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CA ISO
Real Time
Voltage Security
Assessment
(VSA) Project

Summary of Survey Results On Methodologies for use in Real Time Voltage Security Assessment

For:

Energy Commission and CA ISO
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Electric Power Group

CERTS
Consortium for Electric Reliability Technology Solutions

Introduction

The CA ISO Real Time Voltage Security Assessment (VSA) project is designed to research methodologies and analytic approaches for utilization in developing tools for use by dispatchers that provide real time assessment of voltage margins and contingency rankings. As the first step to achieve this objective, CERTS/EPG formulated a survey to reach out to experts in this field for comments, information, suggestions, and recommendations. The Survey can be found in Appendix A. Two projects were suggested to the reviewers. The first was a proposal to develop a Real-Time Voltage Security Margin Assessment tool with the ability to identify abnormal reductions of nodal voltages, weak elements and regions most affected by voltage problems. The other was to develop a Real-Time Angle Stability Margin Assessment tool with the ability to use Phasor Measurement Unit (PMU) data to calculate "distance to instability".

Survey Overview

The surveys were sent to fifty-one experts in universities and in the power industry. Sixteen reviewers (Appendix D) responded and their responses are listed in Appendix B & C. Eight of these respondents are from the power industry and eight are from academia. Four proposals for commercial software were received from Bigwood Systems Inc (BSI), Vaiman Research (V&R), New England Transmission System Services (NETSS) and Energy Concepts International (ECI).

A summary of research issues, comments and conclusions from responses are provided in Table 1 (below)

Table 1: Summary of Issues, Responses and Conclusions

ISSUE	RESPONSES / COMMENTS	CONCLUSION
Voltage Security Assessment (VSA) (Hyper planes for security regions)	Online hyper plane possible Not as unproven as interior point methods. Ideally suited for phenomena that are local.	Hyper planes well suited for VSA
Methodology for computing hyper planes	Loading & Generation Direction needed. Stress path until voltage collapses. At collapse, determine local boundary.	Use left eigenvector approach
Direct versus Time-domain methods	Time domain iterative methods are proven and robust, capable of handling intermediate discrete actions/events. Example: Generator limits being reached Direct methods rely on simplistic models	Direct Method could be used for fine-tuning the security boundaries after an iterative set of continuation power flows
Weak elements identification	Voltage collapses are concentrated in certain regions in the sense that the voltage falls more in those regions. There is no single element that collapses. That is, voltage collapse occurs system wide with varying participation from all the system buses.	The participation is computed from the right eigenvector of the Jacobian evaluated at voltage collapse corresponding to the zero eigenvalue.
Transient Security Assessment (TSA) (Hyper planes for security regions)	Need detailed dynamical model. Controlling UEP is hard to calculate. Limited observability with PMUs.	Hyper planes not yet validated for application in TSA
Use of phasor measurements for security assessment	Limited observability	Start with small signal stability assessment

Summary of Responses for Real Time Voltage Security Assessment

The responses led to the conclusion that the hyper plane approach to defining security regions is ideally suited for voltage instability assessment. Voltage instability is more of a local area/region phenomenon. Several participants in the survey felt that the algorithms that utilize Direct Methods should be augmented with time domain algorithms to capture system topology change. It was suggested that without time domain simulations, it is not clear how switching conditions could be revealed. The computational methods to be used in VSA could be grouped into 2 broad classes – the Iterative Approach using Continuation Power Flows and the Direct Method. The Direct Method does not provide information on any discontinuous events when the stress parameter is increased. These discontinuous events occur when thermal, voltage or reactive limits are reached.

Summary of Responses for Real-Time Angle Stability Assessment

The majority of respondents felt that transient stability assessment requires very detailed dynamical modeling to be a successful tool in wide area security assessment. A representative from a utility in the East listed concerns about the practical implementation of wide area monitoring such as the validity of the system model to capture phenomena of interest and also the accuracy of angle difference from PMUs of different vendors. Several respondents flagged the issue of un-observability in PMU based measurements and the subsequent problem of determining optimal PMU placement locations. A proposal addressing this item was received from NETSS that focuses on the economic assessment of voltage support measurements known as pilot points.

Conclusions

The majority of responses favor the use of the hyper plane approach in determining Voltage Security Assessment. Also, the majority of responses do not see hyper planes suitable for determining Dynamic Voltage Assessment at this time. Small Signal Stability Analysis is considered to be a good first step for Wide Area Stability Monitoring and assessment using phasor measurements.

Recommendations

1. The primary recommendation is to use the hyper plane approach in computing security regions for Voltage Security Assessment.

   - The Continuation Power Flow has been tested by several researchers in commercial and non-commercial software and is recommended as an initial step in the CA ISO VSA computational engine.

   - An alternate recommendation is a hybrid approach, where a Direct Method could be used for fine-tuning the security boundaries after an iterative set of continuation power flows.

2. Continue research in the following areas:
   (a) Existing approaches that can be applied for modal and coherency analysis (Small Signal Analysis)
   (b) Methods to develop practical applications for Dynamic Security Assessment (DSA).

APPENDIX A – CA ISO RTWSA Survey

REAL TIME WIDE-AREA SECURITY ASSESSMENT FOR CA ISO SYSTEM
REQUEST FOR COMMENTS AND FEEDBACK

REQUEST OBJECTIVE: The California Independent System Operator (CA ISO) and other Grid and Transmission System Operators in California are exploring avenues to better optimize utilization of the existing transmission system via development of state-of-the-art real time wide-area security assessment applications using both traditional SCADA data and new phasor metering technologies providing sub-second measurements of relative phase angles, voltage magnitudes and current line flows. As the first step to achieve this objective, we are reaching out to you as experts in this field for comments, information, suggestions, and recommendations on the two applications and corresponding algorithms and methodologies described in the following sections. Additionally, alternate new, proven, methodologies to develop a state-of-the-art application to optimize the operating limits of the CA ISO system while maintaining adequate wide-area security and reliability are also welcome.

REAL TIME APPLICATIONS BEING CONSIDERED: The CA ISO is interested in real time system security via two projects. Both projects will be based on similar advanced methods for calculating angle, voltage and transient stability limits. In order to obtain fast security margin evaluation in real-time, the security regions will be calculated offline as a set of periodically updated (interconnection wide) constraints. The CA ISO proposal is aimed at developing a real-time dispatcher's security system display that will include the results of the two applications described below:

PROJECT 1: Develop a Real-Time Angle Stability Margin Assessment tool with the following characteristics:

- Real-time wide area monitoring using Phasor Measurement Unit (PMU) data to calculate "distance to instability".
- The security margin for the current moment and system configuration is estimated.
- The approximated stability boundaries are determined in coordinates of relative phase angles.
- The system is unobservable because the interconnection state cannot be determined based on PMU data.
- The analysis is conducted for the entire interconnection based on available geographically dispersed measurements.

PROJECT 2: Develop a Real-Time Voltage Security Margin Assessment tool with the following characteristics:

- Real-time voltage security margin determination by (offline) operating constraints calculation.
- Identification of abnormal reductions of nodal voltages, weak elements and regions most affected by voltage problems.
- The analysis is conducted for local control areas, e.g. California ISO area.
- The boundaries are in coordinates of nodal power injections and power flows in selected lines such as cut-sets & paths.
- The project deals with the observable part of the system, such as the control area and potentially its closest vicinity.

METHODOLOGIES AND TECHNOLOGIES BEING CONSIDERED: The focus would be on calculating global "metrics" for the stability margin instead of "bus oriented" indices. It is hoped that Direct Methods for calculating security regions offline will be used to obtain fast stability margin evaluation in real-time. Some publications on Direct Methods & Phasors have been listed as a sample of the ideas being investigated by CA ISO.

- A. G. Phadke, J. S. Thorp, K. J. Karimi: "State Estimation with Phasor Measurements", IEEE Transactions on Power Systems, Vol. PWRS-1, No. 1, February 1986.
- Y. V. Makarov, D. J. Hill, and Z. Y. Dong, "Computation of bifurcation boundaries for power systems: a new Delta-plane method" IEEE Trans. on Circuits and Systems - I: Fundamental Theory and Applications, Vol. 47, No. 4, April 2000, pp. 536-544.
- Hsiao-Dong Chiang, Chia-Chi Chu, Gerry Cauley, "Direct stability analysis of electric power systems using energy functions: Theory, applications, and perspective", Proceedings of the IEEE, 13, pp. 1497-1529, 1995.
- F. Alvarado, I. Dobson & Y. Hu, "Computation of Closest Bifurcations in Power Systems", IEEE Transactions on Power Systems, Vol 9, No 2, May 1994, pp. 918-22.

APPENDIX B – Survey Responses Specific to VSA & TSA

Reviewer	*VSA using Hyperplane Methods*	*TSA using Hyperplane Methods*
[1]	❑ Recommends hyperplane approach for VSA. Furthermore suggests online hyperplane computation if loading directions and generating unit dispatch vectors are known a priori. Needs only up to 10 load flow runs with to compute “weak” elements.	❑ Data are more demanding than VSA ❑ Recommends using PMU measurements for modal estimation (model independent technique) to assess small signal stability
[2]	❑ Adopted similar direct methods for contingency ranking and also in hybrid system aimed to give a measure of angle as well as voltage stability. These experiences demonstrate the applicability of the proposed methodologies. ❑ Practical security boundary must account for grid topology changes (implying online security assessment).	❑ Methods like the one proposed in this project have not been implemented by any grid operator, even if monitoring of system variables for angle and voltage stability assessment has been a concern in several research activities. ❑ Optimal number & placement of PMUs is required to correctly evaluate system stability (complete observability).
[3]	❑ More information needed about the hyperplane approach to VSA.	❑ Computational complexity in computing controlling unstable equilibrium point is a big drawback
[4]	❑ Has real potential – and it is not as unproven as some other concepts like interior point optimization.	❑ Problem is limited observability ❑ Requires time domain verification
[5]	❑ Seems to be ideally suited for voltage instability where the phenomena is more localized and ideally suited for decision based on measurements ❑ Not convinced that Practical Dynamic Security Region direct method has any particular computational advantage over other methods	❑ Recommends EPRI-Siemens Approach ❑ Direct method used for ranking contingencies ❑ Full blown time domain program with energy indicators is used determine stability
[6]	❑ Experience has shown that secure operating space calculations done off line rarely match exact real time conditions, which may well be away from design conditions, implying online security assessment or adequate safety margins.	❑ Investigated various grid margin indices with the EPRI-Siemens product but were unable to develop a suitable production metric. Integration of both continuous (load growth) and non-continuous (contingency) factors into a single metric was a major challenge.
[7]	❑ Least squares approximation of hyper planes with load flow simulations is prone to error enhancement for bad state estimator measurements.	❑ It is not clear how switching conditions can be revealed without “time-domain” simulations.
[8]	❑ Proposes New Electricity Transmission Software Solutions (NETSS) for voltage optimization, and the economic assessment of voltage support measurements (known as pilot points). ❑ It is important to determine the right locations to measure. Results depend on voltage dispatch strategies, loading conditions and system-specific equipment status.	❑ Pilot points will help in PMU placement.

APPENDIX C – Survey Responses related to General Issues

Reviewer	*General comments on tools and methodologies that were discussed in the Survey*
[9]	❑ Advises to use equations like J'(X) F(X) =0 to search for the closest points of the steady-state stability boundary. He also warns that the thermal constraints are often more limiting than stability constraints.
[10]	❑ Methods not yet been utilized by grid operators. ❑ Emphasizes mode meter and system stiffness. ❑ Refers to WACS paper by Carson Taylor.
[11]	Suggested the advantages of the following V&R products: ❑ For off-line computations the exact boundary of dynamic security region (security nomogram) is automatically constructed using V&R's Boundary of Operating Region (BOR) software. ❑ For on-line computations, sensitivity-based *n*-dimensional boundary of operating region can be computed using BOR. The approximated boundary may be computed using Direct methods.
[12]	❑ Visualization of voltage stability region in cut-set space has been implemented and a visualization system of dynamic security region in injection space to guarantee transient stability is in development for Henan Power System of CHINA ❑ It might be used in monitoring, assessment and optimization of security. "Up to now almost all research results of mine are about the dynamic security region in power injection space and the voltage stability region in cut-set power space. I think it might be used not only in security monitoring and control, but also in probabilistic security assessment."
[13]	❑ Submitted a Proceeding of IEEE paper on WACS accepted for publication in May 2005. This paper co-authored by Taylor describes an online demonstration of a new response based wide area control system with discontinuous actions for power system stabilization.
[14]	❑ Submitted a product overview of Energy Concepts International software "QuickStab".
[15]	❑ Submitted a company overview and product list of Bigwood systems. ❑ This included information that showed partnerships with ABB to install BCU-DSA at the EMS of three power companies. BCU method is the only method used in EPRI Direct 4.0 and BCU method has been implemented by Siemens, at the Northern Power Company.
[16]	❑ Provided areas of concern in the implementation of wide area monitoring such as: ❑ Validity of the system model to capture the phenomena of interest. ❑ Accuracy of angle measurements by PMUs. ❑ Accuracy of angle differences from PMUs of different vendors. ❑ Determining acceptable vs. unacceptable levels of angular separations among various pairs of PMU

APPENDIX D LIST OF SURVEY RESPONDENTS
Ian Dobson (Wisconsin-Madison
Enrico De Tuglie (Politechnico di Bari)
M. Anantha Pai (University of Illinois)
Gerald T. Heydt (Arizona State)
Vijay Vittal (Arizona State)
Raymond Vice (Southern Co)
Anatoliy Meklin (PG&E)
Marija D. Ilic (Carnegie Mellon)
Alexander Kontorovich (Israel)
Bill Mittelstadt (BPA)
Marianna Vaiman (V&R Company)
Yixin Yu (Tianjin University)
Carson Taylor (BPA)
Savu Savulesco (ECI)
H-D Chiang (Cornell)
Navin Bhatt (AEP)

APPENDIX E.1 – Literature Survey on Stability

[1] C Taylor, “CIGRE Task Force 38.02.17 Advanced Angle Stability Controls”Dec 99.

[2] Y. Zeng, J. C. Fan, and Y. X. Yu, "Practical Dynamic Security Regions of Bulk Power Systems," Automation of Electric Power System, vol.25, No.16, pp.6-10, 2001.

[3] Y. X. Yu and W. P. Luan, "Practical Dynamic Security Regions of Power Systems," Proceedings of the CSEE, vol.10, Electrical Mathematics Supplement, pp.22-28, 1990.

[4] F. Feng and Y. X. Yu, "Dynamic Security Regions of Power Systems in Injection Spaces," Proceedings of the CSEE, vol.13, No.3, pp.14-22, 1993.

[5] Chadalavada, V., V. Vittal, et al., "An On-Line Contingency Filtering Scheme for Dynamic Security Assessment," IEEE Transactions on Power Systems, Vol. 12, No. 1, pp. 153-161, February 1997.

[6] Ilic-Spong, M., J. Christensen, and K.L. Eichorn, "Secondary Voltage Control Using Pilot Point Information," IEEE Transactions on Power Systems 3, 660-668, May 1988

[7] Ilic, M.D., S.X. Liu, G. Leung, C. Vialas and M. Athans, "Improved Secondary and Tertiary Voltage Control," IEEE Transactions on Power Systems, 10, November 1995, pp. 1851-1862.

[8] V. A. Mateev, “A Method of Numerical Solutions of Sets of Nonlinear Equations”, Zhurnal Vychislitelnoi Matematiki Matematicheskoi Fiziki, vol.4, # 6, pp983-994,1964.

[9] Yixin Yu, Yuan Zeng, Chunhua Huang, Stephen T. Lee and Pei Zhang. “A Practical Direct Method for Determining Dynamic Security Regions of Electrical Power Systems by Power Perturbation Analysis” International Conference on Electrical Engineering 2004 (ICEE2004), July 4-8, 2004, Sapporo, Japan.

[10] Hsiao-Dong Chiang, Chia-Chi Chu, Gerry Cauley, “Direct stability analysis of electric power systems using energy functions: Theory, applications, and perspective”, Proceedings of the IEEE, 13, pp. 1497-1529, 1995.

[11] Hsiao-Dong Chiang, Cheng-Shan Wang and Hua Li, “Development of BCU classifiers for on-line dynamic contingency screening of electric power systems”, IEEE Transactions on Power Systems, 14, pp. 660-666, 1999.

[12] James Momoh, Yuri V Makarov, William Mittelstadt, “A Framework of Voltage Stability Assessment in Power System Reliability Analysis”, IEEE Transactions on Power Systems, Vol. 14, No.2, May 1999.

[13] Ilic, M.D. and J. Zaborszky, Dynamics and Control of Large Electric Power Systems, Wiley Interscience, May 2000

[14] F. Alvarado, I. Dobson & Y. Hu, “Computation of Closest Bifurcations in Power Systems”, IEEE Transactions on Power Systems, Vol 9, No 2, May 1994, pp. 918-22.

[15] Voltage Stability Analysis Program (VSTAB), Version 2.1, User’s Manual, EPRI Research ProjectRP30400-01, August 1992.

[16] Chih-Wen Liu Thorp, J.S “A novel method to compute the closest unstable equilibrium point for transient stability region estimate in power systems” IEEE Trans. on Circuits and Systems - I: Fundamental Theory and Applications, Volume: 44, # 7, July 1997 pp. 630-635

[17] A. M. Kontorovich and A. V. Krukov, “Definition of Power Flow Limit Conditions by the Permanent Loading Method”, Proceedings of the Leningrad Polytechnic Institute, vol. 380, 1981, pp. 104-108.

[18]Y. V. Makarov, A. M. Kontorovich, D.J.Hill and I.A.Hiskens, “Solution Characteristics of Quadratic Power Flow Problems”, Proceedings of the 12th Power Systems Computation Conference, Vol. 1, Dresden, Germany, August 1996, pp. 460-467.

[19]] P.W.Sauer and B.C.Lesieutre, “Power System Load Modeling”, J.H.Chow, P.V.Kokotovic and R.J.Thomas, (edit) Systems and Control Theory for Power Systems, Springer-Verlag 1995, pp. 283-313.

[20] Y. V. Makarov, D. J. Hill, and Z. Y. Dong ,“Computation of bifurcation boundaries for power systems: a new Delta-plane method” IEEE Trans. on Circuits and Systems - I: Fundamental Theory and Applications, Vol. 47, No. 4, April 2000, pp. 536-544.

APPENDIX E.2 – Literature Survey on Phasors in SPS

[1] Niusha Rostamkolai, Ph.D. dissertation, Virginia Tech 1986, Adaptive Optimal Control of AC/DC Systems.

[2] N. Rostamkolai, A.G. Phadke, J.S. Thorp, W.F. Long, Measurement based optimal control of high voltage AC/DC systems, IEEE Trans. on Power Systems, Vol. 3 No. 3, August 1988, pp 1139-1145.

[3] Edgardo Manansala, Ph.D. dissertation, Virginia Tech August 1989, Adaptive power system control.

[4] Edgardo C. Manansala, A.G. Phadke, An optimal centralized controller with nonlinear voltage control, Electric Machines and Power Systems, 19, 1991, pp 139-156.

[5] L. Mili, T. Baldwin, A.G. Phadke, Phasor measurements for voltage and transient stability monitoring and control, Workshop on Application of advanced mathematics to Power Systems, San Francisco, Sept. 4-6, 1991.

[6] A.F. Snyder, N. Hadjsaid, D. Georges, L. Mili, A.G. Phadke, O. Faucon, S. Vitet, Inter-area oscillation damping with power system stabilizers and synchronized phasor measurements, PowerCon 1998, China.

[7] M.A. Smith, Improved Dynamic Stability Using FACTS devices with phasor measurement feedback, MS Thesis, VTech, 1994.

[Extracted from Marek Zima, Special Protection Schemes in Electric Power Systems Literature survey ETH, 2002.]

The best trend, which has appeared in the last decade, is Synchronized Phasor Measurement Technology. The main idea is to measure the voltage and current phasors in the same time at the selected locations in the network, transmit them into a central point, where they can be compared, evaluated and further processed. The devices performing the measurements are called PMU (Phasor Measurement Unit). PMU is basically a conventional RTU (Remote Telemetry Unit) equipped with the receiver of GPS signal synchronizing the measurements and tagging the time stamp to them. PMU is also capable of pre-processing of data (Fourier transformation etc.). The PMU technology was originally developed in eighties by Thorp, Phadke and others at Cornell, Virginia Polytechnic Institute and American Electric Power. Since the quantities measured by PMUs are voltage and current phasors, the linear relation between them holds when modelling the branches in the network (i.e. π - equivalent of line and transformer). This feature/property permits linear State Estimation process, thus avoiding repetitive manipulations with large matrices in iterative procedure as it is in the traditional case. This significantly reduces the computational time and errors level. This approach has probably been derived first time in [Phadke, 1986] where the authors have formulated the linear State Estimation equations and applied them on 118 buses IEEE test system. The authors assume that all substations are equipped with PMUs measuring all voltages and some selected currents. The high cost of both PMUs themselves (although nowadays this is not as critical issue as it used to be, the price of PMU is approximately 3 500 USD) and the communication links to all substations force to keep the number of installed PMUs to a minimum.

[Phadke 86] A. G. Phadke, J. S. Thorp, K. J. Karimi: “State Estimation with Phasor Measurements”, IEEE Transactions on Power Systems, Vol. PWRS-1, No. 1, February 1986

APPENDIX E.3 – Definition of Instability Phenomena

- Frequency Instability – is inability of a power system to maintain steady frequency within the operating limits.
- Voltage Instability – is the inability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance, increases in load demand, or change in system conditions causes a progressive and uncontrollable drop in voltage. A system is voltage unstable if, for at least one bus in the system, the bus voltage magnitude decreases as the reactive power injection in the same bus is increased.
- Transient Angular Instability (also called Generator's Out-of-step) – is the inability of the power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursions of generator angles and is influenced by the nonlinear power-angle relationship.
- Local mode of Small-signal Angular Instability (also mentioned as Generator's Swinging or Power Oscillations) – is the inability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purposes of analysis. *Local modes* or *machine-system modes* are associated with the swinging of units at a generating station with respect to the rest of the power system. The term *local* is used because the oscillations are localized at one station or small part of the power system.

[Extracted from Marek Zima, Instability Phenomena in Electric Power Systems Literature survey ETH, 2002]

An idea of preventive analysis conducted in regular on-line cycles adopting N-1 rule and applying the results immediately after the detected contingency, is probably the only solution for the phenomena on very fast time scale. In the voltage instability case it means calculations of a minimal load shedding necessary to stabilize the power system subjected to any contingency from the selected range. Thus, an optimization problem can be formulated, where the function to be minimized is the amount of load shedding subject to the following constraints: solvability of static power flow equations (this essentially means, that minimal feasible solution can be found in the maximum loadability point), allowed voltage limits, angle stability inequality constraints and dynamic equality constraints . Continuation Power Flow (CPF) can overcome the numerical problems indicated above. In principle, it is slightly reformulated conventional power flow. The equations are augmented by the term quantifying the load increase and containing new variable – load parameter. A new equation is introduced, which basically forces a continuation parameter chosen in the predictor step to hold its value in the iterative correction process. This continuation parameter is optimally loading in the beginning of the PV –curve and when approaching to "nose", voltage. Various techniques have been developed for predictor step in order to speed up the computations and increase the accuracy. Very good explanatory example of the tangent method and the secant predictor (in fact linear approximation estimate) can be found in [Chiang, 1999]. CPFLOW has probably become the most widely accepted tool for the voltage instability assessment/evaluation and a huge number of papers have been written about it.

[Chiang 99] Hsiao-Dong Chiang, Cheng-Shan Wang and Hua Li, "Development of BCU classifiers for on-line dynamic contingency screening of electric power systems", IEEE Transactions on Power Systems, 14, pp. 660-666, 1999.