



Next Generation On-Line Dynamic Security Assessment

Final Project Report

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



Next Generation On-Line Dynamic Security Assessment

Parts I and II

Final Project Report

Parts I and II Project Team

Vijay Vittal, Project Leader

Feng Ma and Guanji Hou, Graduate Students

Arizona State University

PSERC Publication 11-09

November 2011

Information about this project

Vijay Vittal
Ira A. Fulton Chair Professor
Department of Electrical Engineering
Arizona State University
PO Box 875706
Tempe, AZ 85287-5706
Tel: 480-965-1879
Fax: 480-965-0745
Email: vijay.vittal@asu.edu

Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: <http://www.pserc.org>.

For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
577 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-965-0745

Notice Concerning Copyright Material

PSERC members are given permission to copy without fee all or part of this publication for internal use if appropriate attribution is given to this document as the source material. This report is available for downloading from the PSERC website.

© 2011 Arizona State University. All rights reserved.

Acknowledgements

This is Parts I and II of the final report for the Power Systems Engineering Research Center (PSERC) research project titled “Next Generation On-Line Dynamic Security Assessment.” (PSERC project S-38) We express our appreciation for the support provided by PSERC’s industrial members and by the National Science Foundation under the Industry/University Cooperative Research Center Program.

We specifically thank:

- Jianzhong Tong – PJM
- Eugene Litvinov – ISO New England
- Jinan Huang – Institut de Recherche d'Hydro-Québec (IREQ)
- Doug McLaughlin – Southern Co.
- Sharma Kolluri – Entergy
- Dede Subakti – California Independent System Operator (CAISO).

Executive Summary

This project addresses five elemental aspects of analysis for the enhanced performance of on-line dynamic security assessment. These five elemental components include: a) A systematic process to determine the right-sized dynamic equivalent for the phenomenon to be analyzed, b) Employing risk based analysis to select multi-element contingencies, c) Increased processing efficiency in decision-tree training, d) Using efficient trajectory sensitivity method to evaluate ability for changing system conditions, and e) Efficient determination of the appropriate level of preventive and/or corrective control action to steer the system away from the boundary of insecurity. An overview of the work accomplished in each part is presented below:

Part I. Determination of the right-sized dynamic equivalent (work done at Arizona State University)

To account for the challenges associated with rapid expansion of modern electric power grid, power system dynamic equivalents have been widely applied for the purpose of reducing the computational effort of dynamic security assessment. Dynamic equivalents are commonly developed using a coherency based dynamic equivalencing approach in which a study area and external area are first demarcated. Then the coherency patterns of the generators in the external areas are determined. A commonly used method is to introduce faults on the boundary of the study area and to group the generator with similar dynamic responses in the external area. Other methods, such as slow coherency-based method and weak-link method have also been proposed. As a result, the coherent generators in the external area are equivalenced. Network reduction is then performed at the interface between the study area and the external area to suitably interconnect the equivalent generators. In the process of building a dynamic equivalent, the definition of the retained area can significantly impact the effectiveness of the final reduced system. As more components are included in the retained area, more attributes related to the dynamic characteristics of the study area can be retained. In conventional dynamic equivalencing applications, the study area and external area are arbitrarily determined without examining the phenomenon of interest with respect to the system dynamic behavior. An improperly defined retained area boundary can result in detrimental impact on the effectiveness of the equivalenced model in preserving dynamic characteristics of the original unreduced system. Additionally, under realistic situations, generator coherency information obtained under one particular operating condition might not be applicable to another operating condition. For a new system condition the process of re-evaluating the generator coherency is time-consuming, especially for large-scale power systems. Therefore significant strides can be made if an efficient technique can be developed to predict the variation in coherency behavior as system condition changes.

The approach that has been implemented in this project first considers the system representation that is available in the control center and for which the supervisory control and data acquisition (SCADA) implementation is available. The boundary of this system representation is then transferred to the planning case being considered for dynamic equivalencing. This represents the initial boundary of the study area. Tie-line interfaces between the study area and external area are identified. Then three criteria, namely the

power transfer distribution factors (PTDFs), the estimated generator rotor acceleration during the fault duration, and the oscillatory mode participation factors are applied to identify the critical generators in the initial external area that exert significant impacts on the dynamic performance of the study area. Based on this determination, the buffer area to be additionally retained can be formed by including these identified generators. The coherent generators in the new external area are then equivalenced, followed by network reduction and load aggregation. The proposed approach is efficient in the sense that the criteria, such as PTDFs and mode participation factors can be readily assessed in many commercial software packages (e.g. PowerWorld, PSS/E, and DSA Tools); while the rotor acceleration-based criterion can be readily computed without the need of time-domain simulation.

To account for the impacts of system condition change on dynamic equivalents, an eigensensitivity-based approach has been proposed in this project to trace the changes in generator slow coherency patterns. Instead of computing the slow coherency patterns from scratch for a new operating condition, the proposed method aims at capturing the significant changes in generator slow coherency after either generation level, load level, or system topology is changed. Based on the predicted coherency patterns, the retained area boundary is adjusted by including the critical generators in the initial external area that become tightly coherent with the initial retained area. The advantages of the proposed approach in saving computational time and improving the equivalencing accuracy for varied operating condition are significant.

The research conducted also reveals that the improvement resulting from revising the retained area boundary might become insignificant when the retained area is already large enough. This limitation is important in today's environment because detailed information regarding the component models and system topologies in the entire system is often inaccessible to a signal entity under the restructured environment. To address this issue, a novel hybrid dynamic equivalent, consisting of both a coherency-based equivalent and an artificial neural network (ANN)-based equivalent, has been proposed. The ANN-based equivalent complements the coherency-based equivalent at the retained area boundary buses. It is designed to compensate for the discrepancy between the full system and the conventionally reduced system. The test on a portion of the WECC system shows that the hybrid dynamic equivalent method can improve the accuracy of the coherency-based equivalent for both the trained and untrained cases. Additionally, the measurements collected by the synchronized phasor measurement units (PMUs) also allow the proposed method to improve the dynamic models for on-line dynamic security assessment (DSA).

The approaches developed have been tested on a large portion of the WECC system and on a test case provided by ISO-NE which includes a significant portion of the Eastern interconnection. The techniques developed have also been used in conjunction with the new version of DYNRED developed by Powertech Labs. This represents significant large scale testing of the method and demonstrates its capability of technology transfer to PSERC member companies. The student working on this portion of the project also performed a summer internship at ISO-NE where the method was applied to the ISO-NE system and demonstrated.

Part II. Trajectory sensitivity analysis to determine stability limits under changing system conditions (work done at Arizona State University)

Currently some utilities have existing time domain simulation based approaches to perform DSA in near real time. However, when the network topology or the operating condition changes significantly in a short time horizon, the derivation of the stability limits is computationally burdensome. In this part of research effort, an approach to compute stability limits based on a computationally enhanced trajectory sensitivity analysis has been developed to improve the computational efficiency and accuracy. The most attractive advantage of the trajectory sensitivity approach is that it can provide valuable insights into system responses due to parameter changes within a very short time at the expense of only a negligible amount of extra computational burden.

Firstly, various system parameters sensitivity calculation software packages have been implemented. The implementations include sensitivity to system generation change, load change, load modeling parameters change, generator control parameters change, network topology change and FACTS control parameters change. A Graphic User Interface (GUI) is also developed to simplify the usage. The implementations are fully tested by comparing the approximated system variable trajectories based on the base case with the actual perturbed trajectories obtained by running repeated time domain simulation for the changed condition. The results show the correctness of the implementation and enhanced performance of the trajectory sensitivity method.

Secondly, the computational efficiency problem is also addressed. The trajectory sensitivity method requires augmenting the existing system differential algebraic equations (DAEs) with a new set of sensitivity DAEs corresponding to each system parameter changes. This increases the computation burden. A high performance parallel computing platform has been utilized to reduce this burden. It is observed that each parameter sensitivity calculation is independent of other parameter sensitivity calculations. Moreover, they share the same Jacobian matrices for the solutions. Therefore, when multiples element sensitivities are evaluated, they can be performed in this cluster simultaneously. The test of this cluster shows great efficiency improvement.

The third issue tackled in this research effort is the linear approximation accuracy. The application basis of the trajectory sensitivity method is the first order linear approximation. When there is a small change in certain parameter, the system responses for this changed condition can be approximated based on the base case and the sensitivities evaluated along the base case. However, there is no quantitative measurement on the relation between the linear approximation accuracy and the perturbation size. In this research effort, it is found that there is a relationship between the bound on the linear approximation error and the bound on the product of the maximum normalized sensitivity and the perturbation size. This relationship appears to be system independent and system operating point independent. Thus, the error-perturbation size analysis method based on this finding serves as a general application guide to evaluate the accuracy of the linear approximation.

The uncertainty problem of power system modeling is also addressed using the trajectory sensitivity method. Currently most widely used methods mainly rely on the Monte Carlo type simulation to estimate the probability distribution of the outputs. These methods

require repeated simulations for each possible set of values of load models. Therefore, these approaches are computationally intensive. The trajectory sensitivity analysis can provide an alternative approach to deal with this problem. When load modeling parameter uncertainty is considered, the possible system operational boundary can be obtained by linear approximation with load parameter sensitivity information evaluated along a base case simulation in the time horizon. Based on this operational boundary, the amount of control needed to maintain the system voltage stability should not be fixed. Rather it should be within a certain defined range. An example to study the uncertainty of the composite load modeling and its effect on the system voltage stability problem is given.

The applicability of the trajectory sensitivity approach to a large realistic network is demonstrated in detail. This work applies the trajectory sensitivity analysis method to the WECC system. Several typical power system stability problems have been addressed:

1. The angle stability problem

A systematic preventive control analysis method in terms of generation rescheduling to maintain the system transient angle stability is developed and demonstrated

2. The voltage stability problem

The trajectory sensitivity approach is used to determine the system operational boundary corresponding to a set of uncertain parameters. Several preventive control actions are then determined according to this operational boundary rather than one fixed operating point. This consideration provides border information for control decision making

3. Interface real power flow limit calculation

The trajectory sensitivity method is also applied to calculate the interface real power flow limit. First the generation limits of the key generators in the interface are calculated utilizing the trajectory sensitivity method. Then the flow limit through the interface can be determined by the limits of the key generators and their PTDFs.

All these approaches have been demonstrated on a large realistic model of the WECC system. The software was developed in conjunction with an open source time domain software package called PSAT. All the elements of the development can be easily transported to any member company for demonstration and use.

Project Publications

[1] F. Ma, and V. Vittal, "Right-sized power system dynamic equivalents for power system operation," to appear in the *IEEE Trans. on Power Syst*, TPWRS.2011.2138725.

[2] F. Ma, X. Luo, and V. Vittal, "Application of dynamic equivalencing in large-scale power systems," to appear in the proceeding of *IEEE PES 2011 General Meeting*, Detroit, MI, July 24–28, 2011, Paper no. 2011GM0804.

[3] G. Hou, and V. Vittal, "Cluster computing-based trajectory sensitivity analysis application to the WECC system," *IEEE Trans. on Power Syst.*, v. 26, No. 3, pp. 1 – 8, 2011.

Student Theses

[1] F. Ma, "Improved Coherency-based Dynamic Equivalent," PhD Dissertation, Arizona State University, November 2011.

[2] G. Hou, "Trajectory Sensitivity Based Dynamic Security Assessment," PhD Dissertation, May 2012.