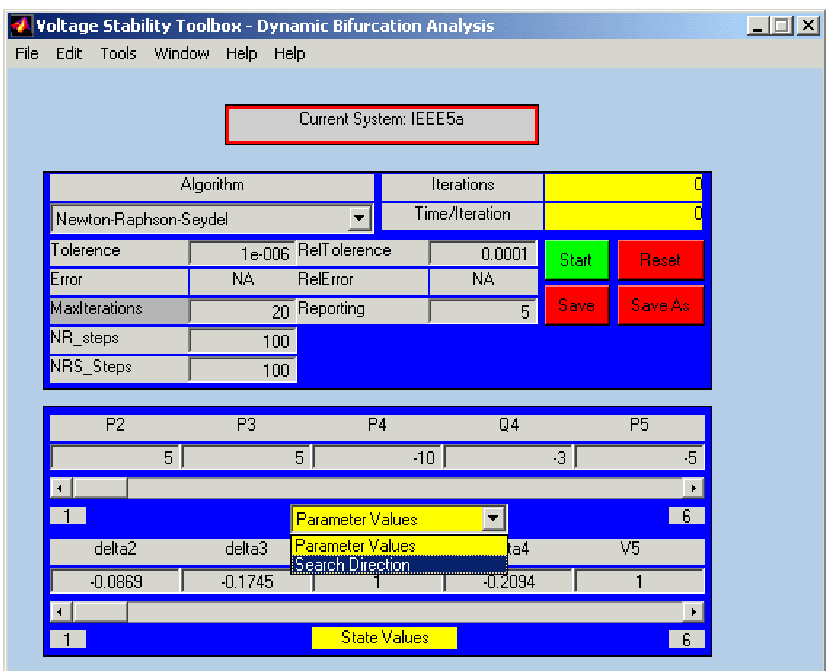

Fig. A.20 The Dynamic Bifurcation Analysis window

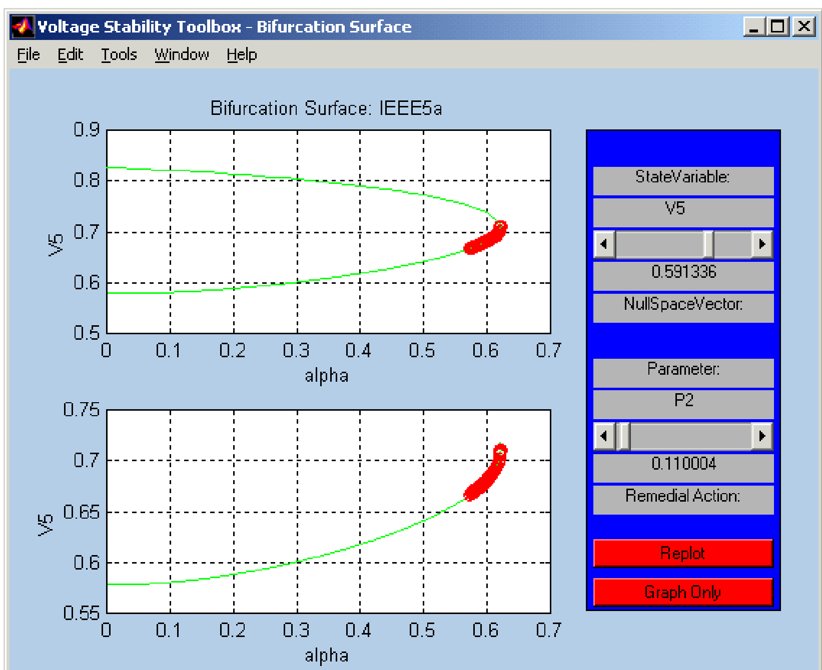

Fig. A.21 A typical result of the dynamic bifurcation analysis

Time-Domain Analysis

Time-domain simulation program is designed to analyze the system dynamic behavior. It enables us to obtain the solution of the coupled differential and algebraic equations at any operating point. For a differential-algebraic equation (DAE) model of power systems, the load flow equations for PV and PQ buses have to be solved in advance of solving the differential equations of the generators. Time-domain simulation program implements an ordinary differential equation (ODE) solver combined with an algebraic solver at each iteration step. A 4^{th} –order Runga-Kutta method is used as an ODE solver while a Newton-Raphson procedure is implemented as an algebraic solver to update the load bus voltage magnitudes and angles at each integration step. In order to perform time-domain analysis, please follow the steps below:

- Run the dynamic bifurcation analysis to compute the nose curve including the lower part of it.
- Select Simulation from the Analysis menu in the main window.
- This will activate the dialog box shown in Fig. A.17.
- Select the corresponding MEX file (IEEE5a.dll for PC or IEEE5a.mexsol for Unix).
- This will activate Dynamic Simulation window as shown in Fig. A.22.
- Select a parameter along the nose curve by using the slider at the top of window (i.e. Current Point Number: 10). The slider allows the user to select any parameter along the nose curve. Observe that the fields of Parameter Values and States Values are being updated as you move the slider from the left to the right.

- Set an initial condition for the states by editing the fields of States Values.
- Select final simulation time.
- Push the Start button to run the program.
- Select a state variable (i.e., Selected Variable: theta (3)) and push to the Plot button to obtain the dynamic behavior of the selected state variable. An example of the simulation result is shown in Fig. A.23.

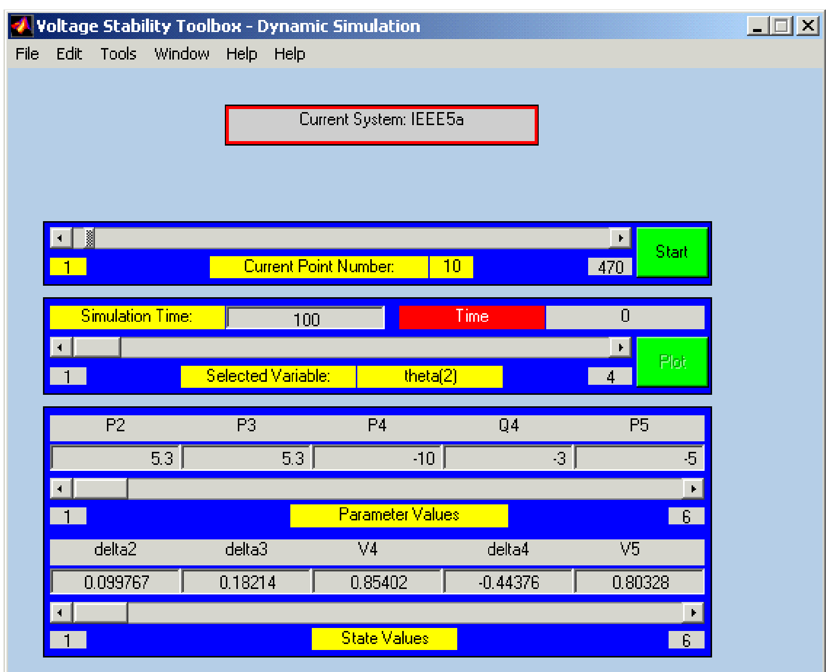

Fig. A.22 The Dynamic Simulation window

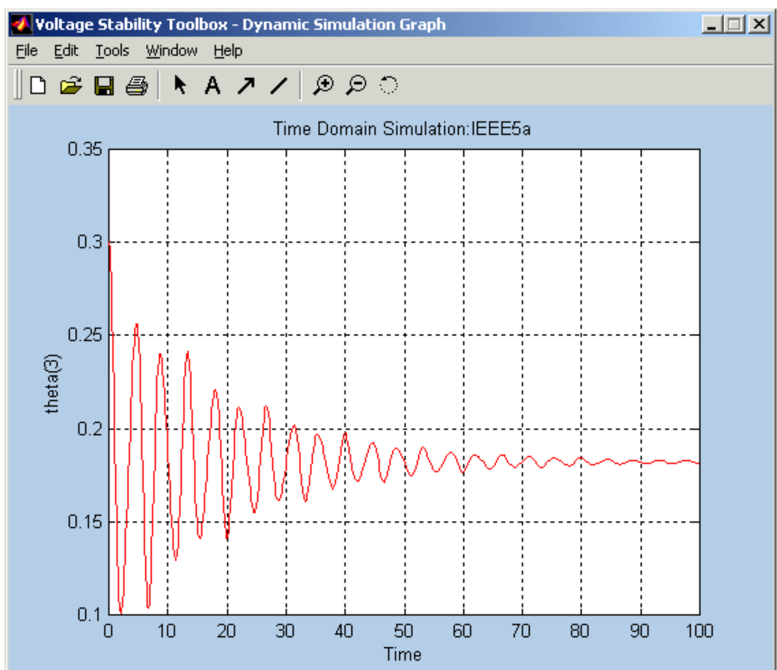

Fig. A.23 A typical result of the time-domain analysis

Plotting the Eigenvalues of the System Matrix

To plot the eigenvalues of the reduced system matrix $[A_{SYS}]$, please follow the steps below:

- Run the dynamic bifurcation analysis.

- Select Eigenvalue of System Matrix from the Analysis menu in the main window.

- The resulting window plots the real parts of the eigenvalues vs. the imaginary part of the eigenvalues as shown in Fig. A.24.

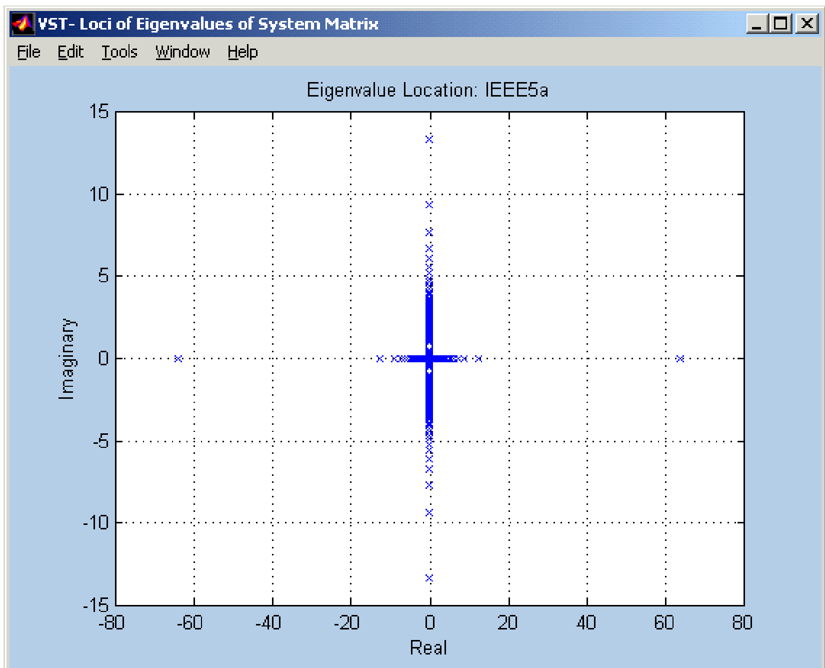

Fig. A.24 The eigenvalues of the reduced system matrix

Sensitivity around the Saddle Node Bifurcation

To obtain sensitivity information around the saddle node bifurcation point, please follow the steps below:

- Run the dynamic bifurcation analysis.
- Select Sensitivity Around Saddle Node Bifurcation from the Analysis menu in the main window.
- The resulting plot is illustrated in Fig. A.25. The first graph shows the null space vector used to determine which variables are the most sensitive to voltage stability at the SN bifurcation point according to the magnitudes. The second graph displays the remedial action information that is useful for corrective control actions.

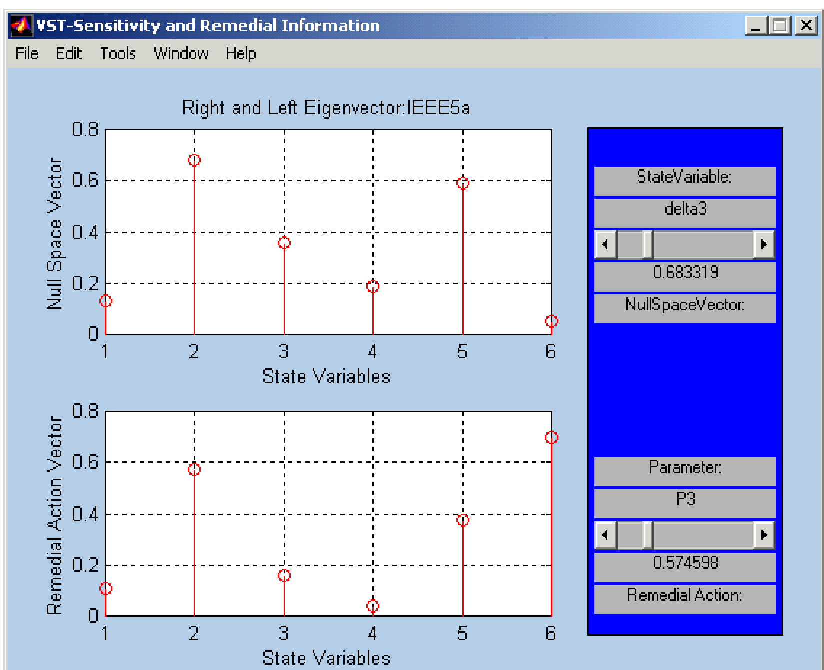

Fig. A.25 Absolute values of components of the right and left eigenvectors corresponding to the zero eigenvalue of the system matrix

Singular Points Analysis

The singular points analysis program implements a two-stage algorithm (NR→NRS) in the constraint manifold to compute the singular points at a fixed set of bus injections. As explained in detailed in Chapter 4, it parameterizes all the generator angles and compute the singular points as a saddle node bifurcation point of the algebraic variables (load bus voltage magnitudes and angles).

To compute a singular point at a fixed parameter value, please follow the steps below:

- Run the dynamic bifurcation analysis to compute the nose curve including the lower part of it and locate the bifurcations of the system equilibria.
- Select Singular Point Analysis-NR and NRS from the Analysis menu in the main window.
- This will activate the dialog box shown in Fig. A.17.
- Select the corresponding MEX file (IEEE5a.dll for PC or IEEE5a.mexsol for Unix).
- This will activate the Singular Point Analysis window as shown in Fig. A.26.
- Select a parameter (bus injections) along the nose curve by using the slider at the top of window (i.e., Current Point Number: 39). The slider allows the user to select any of the parameter values along the nose curve up the SN bifurcation point.
- Set the control variables of the algorithm such as tolerance, max_iterations, NR_Steps, and NRS_Steps, etc.

- Select all the generator angles. To able to do, first select search direction for the states at the bottom field of the window and type "1" in the editable field corresponding to the last generator's angle.
- Push the Start to run the program.
- The singular point at the corresponding parameter will be saved as a vector.
- One can run the program at various parameter values to compute singular points along the nose curve and depict them together with the nose curve for the selected bus variables, as illustrated in Chapter 5.

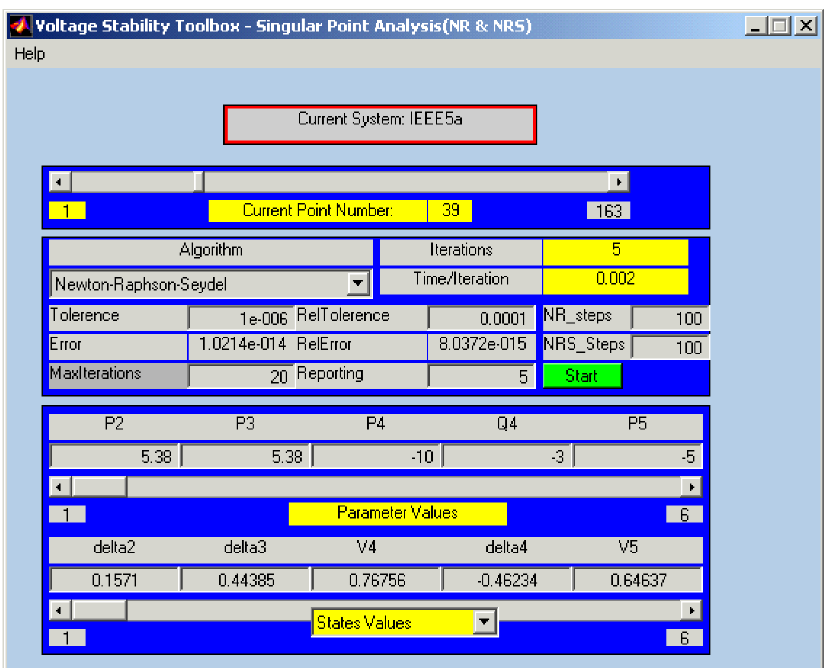

Fig. A.26 The Singular Point Analysis window

Editing the Existing System Data

To view or modify the existing system data, please follow the steps below:

- Load the system data to be viewed or modified (i.e., IEEE5a.dat).
- Select Edit VST Data from the Analysis menu in the main window.
- This will activate the Edit window as shown in Fig. A.27.
- Modify bus, branch, and generator data in the corresponding field.
- Save the modified system data.

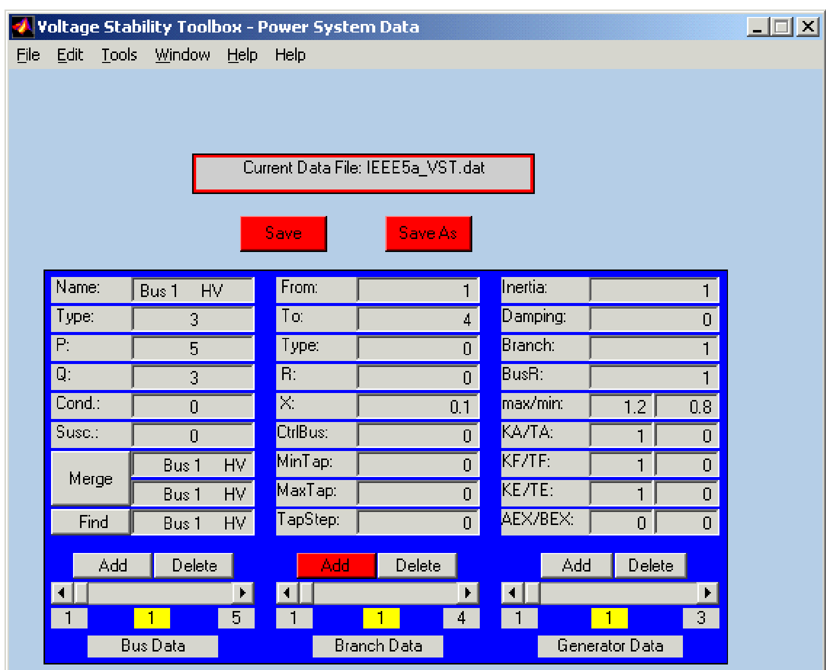

Fig. A.27 The Edit window

A.4 Software and System Requirements

To be able to use the Voltage Stability Toolbox, one needs to have the followings:

- Matlab Version 5 (available from The MathWorks)

- Matlab Extended Symbolic Toolbox (available from the MathWorks)

- Windows 95 Windows, NT Workstation 4.0 or UNIX

- Voltage Stability Toolbox files that are available at our homepage: http://power.ece.drexel.edu/