

Modern Tools for the Small-Signal Stability Analysis and Design of FACTS Assisted Power Systems

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Abstract: This paper describes the state-of-the-art on the small-signal stability analysis and design of FACTS assisted power systems. The benefits of integrating all these tools into a comprehensive package and properly employing graphical interface, including animation of algorithm results, are highly emphasized.

Keywords: *small-signal stability, poorly-damped oscillations, power system dynamics, voltage stability, transfer function, control systems, large-scale systems, sparse eigenanalysis, modal analysis, graphical interface.*

INTRODUCTION

There has recently been an intense development of eigenanalysis tools for power systems dynamics and control. This paper provides an up-to-date review of the major algorithms available. Comments on other relevant but yet unpublished algorithms are also made.

The problem of multiple, decentralized controller synthesis in large, FACTS assisted power systems is addressed.

A good part of the paper is dedicated to showing the high productivity gains achieved when using a well designed package for graphical display and animation of results.

The pressing needs for better utilization of existing transmission and generation equipment will eventually dictate a wider use of FACTS devices. The higher complexity and stricter requirements on power system controls, under both steady-state and dynamic conditions, calls for the immediate development and use of more sophisticated computer tools. The material in this paper may help the further development of one of these tools.

ALGORITHMS FOR THE ANALYSIS AND CONTROL OF THE SMALL SIGNAL STABILITY OF LARGE SCALE POWER SYSTEMS

Until the early eighties, the small signal stability analysis of power systems was based on the conventional state-space description. The state matrix, in this application, is quite dense and the use of sparsity oriented methods would not yield any computational gains. The only alternative was to use the numerically robust QR routine to produce the full eigensolution, which is computationally expensive. The QR eigensolution of a non-symmetric, real matrix of order 500, for example, requires almost one hour of CPU on a 66 MHz PC486.

The conventional state-space description is obtained through the elimination of the algebraic variables of the mathematical model. In many applications, the power system case included, the algebraic variables in the model are usually more numerous than the state variables.

A report in CIGRE [1] recognized the large benefits of working with the unreduced set of differential-algebraic equations linearized at an operating point. The resulting power system Jacobian is large and highly sparse, allowing efficient use of sparsity oriented programming. The computation of all system eigenvalues, not practical for large power systems, was since then replaced by the computation of only the eigenvalues of interest.

Many important developments occurred in the last fifteen years, some only transposing the algorithms, which originally operated on the conventional state-space description, to the non-reduced system description. Many other original concepts have also been developed as a natural consequence of using the more flexible and simpler non-reduced formulation. The use of a non-reduced formulation has also gained considerable attention in the recent control systems literature, where it is called "descriptor systems".

The algorithms which are already established as computationally efficient in the stability analysis of large power systems are listed below:

1. Single eigenvalue nearest to a given point in the complex plane and its associated left and right eigenvectors (Inverse Iteration and Generalized Rayleigh Quotient Iteration) [1,2].

2. Frequency response plots for any system transfer function [1,2].
3. Eigenvalue/vectors strongly associated with the system electromechanical oscillations (AESOPS Method) [2,3,4].
4. Transfer function zeros for SISO and MIMO systems [5].
5. System time response to applied step disturbances [2,6].
6. Mode shapes; participation factors; controllability and observability factors [3,4,7].
7. Transfer function residues; eigenvalue sensitivities to changes in system parameters [8,9].
8. Several eigenvalues near a point in the complex plane and associated eigenvectors (Lop-Sided Simultaneous Iteration and Modified Arnoldi Methods) [4,10,11].

Other eigensolution algorithms which are still very recent, or not fully proven, or not yet published deserve special attention. The list below inevitably reflects the authors' biased views and experiences:

9. Compute, through a single-vector iterative scheme, only the most relevant poles in a high-order scalar transfer function [12].
10. The two-stage Hybrid algorithm [13], utilizing the almost forgotten Bi - iteration algorithm [13] as the first stage and then several independent processes of the generalized Rayleigh quotient as the second stage.
11. More complex matrix transforms (S-Matrix, Cayley, Möbius) to achieve better convergence characteristics and/or to yield improved control over the eigenvalues of interest [14,15].
12. The very recent Refactored Bi-iteration algorithm, whose authors claim unprecedented convergence characteristics [16].

The authors are aware that very important developments by other groups will be published soon.

References [12,16] describe new numerical linear algebra algorithms which can be applied to matrix problems in any field of engineering or mathematics.

Selective modal analysis [7] has always attracted large interest for correctly focusing on only the relevant eigenvalues to a given engineering problem. This means that in the study of poorly damped oscillations (ranging from 0.2 to 2 Hz), only the eigenvalues strongly associated with these oscillations are to be calculated.

The AESOPS algorithm [3] and its subsequent improvements can be classified as selective modal analysis methods, since they are meant to compute the dominant oscillation modes in the torque-angle loop of a given generator. A recent addition to this class of methods is the

already described algorithm for the computation of dominant poles in very high order transfer functions [12].

A good part of the sparsity oriented eigenanalysis algorithms and methodologies developed for oscillatory electromechanical stability have been more recently applied to the study of voltage stability of large power systems [17,18,19].

The same algorithms can also be applied to the subsynchronous resonance problem, which requires the dynamic representation of the RLC components of the network and involves higher frequency (20 to 40 Hz) phenomena. The same concepts of a non-reduced set of equations to describe the dynamic behavior of the electrical network can be utilized. This approach is currently being investigated in [20].

Parallel processing will eventually become widely used to perform computer intensive tasks which allow natural parallelization. It will be used in on-line applications and off-line interactive computation since both have tight time constraints. On-line voltage stability assessment software is presently under development to strengthen further the crucial role of modern Energy Management Systems. The parallel computation times given in [21,13] show that partial eigensolutions of large matrices can be obtained in a time frame and with hardware cost compatibles with EMS applications.

More need be said about the recently developed Refactored Bi-iteration algorithm [16]. Existing Subspace Iteration methods perform only one spectral transformation to the system matrix per program run and therefore require only one matrix factorization. The Refactored Bi-Iteration method performs, at every iteration, one matrix factorization for each yet non-converged trial vector in the subspace. The higher computational load per iteration of the proposed RBI method is largely compensated by the reduced number of iterations (below 10) needed for high accuracy convergence of the entire left and right subspaces being iterated. All trial vectors always converge in a reduced number of iterations, irrespective of the subspace dimension or of the given initial shifts. The method can be seen as a multi-vector (subspace) generalization of the single-vector Rayleigh Quotient iteration for unsymmetric matrices [2,13,16]. The method has shown excellent performance in solving for eigenvalue clusters.

A most valuable and unique feature of the RBI method is the ability to start with as many initial shifts as the number of trial vectors utilized. The location of the various initial shifts can be chosen completely independent from one another. They should preferably be located in the complex plane region associated with the oscillatory modes usually involved in the physical phenomenon under analysis. For electromechanical oscillation problems, the frequency range of interest is from 0.2 to 2 Hz (1.2 to 12.5 rad/s). If all the poorly damped (or slightly unstable) eigenvalues are to be computed on a single run, it is best to place a sufficient number of initial

shifts along the imaginary axis, ranging at least from $j1.2$ to $j12.5$.

The dominant pole algorithm in [12] only produces eigenvalues which are dominant in a transfer function of interest. The user is therefore freed from the repetitive task of verifying if the converged eigenvalue is of interest to the analysis in hand. Root Locus plots, for instance, could be fairly rapidly and automatically obtained for large systems. Being a single-vector iterative method, repeated solutions are however frequently obtained even for widely different initial estimates. The use of a sparse preserving implicit deflation procedure [15] ensures that different eigenvalues are obtained.

Model reduction is an important issue to the control system field and its applications in power system dynamics [22,23,24,25]. Highly reduced power system transfer function models prove effective for controller design [23]. Once the dominant transfer function poles have been found, the calculation of its residues can be efficiently carried out. From this information, one can build a reduced transfer function model whose accuracy can be varied at will with the number of dominant poles considered.

The two following questions have frequently been raised: How could one be assured that all dominant poles have been found? Can one envision the development of a more powerful algorithm, which simultaneously computes all the relevant poles of a given transfer function? The answers to these two questions are given in the following paragraph.

The authors have already developed a mathematically rigorous algorithm for the simultaneous computation of the various dominant poles of a given scalar transfer function. This algorithm is now fully tested and a technical report is being prepared [26]. Mathematically speaking, there can be no assurance that all dominant transfer function poles will be found by the new method. However, an engineering oriented search method has been devised which practically ensures that all relevant poles have been found.

Controller Synthesis for Multivariable Systems

So much about analysis tools, that something must be said about controller design tools for MIMO systems. Unfortunately, controller synthesis tools are not at the same level of development concerning large power system dynamic problems. The authors have experience with the use of the sequential loop closure technique [22,27] for the design of multiple control loops. This is a frequency response based technique, whose use becomes quite laborious in the presence of various undamped oscillation modes and control loops to be designed.

Partial pole location techniques have been applied to damp oscillations and can simultaneously tune various power system stabilizers [28,29]. The authors have implemented the algorithm described in [28,29]. This is fixed-point iteration method and its performance is disappointing: convergence to

one existing solution may be very slow or highly dependent on the ordering of equations. Partial pole location, even with proper loop scheduling [22,27], may turn unstable other closed loop eigenvalues. As an example, note that when tuning power system stabilizers one may obtain increased damping of the electromechanical mode at the cost of destabilizing the "exciter mode" [6,30]. The authors have based their loop-scheduling studies on the analysis of transfer function residues and critical transmission zeros [5,8,27,30]. Perhaps the most promising method for the simultaneous design of various stabilizers is the optimal decentralized control algorithm reported in [28]. The actual control structures used successfully in the industry are preserved in the algorithm of [28], which also efficiently exploits the system matrix sparsity.

The Power of Graphics

Interactive computation has greatly potentialized the role of computers in engineering, power system analysis included. Graphical interface is inseparable from interactive computation, and increases productivity in data preparation, analysis of results, problem understanding and algorithm development.

The statistics provided in [31] shows that, for a simple power flow scheduling exercise, engineers performed the requested task in about half the time if a well designed, friendly graphical interface was utilized.

We have been perfecting a simple graphical display and animation package for our small - signal stability software over the last few years. Large gains in productivity were achieved in both engineering studies and algorithm development with the use of graphics.

GRAPHICAL ANALYSIS OF RESULTS

Figures 1 to 7 are enhanced versions of monitor screens of the authors' interactive package. The power system analyzed is the 616 bus, 995 line, 50 generator model of the South-Southeast Brazilian System described in [5,8,27]. All these figures were taken from [27], where a stabilization study was carried out based on TCSC modulation for damping the eight poorly-damped oscillatory modes. The acronym TCSC stands for Thyristor Controlled Series Compensation.

The captions in Figures 1 to 7 almost suffice to give the reader a good understanding about their meaning and contents. The names and integers within Figures 2 and 3 identify and rank the system generators which participate most in the oscillation modes. Those at Figure 4 identify and rank the transmission lines most appropriate for locating the TCSC damping devices.

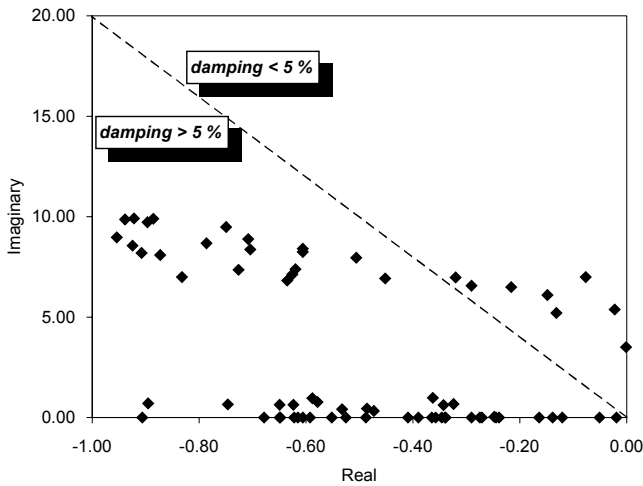


Figure 1. Eigenvalues for 50-Generator System Without Damping Devices (362 State Variables)

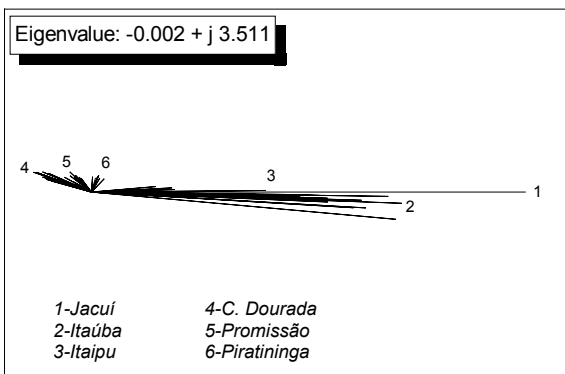


Figure 2. Rotor Speed Mode Shape of the South-Southeast Inter-area Mode (0.56Hz)

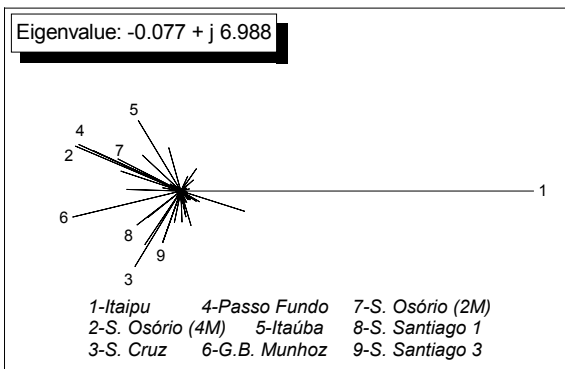


Figure 3. Rotor Speed Mode Shape of the Itaipu "Local" Mode (1.11Hz)

The TCSC location most appropriate for damping the inter-area mode (Figure 2) is the Assis-Maringá 230 kV transmission line, which yielded the $\Delta P_{kj}(s)/\Delta B_{kj}(s)$ residue of largest modulus. Figure 4 depicts the major line residues in phasor diagram form. Note that, despite the large number of system lines (995) and the inter-area nature of the mode, only eleven lines have residues of magnitude greater than 10% of

the largest one. Therefore, this is a very effective ranking procedure.

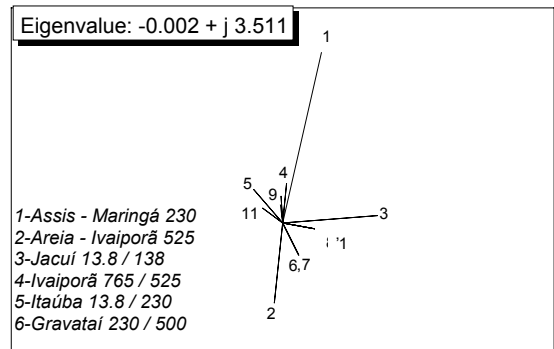


Figure 4. Residues for the Transfer Functions $\Delta P_{kj}(s)/\Delta B_{kj}(s)$ for $s = -0.002 \pm j3.511$

Eight TCSC damping devices were located in critical system lines and adequately tuned, bringing all system modes to above a 5% damping level. This multi-controller tuning exercise was successfully carried out with both the sequential loop closure [22,27] and partial pole location [28,29] techniques. Figure 16 shows the loci of the system eigenvalues in the presence of the eight TCSC oscillation damping devices whose signals were derived from generator rotor speeds.

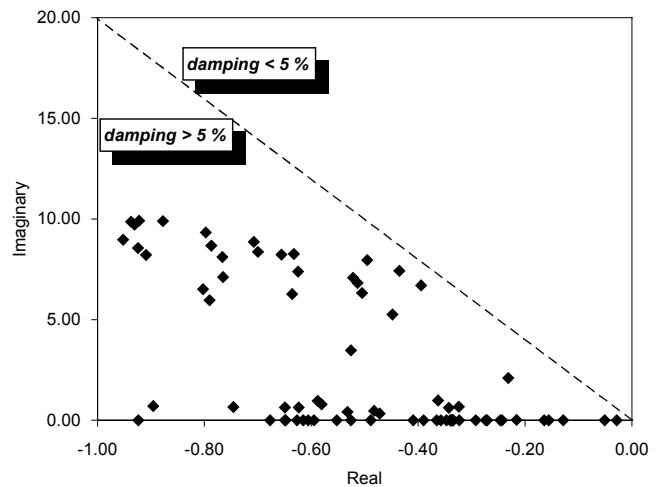


Figure 5. Eigenvalues for 50-Generator System with Eight TCSC Damping Devices (375 State Variables)

Step response results for the linearized system are shown for a simultaneous disturbance to the mechanical power of three large generators. This disturbance excites some of the major system modes. The variables pictured in the plots are the electrical power outputs of the same generators. The system step responses, in the absence and presence of the eight TCSC damping devices, are shown in figures 6 and 7 respectively.

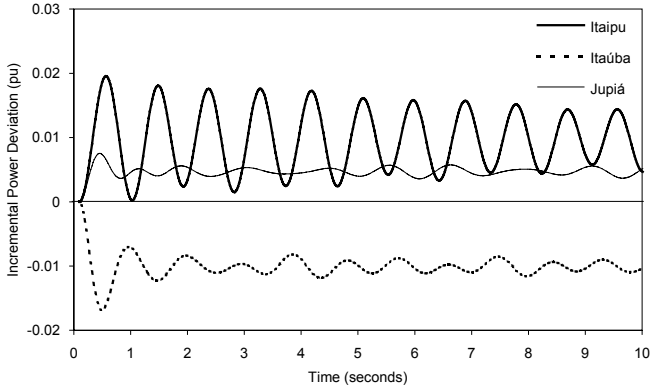


Figure 6. Step Response for 50-Generator System without Damping Devices (362 States)

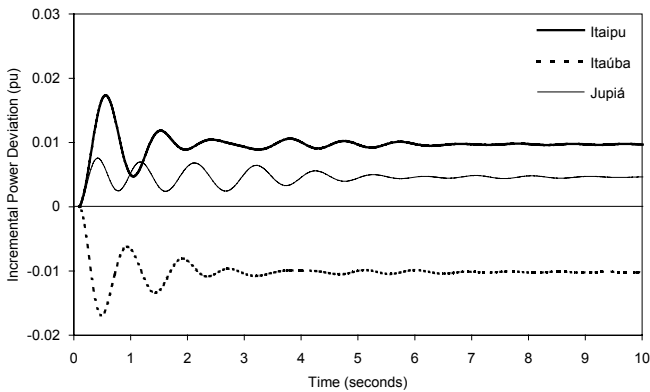


Figure 7. Same Step Disturbance Applied to 50-Generator System with Eight TCSC Damping Devices (375 States)

Figures 8 to 14 are actual monitor screens produced during program execution. Figure 8 shows a frequency response plot obtained in the study of the New England Test System and fully reported in [12].

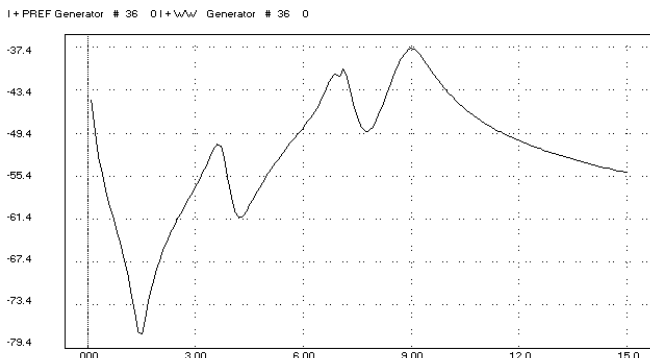


Figure 8. Bode Magnitude Plot for $\Delta\omega^{36}(s) / \Delta P_{mec}^{36}(s)$ for the New England Test System [12].

The development of an efficient Root-Locus algorithm for large scale systems was pursued by the authors for a long time. This has been recently achieved with the use of the dominant pole algorithm associated with sparse

deflation techniques [32]. The Root Locus plot displayed in Figure 9, related to the (six-machine plus one HVDC link) benchmark system of [30], was automatically obtained with this algorithm. A color code is used in the monitor screen pictures to readily identify the different critical transfer function poles (system eigenvalues). The direction and relative speeds of the several pole displacements in the root-locus plot can be easily grasped through an user-controlled visual animation facility.

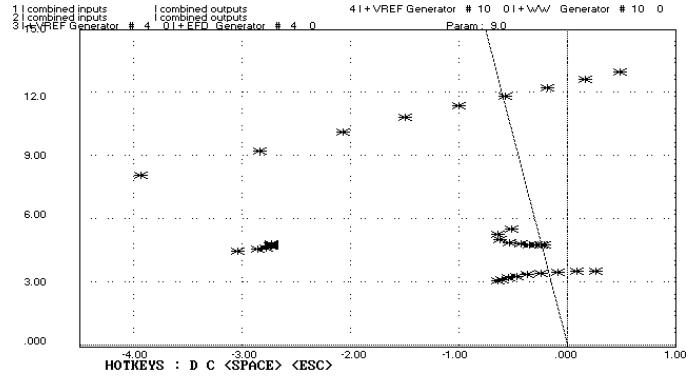


Figure 9. Root-Locus Plot for Varying PSS Gain of Benchmark System [30].

In the small signal analysis of voltage stability problems, the eigenvalues of interest are real. Therefore, the bus voltage mode shapes can be better visualized through bar charts. Figure 10 depicts the major voltage collapse mode for the Rio de Janeiro Area, detailed discussed in [19].

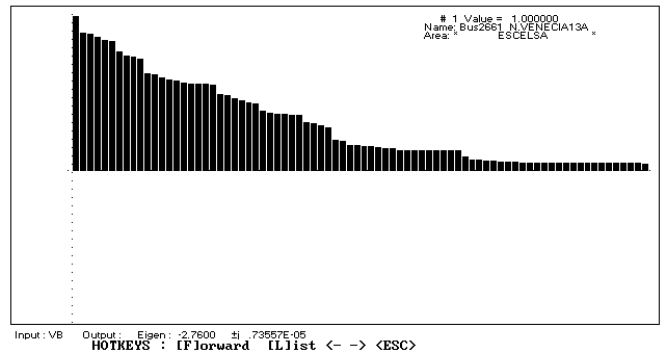


Figure 10. Bar Chart of a Voltage Collapse Mode for the Rio de Janeiro Area [19].

Graphical Animation of Algorithm Performance

This paper section is about the benefits of graphical animation to problem understanding, teaching activities and also the development of new algorithms.

Figures 11 to 13 are about the transfer function dominant pole algorithm [12] applied to the New England Test System. Figure 11 depicts the trajectory of the dominant eigenvalue estimate for the transfer function $\Delta\omega^{35-36}(s) / \Delta P_{mec}^{35-36}(s)$. The values and locations of the nine numerals within the figure denote the iteration number and the current estimate for the dominant transfer function pole (eigenvalue).

A high precision convergence to $\lambda = -.467 + j8.96$ is achieved in nine iterations. The initial estimate is labeled “1” and has a value of $j2$. The full eigenvalue spectrum for the New England system is also pictured in Figure 11.

The reasoning behind the method’s convergence trajectory can be easily visualized from the plot of the dominant pole-zero spectrum for the $\Delta\omega^{35-36}(s) / \Delta P_{mec}^{35-36}(s)$ transfer function (see Figure 12). The convention for Figure 12 is as follows: dots denote the dominant zeros and crosses the dominant poles. The remaining poles of the eigenvalue spectrum disappeared by pole-zero cancellation, which is inherent to a transfer function description. Note in Figure 12 that the dominant pole (eigenvalue) $\lambda = -.467 + j8.96$ stands practically alone in the dominant spectrum. Its large impact on the system frequency response is clearly seen in Figure 13.

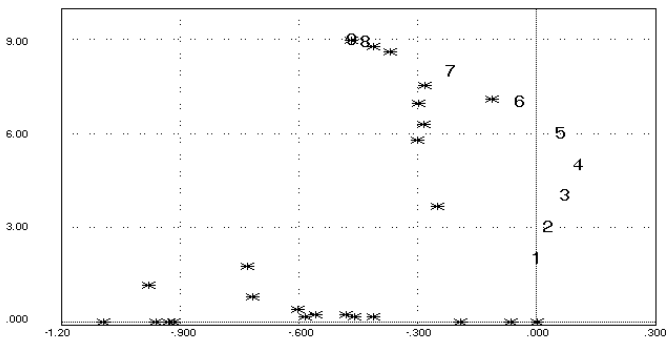


Figure 11. Trajectory of Eigenvalue Estimate with Final Convergence to the Dominant Pole of Transfer Function $\Delta\omega^{35-36}(s) / \Delta P_{mec}^{35-36}(s)$ of the New England Test System.

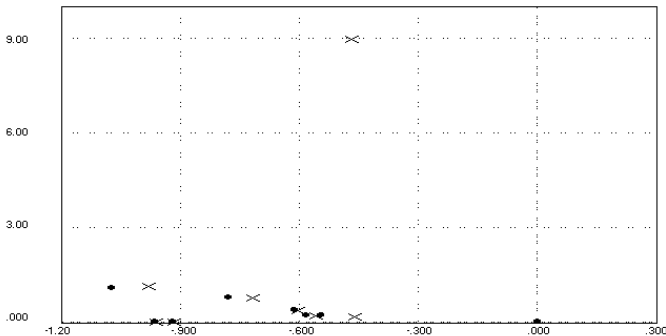


Figure 12. Dominant Pole-Zero Spectrum for Transfer Function $\Delta\omega^{35-36}(s) / \Delta P_{mec}^{35-36}(s)$ of the New England Test System

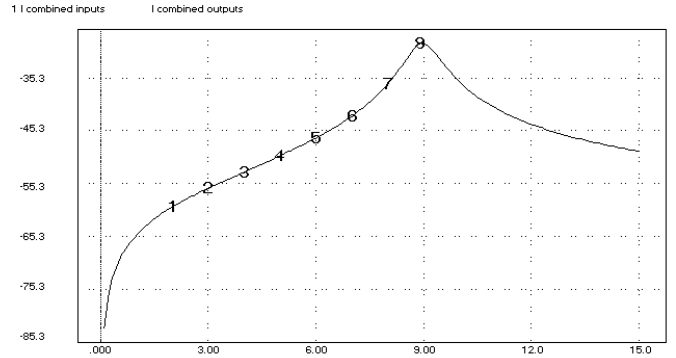


Figure 13. Bode Magnitude Plot for Transfer Function $\Delta\omega^{35-36}(s) / \Delta P_{mec}^{35-36}(s)$ of the New England Test System

The eigenvalue convergence pattern shown in Figure 11 can also be visualized with the help of the transfer function Bode magnitude plot (see Figure 13). The numerals, denoting the iteration number, are placed over the magnitude plot at points whose x-coordinate reflect the imaginary parts of the dominant pole estimates.

Figure 14 depicts the convergence performance of the recently developed Refactored Bi-Iteration algorithm [16] for the previously described 50-generator, 362-states power system model. The dots represent the ten initial complex shifts provided. The values and locations of the numerals denote the iteration where high accuracy convergence occurred and the complex-plane loci of the converged eigenvalues, respectively.

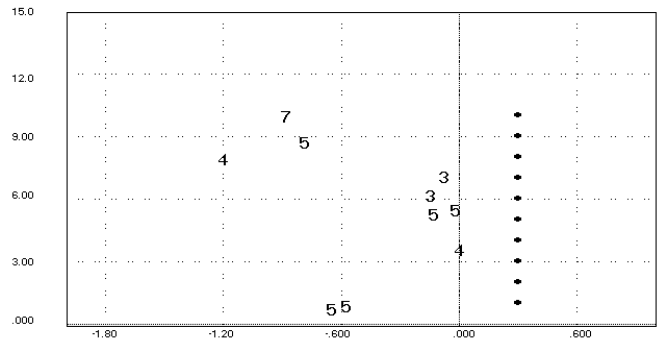


Figure 14. Eigenvalue Convergence Pattern for Refactored Bi-Iteration Algorithm (362 State Variables).

CONCLUSIONS

This paper has several objectives:

- 1) Review the state-of-the-art algorithms for the analysis and control of small-signal stability of large power systems.
- 2) Describe the synergetic combination of algorithms and adequate graphical interface. Modern small-signal stability packages make complementary use of various analysis and synthesis tools. A friendly graphical interface is therefore the right environment to promote more

effective analysis and design in large power system dynamic studies.

- 3) Emphasize the advantages of graphically visualizing the convergence performance of eigensolution algorithms to research and development work as well as to teaching activities.
- 4) Ignite new ideas for the development of even more practically oriented eigensolution algorithms.
- 5) Attract interest and research into the difficult problem of multiple controller synthesis in large scale power systems, considering robustness issues [33,34]. We strongly believe that the final answer to this problem will heavily involve optimization techniques. These tools will be fundamental to ensure better design and operation of FACTS assisted power systems.

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