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Small Signal Stability Analysis of Switching Dynamical Systems

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Abstract: Integration of power electronic switching systems into electric utility systems and electric motion systems creates the possibility of new instabilities in these systems. The analysis of these systems is a challenging problem since it is difficult to develop a high fidelity analytical model that captures the complex dynamical interaction of these systems. Averaging models often do not provide the required accuracy and therefore they cannot always predict the stability properties of the system. To meet this challenge, a new small signal stability analysis method has been developed. The method is based on computation of the transition matrix over a specified time interval. Since these systems are generally periodic the time interval is selected equal to one cycle of the fundamental frequency. The method is applicable to any system and it is especially suited to switching systems with or without nonlinear elements. In this paper we are interested in systems with PEBB (Power Electronic Building Block)driven motion subsystems (i.e. any type of electric motors). An application example is presented.

Introduction

Advances in power electronics and control methodologies have resulted in increased power levels and operational speeds of power electronic devices. The new technologies, referred to as FACTS (Flexible AC Transmission System) devices and PEBB (Power Electronic Building Block) devices, are being interfaced with existing power systems and end-use equipment and new topologies for power systems are contemplated. As an example, PEBB modules are new high-power, fast switching components with on-demand re-configurable control schemes. PEBB devices are pushing the envelope of possibilities initiated by FACTS devices. PEBB devices have distinct advantages as drivers of electromotion systems because of their ability for soft starting and other control options. PEBB devices instigate the re-examination of power system topologies and the integration of AC and DC technologies for power transmission. The resulting PEBB based power system is characterized with increased complexity. Specifically, the switching operation of PEBB devices and increased controls create new dynamic interactions. One aspect of this new paradigm is the complex interactions of the multiple PEBB devices and the possibility of new instabilities. This paper focuses on the stability issue of PEBB based power systems.

Stability analysis of switching systems is always a challenging task. This paper presents a fresh approach for small signal stability analysis of power systems with switching power electronic subsystems. The approach is based on the concept of the Virtual Test Bed that provides the framework for continuous simulation and testing of power systems and interconnected power electronic devices. Within the Virtual Test Bed framework, small signal stability can be continuously performed on a specified time window. Typically, the time window is selected to be one cycle of the fundamental frequency, sliding, so that the end of the time window is always the present time.

Small Signal Stability Methodology

Consider a dynamical system that is described by a set of differential equations. The general form of these equations is:

$$\begin{bmatrix} e(t) \\ 0 \end{bmatrix} = \begin{bmatrix} g_1(\frac{dx(t)}{dt}, \frac{dy(t)}{dt}, x(t), y(t), u_o(t)) \\ g_2(\frac{dx(t)}{dt}, \frac{dy(t)}{dt}, x(t), y(t), u_o(t)) \end{bmatrix} \quad (1)$$

where

- $e(t)$: vector of external excitations,
- $x(t)$: vector of observable states,
- $y(t)$: vector of internal state variables
- $u_o(t)$: vector of independent controls (open loop).

Assume that these equations are numerically integrated over a time interval (t_k-h, t_k). The result can be written in the following form:

$$\begin{bmatrix} x(k+1) \\ y(k+1) \end{bmatrix} = \Phi(k+1,k) \begin{bmatrix} x(k) \\ y(k) \end{bmatrix} + E(k) \quad (2)$$

where E(k) is a function of external (open loop) excitations, and $\Phi(k+1,k)$ is the state transition matrix from time interval k to time interval k+1. Let T be the fundamental period of operation of the system. The number of intervals of duration h in one period T is N=T/h. Repeating the above process N times with proper elimination procedures, one obtains:

$$\begin{bmatrix} x(k+N) \\ y(k+N) \end{bmatrix} = \Phi(k+N,k) \begin{bmatrix} x(k) \\ y(k) \end{bmatrix} + EN(k) \qquad (3)$$

In the above equation, $\Phi(k+N,k)$ is the state transition matrix from time interval k to time interval k+N, or the one cycle transition matrix. The eigenvalues of the one cycle transition matrix define the small signal stability properties of the system. For example, if the eigenvalues of the one cycle transition matrix are single and within the unit circle, the system is asymptotically stable. The stability properties for other cases are also well established, for example multiple eigenvalues within the unit circle, or eigenvalues on the unit circle or eigenvalues outside the unit circle.

The proposed method is based on numerical computation of the one cycle transition matrix, subsequent eigenvalue analysis of the transition matrix and extraction of the stability properties of the system. The details of the method are presented next.

Numerical Computation of System Transition Matrix

It is impractical (and difficult) to derive the dynamical equations of any arbitrary dynamical system in the form (1). However, for the computation of the transition matrix it is not necessary to have the overall dynamical equations of the system. Instead, we can construct the transition matrix from the proper manipulation of the dynamical equations of each device that makes up the system under consideration. This is achieved as follows. First, any power system device is described by a set of algebraic-differential-integral equations. It is always possible to cast these equations in the following general form:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} f_1(\dot{v}(t), \dot{y}(t), v(t), y(t), u(t)) \\ f_2(\dot{v}(t), \dot{y}(t), v(t), y(t), u(t)) \end{bmatrix} \qquad (4)$$

where

i (t): vector of through variables (i.e. currents),
v (t): vector of across variables-states (i.e. voltages),
y(t) : vector of device internal state variables
u (t): vector of independent controls.

Note that this form includes two sets of equations, which are named *external equations* and *internal equations* respectively. The terminal currents appear only in the external equations. Similarly, the device states consist of two sets: *external states* (i.e. terminal voltages, v(t)) and *internal states* (i.e. y(t)). The set of equations (1) is consistent in the sense that the number of external states and the number of internal states equals the number of external and internal equations respectively.An example of above modeling is a PEBB device represented with linear elements. Between switchings, the model is described with a linear differential equation of the form:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix}$$

The above Equations are integrated using a suitable numerical method. Assuming an integration time step h, the result of the integration is manipulated to be in the following form:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} - \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} v(t-h) \\ y(t-h) \end{bmatrix} - \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} i(t-h) \\ 0 \end{bmatrix}$$

Now consider the connectivity constraints among the devices of the system. Kirchoff's current law (KCL) applies to each node. Application of KCL at each node will result in elimination of all device terminal currents. The overall network equation has the form:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{s11} & Y_{s12} \\ Y_{s21} & Y_{s22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} - \begin{bmatrix} P_{s11} & P_{s12} \\ P_{s21} & P_{s22} \end{bmatrix} \begin{bmatrix} v(t-h) \\ y(t-h) \end{bmatrix} - \begin{bmatrix} Q_1(t-h) \\ Q_2(t-h) \end{bmatrix}$$

or the equivalent:

$$\begin{bmatrix} v(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} Y_{s11} & Y_{s12} \\ Y_{s21} & Y_{s22} \end{bmatrix}^+ \begin{bmatrix} P_{s11} & P_{s12} \\ P_{s21} & P_{s22} \end{bmatrix} \begin{bmatrix} v(t-h) \\ y(t-h) \end{bmatrix} + \begin{bmatrix} Y_{s11} & Y_{s12} \\ Y_{s21} & Y_{s22} \end{bmatrix}^+ \begin{bmatrix} Q_1(t-h) \\ Q_2(t-h) \end{bmatrix}$$

where the superscript + indicates generalized inverse. Note that the above equation represents the state transition equation for the entire system from time t-h to time t. The one-cycle transition matrix is:

$$\Phi(t+h,t) = \begin{bmatrix} Y_{s11} & Y_{s12} \\ Y_{s21} & Y_{s22} \end{bmatrix}^+ \begin{bmatrix} P_{s11} & P_{s12} \\ P_{s21} & P_{s22} \end{bmatrix}$$

Eigenvalue analysis of the transition matrix provides the small signal stability of the system. In general, however, and especially for switching systems, we are interested in the transition matrix over at least one period of operation of the system. The proposed method provides an algorithm for the recursive computation of the transition matrix over a desired time period and around the operating conditions of the system. To make the presentation clear, we first explain the simulator that computes the trajectory of the system. Next we describe the procedure for computing the one time step transition matrix at any time, t, of the simulation.

Subsequently, we describe the algorithm for the computation of the transition matrix over an arbitrary number of steps.

Proposed Method

The organization of the Virtual Test Bed is illustrated in Figure 1. It consists of a time domain simulator (Network Solver), a library of power system device models (transmission lines, machines, power electronics etc), an animation engine, and a graphical user interface. The system is designed to run continuously. While the simulation is running, the user can monitor the system operation via the graphical user interface. Specifically, any device state can be plotted as a function of time as a rolling oscilloscope trace. In addition, an on-line waveform calculator allows plotting of quantities that are functions of any combination of system states. The user can add or remove plot traces without interrupting the simulation. Furthermore, the user can change any system parameter, and immediately observe the system response.

In addition to generic time function plotting, the animation engine provides advanced visualization options. Specialized animation objects are closely linked with appropriate time domain models. For example, a generator animation object retrieves the internal states of a generator model and creates an animated display of the stator, rotor and the air-gap magnetic field profile. In this paper, we focus on the ability of the system to compute the system transition matrix, its eigenvalues and to display the eigenvalue map interactively. For linear systems the eigenvalue map is invariant but for switching systems with or without nonlinear parts, the eigenvalue map may be changing with the operating conditions.

The VTB continuous operation is achieved using the multithreading capability of a multitasking operating system (Windows 9X/NT). Specifically, the network solver and user interface run as separate computational threads, sharing a common memory area. The solver thread sends a message to the GUI thread whenever new data are available for display. The GUI then retrieves the data from the shared memory area. Conversely, if the user modifies a parameter of the system, the GUI sends a message to the solver to appropriately modify the simulation. Note that the network solver, as well as all device models, is specifically formulated to allow for this capability. The components of the VTB as related to the focus problem of this paper are described next.

Time Domain Device Model

Any power system device can be described by a set of algebraic-differential-integral equations such as (4).

Equations (4) are integrated using a suitable numerical method. Assuming an integration time step h, the result of the integration is approximated with a second order equation of the form:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} diag(v(t),y(t))F_1 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ diag(v(t),y(t))F_2 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ \vdots \end{bmatrix} + \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix} \qquad (5)$$

where b_1(t-h), b_2(t-h) are past history functions. Equations of the above form have been named the Algebraic Companion Form (ACF) of a device model. Note that if the matrices F in the ACF are neglected, equations (5) become linear. The linear form is the well-known resistive companion form that results from the trapezoidal integration method [5]. Therefore the proposed method can be viewed as an extension of the well-known trapezoidal integration method.

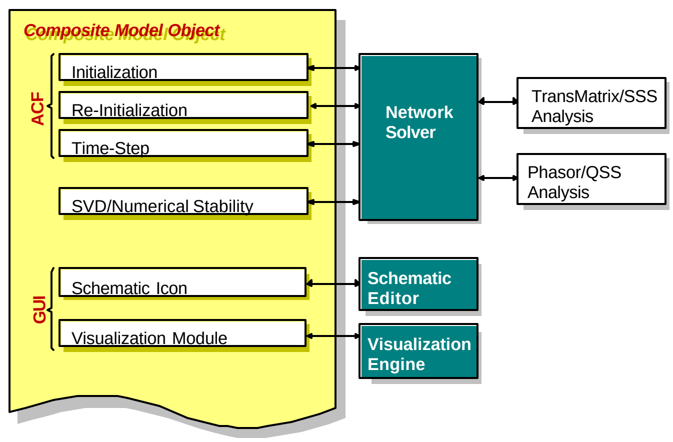

Figure 1. The Virtual Power System Environment

Network Solver

The network solution is obtained by application of Kirchoff's current law at each node of the system. This procedure results in the set of equations (6). To these equations, the internal equations are appended resulting to the equation sets (6) and (7):

$$\sum_k E^k i^k(t) = I_{inj} \qquad (6)$$

internal equations of all devices (7)

where I_{inj} is a vector of nodal current injections, E^k is a component incidence matrix, defined with:

$\{E_{ij}^k\}$=1, if terminal j, component k is connected to node i

=0, otherwise

$i^k(t)$ are the terminal currents of component k.

The component k terminal voltage $v^k(t)$ is related to the system voltage vector v(t) by:

$$v^k(t) = (E^k)^T v(t) \tag{8}$$

Upon substitution of device equations (5), the set of equations (6) and (7) become a set of quadratic equations in terms of the system state vector at time t, x(t).

$$Ax(t) + \begin{bmatrix} diag(x(t)B_1(t)x(t)) \\ diag(x(t)B_2(t)x(t)) \\ \vdots \end{bmatrix} + b(t-h) = 0 \tag{9}$$

These equations are solved using Newton's method.

Note that at each time step, the quadratic device model is an approximation of the nonlinear device equations. For this reason, the above procedure utilizes an iterative algorithm that is applied at each time step.

One-Time Step Transition Matrix

In this section we consider the problem of calculating the system transition matrix at time (t+nh+h) for the time interval (t+nh,t+nh+h), i.e. one time step interval. This transition matrix is computed by manipulating the algebraic equations of all devices in the system in such a way that we obtain a relationship between the state of the system at time (t+nh+h) and the state of the system at time (t+nh). Note that at time t+nh+h of the simulation process, the algebraic companion form for all devices in the system are known. The quadratic terms are neglected. Then the general expression of the linearized equation for device i, is:

$$I_i(t+nh+h) = A_{i,t+nh+h} x_i(t+nh+h) + B_{i,t+nh+h} x_i(t+nh) + C_{i,t+nh+h} I_i(t+nh)$$

where x is the state (including external and internal states). Application of interface constraints (Kirchoff's current law), will result in eliminating the terminal currents at time (t+nh+h), resulting in the system wide equation:

$$0 = \sum_{i=1}^{N} E_i^T A_{i,t+nh+h} E_i x(t+nh+h) + \sum_{i=1}^{N} E_i^T B_{i,t+nh+h} E_i x(t+nh) + \sum_{i=1}^{N} E_i^T C_{i,t+nh+h} I_i(t+nh)$$

Note that above equation is of the form:

$$0 = A_{s,t+nh+h} x(t+nh+h) + B_{s,t+nh+h} x(t+nh) + \sum_{i=1}^{N} E_i^T C_{i,t+nh+h} I_i(t+nh)$$

where:

$$A_{s,t+nh+h} = \sum_{i=1}^{N} E_i^T A_{i,t+nh+h} E_i$$, and

$$B_{s,t+nh+h} = \sum_{i=1}^{N} E_i^T B_{i,t+nh+h} E_i$$

By solving for the system state at time t+nh+h, we recognize that the transition matrix is:

$$\Phi(t+nh+h, t+nh) = -A_{s,t+nh+h}^{\perp} B_{s,t+nh+h}$$

Note that the transition matrix is computed as a byproduct of the simulation process. It is also computed for the prevailing operating conditions.

N-Time Step Transition Matrix

The computation of the n-time step transition matrix follows the same general procedure as for the one-time step transition matrix. The idea is again the same: manipulate the algebraic companion equations in such a way as to obtain a relationship between the system state at time (t+nh+h) and the system state at time (t+h). These manipulations are tedious and require a substantial computational effort. To limit the computational effort, certain information can be stored and used in a recursive algorithm. This algorithm is presented here.

Assume that the following transition matrices have been computed and stored:

$$\begin{aligned} x(t+h) &= \Phi(t+h,t)x(t) + B_1(t) \\ x(t+2h) &= \Phi(t+2h,t)x(t) + B_2(t) \\ &\cdots\cdots\cdots\cdots \\ x(t+nh) &= \Phi(t+nh,t)x(t) + B_n(t) \end{aligned} \tag{10}$$

At the same time assume that the linearized algebraic companion form equations for each device for the last n steps have been stored:

$$\begin{aligned} I_i(t+h) &= A_{i,t+h} x_i(t+h) + B_{i,t+h} x_i(t) + C_{i,t+h} I_i(t) \\ I_i(t+2h) &= A_{i,t+2h} x_i(t+2h) + B_{i,t+2h} x_i(t+h) + C_{i,t+2h} I_i(t+h) \\ &\cdots\cdots\cdots\cdots \\ I_i(t+nh) &= A_{i,t+nh} x_i(t+nh) + B_{i,t+nh} x_i(t+nh-h) + C_{i,t+nh} I_i(t+nh-h) \end{aligned} \tag{11}$$

It is important to realize that as the simulation progresses, the above information is known. We simply store the information and then use it for the computation of the transition matrix. The algorithm consists of the following steps:

Step 1: Form matrix A_s using the following constructor:

$$A_s \leftarrow A_s + E_i^T A_{i,t+nh+h} E_i$$

Step 2: Form the matrix B_s using the following constructor:

$$\begin{aligned} B_s &\leftarrow B_s + E_i^T (B_{i,t+nh+h} + C_{i,t+nh+h} A_{i,t+nh}) E_i \Phi(t+nh, t+h) \\ B_s &\leftarrow B_s + E_i^T C_{i,t+nh+h} (B_{i,t+nh} + C_{i,t+nh} A_{i,t+nh-h}) E_i \Phi(t+nh-h, t+h) \\ &\cdots\cdots\cdots\cdots \\ B_s &\leftarrow B_s + E_i^T C_{i,t+nh+h} C_{i,t+nh} \ldots C_{i,t+4h} (B_{i,t+3h} + C_{i,t+3h} A_{i,t+2h}) E_i \Phi(t+2h, t+h) \end{aligned}$$

Step 3: Compute the transition matrix:

$$\Phi(t+nh+h,t+h)=-A_s^{\perp}B_s$$

Step 4: Perform eigenvalue analysis of the transition matrix and display results:

Step 5: Update equations (10):

$$x(t+2h)=\Phi(t+2h,t)\Phi(t,t+h)x(t+h)+B_2(t+h)$$
$$x(t+3h)=\Phi(t+3h,t)\Phi(t,t+h)x(t+h)+B_3(t+h)$$
....
$$x(t+nh)=\Phi(t+nh,t)\Phi(t,t+h)x(t+h)+B_n(t+h)$$
$$-------------$$
$$x(t+nh+h)=\Phi(t+nh+h,t+h)x(t+h)+B_{n+1}(t+h)$$

Step 6: Update equations (11) and proceed to the next time step (t+nh+2h). The updating of equations (11) involves the computation of the algebraic companion forms (part of the simulator) and storing the linear part.

It should be apparent that the above algorithm provides the n-time step transition matrix at time (t+nh+h). The computational effort is minimized at a price: equations (10) and (11) must be stored, this is indeed a large amount of data.

The usefulness of this analysis is great. Since eigenvalues are computed at each time step and are displayed interactively, the stability properties of the system are immediately understood. One can observe whether all eigenvalues remain within the unit circle (stable system), or any eigenvalue movement towards the unit circle is observed immediately. The proximity of an eigenvalue to the unit circle also provides a measure of the damping level in each mode of oscillation, etc.

Modeling of Controls

Existing control schemes can be included in the proposed method for small signal stability analysis. For state feedback controls, the specific controls are automatically included by simply replacing the control function, u(t), as a function of the state, x(t), prior to the numerical integration of the component equations. Thus this case is trivial. In PEBB based systems the controls are typically based on complex feedback laws. For example the equidistant control of six-pulse based systems, requires the evaluation of the positive sequence voltages that drive the inverter. The positive sequence voltages require the past history voltages of all three phases for at least one period of the fundamental frequency. This type of feedback control and other similar is incorporated into the proposed method as follows. A new state variable is introduced to denote the decision, x_u. This state variable is expressed as a function of the other state variables, i.e.

$$x_u = f_u(x_1, x_2, ...)$$

The dependence of x_u on x_1, x_2, etc. may be expressed as a Fourier transform over a time window, etc. This equation is added to the model equations and the method is applied as described in the previous sections. Note that these equations involve the state variables over a time window and therefore the transition matrix must be defined over a time period at least equal to the time window of the control equation.

Application Examples

The proposed method has been applied to a power system with two static VAR compensators. The static VAR compensators use a six pulse converter for switching the reactors of the compensator. The converters use equidistant feedback control. The single line diagram of the system is illustrated in Figure 2. The system comprises two generators, two step-up transformers, four transmission lines and two static VAR compensators (SVC). Each SVC consists of a transformer and a six pulse converter. For this system, the one cycle (16.666 msec) transition matrix was computed under various conditions. The integration time step was selected to be 10 microseconds. This means that the transition matrix is a 1667 step transition matrix. In this paper, we present results for two specific operating conditions of the system: (a) static VAR compensator 1 is ON while static VAR compensator 2 is OFF line, and (b) both static VAR compensators are ON. Figure 3 illustrates the map of eigenvalues of the one cycle transition matrix for operating condition 1. Figure 4 illustrates the map of eigenvalues of the one cycle transition matrix for operating condition 2. Note the following. For operating condition 2, there is a new eigenvalue that is located closer to the unit circle. This means that the simultaneous operation of the two static VAR compensators has generated this additional mode of oscillations. The location of the eigenvalue suggests that there is less attenuation associated with this mode of oscillation. This example illustrates the ability of the system to capture all the modes of oscillation of the system and to provide their parameters, i.e. frequency and attenuation.

It is important to note that the developed method and associated computer program provide the capability to analyze any system consisting of components that are already supported in the VTB. We constantly add new component models to the program and therefore the capability to perform small signal stability analysis on a variety of systems.

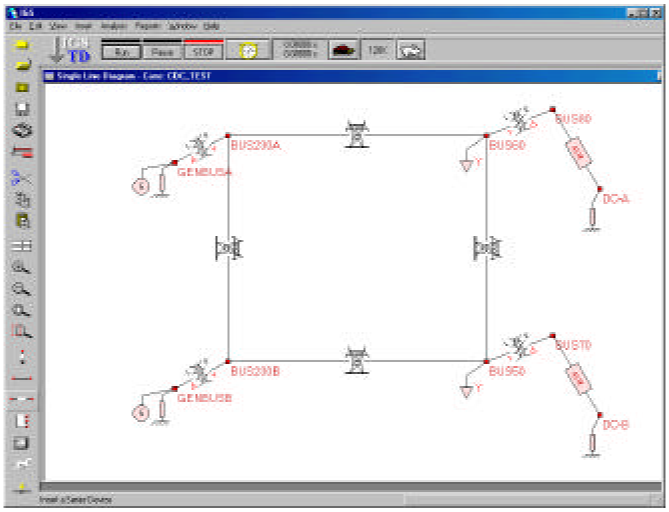

Figure 2. An Example Power System with Static VAR Compensators

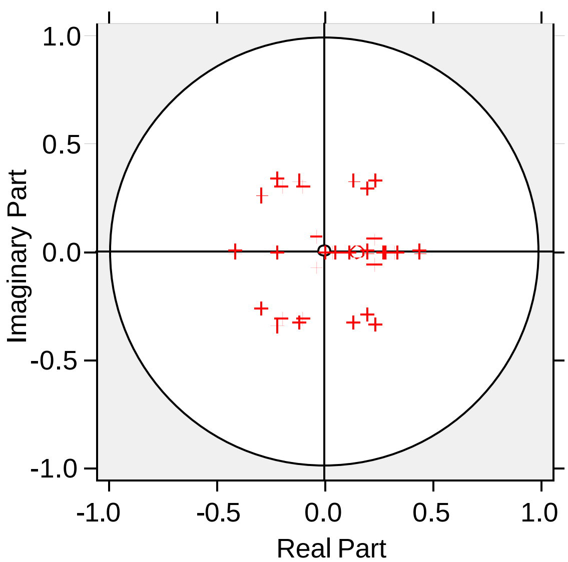

Figure 3. Eigenvalue Map for the System of Figure 2, SVC2 Disconnected, One Cycle Transition Matrix

Summary

A new method for small signal stability analysis has been presented. The method is based on the numerical computation of the system transition matrix over a desirable time interval. The method is applicable to any dynamical system and any feedback control. It is especially suitable to switching systems with or without nonlinear elements. Of special interest are FACTS (**F**lexible **AC** **T**ransmission **S**ystems) and PEBB (**P**ower **E**lectronic **B**uilding **B**lock) driven electromotion systems. The accuracy of the computed transition matrix is dependent upon the numerical integration method used. Results on a practical power system with static VAR compensators have been presented. The example illustrates the capability of the method to identify new modes of oscillation resulting from the interaction of multiple switching devices and their controls.

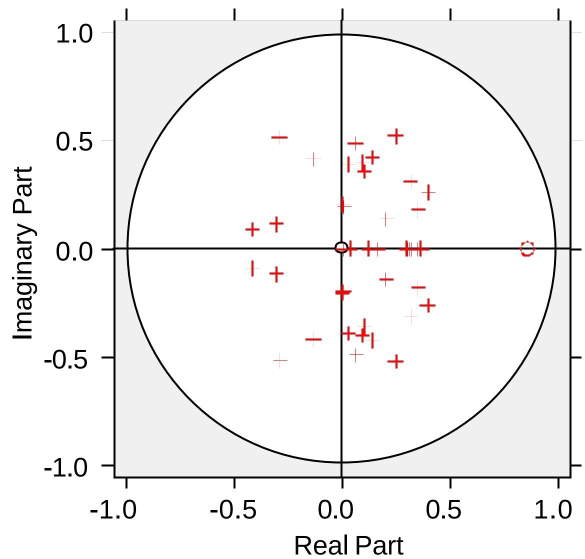

Figure 4. Eigenvalue Map for the System of Figure 2, Both SVC Connected, One Cycle Transition Matrix

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Biographies

A. P. Sakis Meliopoulos (M '76, SM '83, F '93) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, Power Systems Grounding and Transients, Marcel Dekker, June 1988, Ligthning and Overvoltage Protection, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993, and the monograph, Numerical Solution Methods of Algebraic Equations, EPRI monograph series. Dr. Meliopoulos is a member of the Hellenic Society of Professional Engineering and the Sigma Xi.

G. J. Cokkinides (M78). Dr. Cokkinides' interests include power system simulation and control, electromagnetic system modeling, measurement instrumentation, and CAD software development. Current research projects include the development of a power system ground impedance measurement device based on a custom microprocessor controlled multichannel data acquisition system, the development of a GPS synchronized measurement system for the estimation of the harmonic state of a bulk power transmission system, development of a CAD tools for characterization of microelectronic components, development of a comprehensive FEM based tool for dynamic structural analysis.

Roger A. Dougal (M '82, SM '93) joined the faculty at the University of South Carolina in 1983 after earning the Ph.D. degree in electrical engineering at Texas Tech University. He is a professor of Electrical Engineering and is VTB project director. His research interests include physical electronics and modeling and simulation of physical devices, with a current focus being positive temperature coefficient polymer thermistors for current limiting in power systems. Dr. Dougal has received the *Samuel Litman Distinguished Professor of Engineering* award, and has been honored as a *Carolina Research Professor.*