

Final Report for Period: 09/2008 - 08/2009**Submitted on:** 01/01/2010**Principal Investigator:** Meliopoulos, Athan P.**Award ID:** 0080012**Organization:** GA Tech Res Corp - GIT**Submitted By:**

Meliopoulos, Athan - Principal Investigator

Title:

Georgia Tech Proposal to Join PSERC

Project Participants**Senior Personnel****Name:** Meliopoulos, A.**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Dr. Meliopoulos worked on a number of PSERC sponsored projects and supervised the work of several graduate students. The PSERC research projects are (a) Effective Control center visualizations (S-25), (b) Stability monitoring using PMUs (S-27) and (c) Optimal Allocation of Static and Dynamic VAR sources (S-24). Final reports for these projects have been submitted. In addition he participated in the activities of PSERC as the site director for Georgia Tech and coordinated the participation of other Georgia Tech faculty members in the center activities.

Name: Taylor, David**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Glytsis, Elias**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Deng, Shijie**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Dr. Deng participated in two PSERC sponsored research projects (Evaluation of Alternative Market Structures and Compensation Schemes for Incenting Transmission Reliability and Adequacy Related Investments - M-11 and Modeling Market Signals for Transmission Adequacy Issues - M-08) and at three PSERC meetings. In addition he delivered a PSERC seminar and participated in proposal preparation.

Name: Cokkinides, George**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Dr. Cokkinides participated in three PSERC sponsored projects (S-25, S-27, and S-24), supervised graduate students working in these projects and published several technical papers for these projects. The final research project reports for these projects have been submitted and published as PSERC reports. The technical papers will be listed later.

Name: Divan, Deepak**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Professor Deepak Divan participated as the lead senior person in one of the project sponsored by CERTS.

Name: Meisel, Jerome**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Dr. Meisel participated and collaborated with other Georgia Tech personnel and the University of Illinois, Urbana on a PSERC funded project entitled 'Power system level impacts of PHEVs'.

Post-doc**Name:** Mohagheghi, Salman**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Dr. Mohagheghi participated in the development of the laboratory facilities, directed the work of students and he participated in report preparations and technical paper publications.

Graduate Student**Name:** Stefopoulos, George**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Mr. Stefopoulos participated in two PSERC projects (S-27 and S-24). His PhD research work is related to the PSERC project S-24. He participated in the report preparation for both projects. In addition he participated in the preparation of technical papers and presentation of these papers in various professional meetings. The papers are listed in the publications area.

Undergraduate Student**Technician, Programmer****Other Participant****Research Experience for Undergraduates****Organizational Partners****University of Illinois at Urbana-Champaign**

Collaborated on two projects funded by industry members of PSERC

Iowa State University

Collaborated on a PSERC research project (completed) and presently we are collaborating on another.

Arizona State University

Collaborated on a PSERC project. The project investigated innovative techniques for using GPS synchronized measurements for power system stability enhancement.

Texas A&M University Main Campus

Collaborated on writing proposals and continuation of work on system automation.

University of California, Berkeley, Department of Statistics

Georgia Tech personnel (Dr. Deng and Dr. Meliopoulos) collaborated on several research projects funded by PSERC with Dr. Oren of the University of California, Berkeley.

Wichita State University

Georgia Tech personnel (Dr. Meliopoulos and Dr. Cokkinides) collaborated in a PSERC funded project with Dr. Jewell of Wichita State University.

Cornell University

Georgia Tech personnel (Dr. Deng and Dr. Meliopoulos) collaborated in several PSERC funded projects with Dr. Tim Mount of Cornell University.

Other Collaborators or Contacts

Nothing yet to report

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Georgia Tech's activities share the PSERC vision to provide new or improved solutions to power industry problems arising from restructuring and technological changes as well as operational collapse such as the blackout 2003. Georgia Tech researchers participated in the following PSERC research projects.

Market Projects

(M-11) Evaluation of Alternative market structure and Competition Schemes for Incenting Transmission reliability and Adequacy Related Investments.

The final report for above project has been completed and submitted in August 2008.

(M-08) Modeling Market Signals for Transmission Adequacy Issues: Valuation of Transmission Facilities and Load Participation Contracts in Restructured Electric Power Systems

The final report for above project has been revised, finalized and submitted in January 2008.

T&D Projects

(T-38) Substation of the future: feasibility study.

The final report for this project is due Jun 2010.

(T-34) Power System Impacts of Pluggable hybrid vehicles

The report for this project has been completed, submitted and published in September of 2009.

(T-30) Transient Testing of Protective Relays: Study of Benefits and Methodology

The report for above project has been completed and submitted.

Systems Projects

(S-28) Reactive Power Planning against Voltage Collapse with Respect to Unpredictable Component Protection

The final report for this project has been completed and submitted in August 2008.

(S-22) Enhanced State Estimators

(S-27) A Tool for On Line Stability Determination and Control for Coordinated Operation between Regional Entities Using PMUs

(S-24) Optimal Allocation of Static and Dynamic VAR Resources

(S-25) Effective control center visualizations

The reports for above projects have been completed, submitted and published as PSERC reports.

Findings: (See PDF version submitted by PI at the end of the report)

PSERC reports completed and distributed in past five years:

Vijay Vittal (ISU), Peter Sauer (UIU), Sakis Meliopoulos, and George K. Stefopoulos (GIT), On-Line Transient Stability Assessment Scoping Study, PSERC Publication 05-21, January 2005.

Sakis Meliopoulos, David Taylor, Fang Yang, Sun Wook Kang, George Stefopoulos (GIT), Chanan Singh (TAMU), Comprehensive Power System Reliability Assessment, PSERC Publication 05-13, April 2005.

Sakis Meliopoulos, Elias Glytsis, Xi Zhu, Murad Asad, George Stefopoulos (GIT), Mladen Kezunovic (TAMU), Distribution System Electromagnetic Modelling and Design for Enhanced Power Quality, PSERC Publication 05-12, April 2005.

G. T. Heydt, Anjan Bose, A. P. Meliopoulos, Natthaphob Nimpitiwan, Yang Zhang and Q. Binh Dam, 'New Implications of Power System Fault Current Limits', PSERC Publication 05-20, September 2005.

Thomas Overbye, A. P. Meliopoulos, David Wiegmann, George Cokkinides, Matt Davis, George Stefopoulos and Yan Sun, 'Visualization of Power Systems and Components', PSERC Publication 05-65, November 2005.

Shijie Deng, Tim Mount, Shmuel Oren, 'Evaluation of Alternative Market Structure and Compensation Schemes for Incenting Transmission Reliability and Adequacy Related Investments', PSERC Publication 08-16, July 2008.

Ali Abur, Jerry Heydt and A. P. Meliopoulos, 'Enhanced State Estimators', PSERC Publication 06-07, November 2006.

Vijay Vittal, Gerald Heydt and A. P. Meliopoulos, 'A Tool for On-line Stability Determination and Control for Coordinated Operating between Regional Entities Using PMUs', PSERC Publication 07-10, November 2007.

A. P. Meliopoulos, Vijay Vittal, James McCalley, V. Ajjarapu and Ian Hiskens, 'Optimal Allocation of Static and Dynamic VSAR Resources', PSERC Publication 08-06, March 2008.

Mladen Kezunovic, Sakis Meliopoulos, Ward Jewell, 'Transient Testing of Protective Relays: Study of Benefits and Methodology', PSERC Publication 08-05, March 2008.

Thomas Overbye, Sakis Meliopoulos, Esa Rantanen and George Cokkinides, 'Effective Power System Control Center Visualization', PSERC Publication 08-12, May 2008.

Venkataramana Ajjarapu and A. P. Meliopoulos, 'Optimal Reactive Power Control against Voltage Collapse Incorporating Protection System', PSERC Publication 08-08, August 2008.

Sakis Meliopoulos, Jerome Meisel, George Cokkinides and Thomas Overbye, 'Power System Level Impacts of Plug-In Hybrid Vehicles', PSERC Publication 09-12, October 2009.

Papers prepared by PSERC researchers and made available on the PSERC web site in last two years:

(1) A. P. Meliopoulos, G. J. Cokkinides, Floyd Galvan and Bruce Fardanesh, 'Distributed State Estimator ? Advances and Demonstration', Proceedings of the of the 41st Annual Hawaii International Conference on System Sciences, Kona, Hawaii, January 7-10, 2008.

(2) A. P. Sakis Meliopoulos, Vangelis Farantatos, George Cokkinides, Salman Mohagheghi and George Stefopoulos, 'A New Out-of-Step Protection Scheme via GPS Synchronized Data', Proceedings of 16th Power Systems Computation Conference, Glasgow, Scotland, July 14-18, 2008.

(3) George Stefopoulos, George Cokkinides and A. P. Sakis Meliopoulos, 'Quadratic Integration Method for Transient Simulation and Harmonic Analysis', Proceedings of 2008 International Conference on Harmonics and Power Quality, Wollongong, Australia, September 28-October 1, 2008.

(4) George Stefopoulos, George Cokkinides and A. P. Sakis Meliopoulos, 'Optimal Operation of Dynamic VAR Sources for Mitigation of Delayed Voltage Recovery', Proceedings of 2008 Med Power Conference, Thessaloniki, Greece, November 2-5, 2008.

(5) Curtis Roe, Evangelos Farantatos, A. P. Meliopoulos, Jerome Meisel and Thomas Overbye, 'Power System Level Impacts of PHEVs', Proceedings of the of the 42nd Annual Hawaii International Conference on System Sciences, Kona, Hawaii, January 5-8, 2009.

(6) Abhishek Venkatesh, George Cokkinides and A. P. Meliopoulos, '3-D Visualization of Power System Data Using Triangulation and Subdivision Techniques', Proceedings of the of the 42nd Annual Hawaii International Conference on System Sciences, Kona, Hawaii, January 5-8, 2009.

(7) Quang Binh Dam and A. P. Meliopoulos, 'Circuit Breaker Duty Monitoring From the Control Center', Proceedings of the 2009 Power Systems Conference & Exposition, Seattle, Washington, March 15-18, 2009.

Industry/University Seminars given by PSERC researchers (most including web casts available on the PSERC web site):

- (1) Jerome Meisel, PSERC Teleseminar, 'The Case for Plug-In Hybrid Electric Vehicles', December 4, 2-3 pm, 2007.
- (2) Incenting Transmission Reliability and Adequacy Related Investments; Prof Shijie Deng, Georgia Institute of Technology, August 16, 2008.
- (3) PMU-Based Distributed State Estimation with the SuperCalibrator
; A. P. Meliopoulos, Georgia Institute of Technology, June 17, 2008.
- (4) George Stefopoulos, PSERC Teleseminar, 'Voltage Recovery and Optimal Allocation of VAR Support via Quadratic Power System Modeling and Simulation', May 5, 2-3 pm, 2009.
- (5) Sakis Meliopoulos, Jerome Meisel and Thomas Overbye, PSERC Webinar, 'Power System Level Impacts of Plug-In Hybrid Vehicles (PHEV)', December 18, 1-2 pm, 2009.

Training and Development:

PSERC research results were utilized to develop several tools for animation and visualization of power system operations for specific use in the classroom. Specific developments are: (a) animation and visualization of protective relays and used it to enhance the instruction of the short course on power system relaying. (b) analysis and visualization tools for power quality utilized in the course ECE6340, 'Electric Power Quality', (c) visualization and animation of power system spot prices, FTRs and FGRs, and (d) visualization and animation of state estimator performance.

The following short courses have been organized and offered on the Georgia tech campus as follows:

Short Course Title: Power Distribution System Grounding and Transients

September 25-27, 2007

September 23-25, 2008

September 22-24, 2009

Short Course Title: Power System Protection.

October 16-19, 2007

October 20-23, 2008

October 26-29, 2009

Short Course Title: Modern Energy Management Systems.

November 8-10, 2007

November 18-20, 2008

November 16-18, 2009

The faculty and students at Georgia Tech participated in the following PSERC and PSERC related activities during the previous grant period:

Participation in PSERC meetings

- (1) Participated in the PSERC IAB meetings in Wichita, KS, (Dec 2007), presenting project posters and updates.
- (2) Participated in the PSERC IAB meetings in Ames, IA, (May 2008), presenting project posters and updates.
- (3) Participated in the PSERC IAB meetings in College Station, TX, (December 2008), presenting project posters and updates.
- (4) Participated in the PSERC IAB meetings in Ithaca, NY, (May 2009), presenting project posters and updates.

Georgia Tech hosted the PSERC IAB Meeting in December 2-4, 2009 on the Georgia Tech campus.

Participation in Professional Meetings

- (1) Organized, attended and participated in the PSERC sessions at the 2007, 2008, and 2009 Hawaii International Conference on System Sciences.
- (2) Contributed to the IEEE Power Engineering Society 2008 General Meetings
- (3) Participated in multi-university PSERC tele-seminar exchanges (presented several of them - see list in previous section).

Participation in PSERC Workshops

- (1) Participated in PSERC industry/university collaboration meetings on PSERC research, education and management activities: Summer Research Planning Retreat (Sedona, AZ, July/August 2007).
- (2) Participated in PSERC industry/university collaboration meetings on PSERC research, education and management activities: Summer Research Planning Retreat (Lake Tahoe, CA, August 2008).
- (3) Participated in PSERC industry/university collaboration meetings on PSERC research, education and management activities: Summer Research Planning Retreat (Breckenridge, CO, August 2009).

Georgia Tech participated in the IEEE Distinguished Lecturer program. In the last year the following activities occurred:

- (1) A. P. Meliopoulos, 'Technology and the Smart Grid,' IEEE Distinguished Lecture, Salt Lake City IEEE Section, February 27, 2009.
- (2) A. P. Meliopoulos, 'Distributed Generation and microGrids,' IEEE Distinguished Lecture, New Orleans IEEE Section, August 31, 2009
- (3) A. P. Meliopoulos, 'Power System Grounding,' IEEE Distinguished Lecture, Iowa-Illinois IEEE Section, October 30, 2009.

Outreach Activities:

PSERC research results were utilized in continuing education courses offered to practicing engineers. Specifically, PSERC research results were utilized to develop several tools for animation and visualization of power system operations for specific use in the classroom. Specific developments are: (a) animation and visualization of protective relays and used it to enhance the instruction of the short course on power system relaying. (b) analysis and visualization tools for power quality utilized in the course ECE6340, 'Electric Power Quality', (c) visualization and animation of power system spot prices, FTRs and FGRs, and (d) visualization and animation of state estimator performance.

Two conferences were also offered by Georgia Tech:

Conference 1 Title: Georgia Tech Power System Fault and Disturbance Analysis

May 1-2, 2008

April 20-21, 2009

Conference 2 Title: Georgia Tech Protective Relaying Conference

May 3-5, 2008

April 22-24, 2009

In addition, the seventh international conference on power system dynamics was organized by Georgia Tech (Charleston, SC, August 2007).

Journal Publications

A. P. Meliopoulos, G. Cokkinides, M. Asad, "Issues of Reactive Power and Voltage Control Pricing in a Deregulated Environment", Decision Support Systems, p. 303, vol. 30, (2001). Published,

A. G. Bakirtzis, Y. Ha Kim, and A. P. Meliopoulos, "Monte Carlo Simulation for Evaluating Retail Wheeling Effects", Electric Power Systems Research, p. 137, vol. 60, (2002). Published,

A. P. Meliopoulos, "Impact of Grounding System Design on Power Quality", IEEE Power Engineering Review, p. 3, vol. 21, (2001). Published,

A. P. Meliopoulos, G. J. Cokkinides, "A Virtual Environment for Protective Relaying Evaluation and Testing", IEEE Transactions on Power Systems, p. 104, vol. 19, (2004). Published,

A. P. Meliopoulos, G. J. Cokkinides, "Substation Lightning Shielding and Risk Assessment", European Transactions on Electrical Power, p. 407, vol. 13, (2003). Published,

Haibin Sun, Shi-Jie Deng, A. P. Meliopoulos, "Impact of Market Uncertainty on Congestion Revenue Right Valuation", Journal of Energy Engineering, p. , vol. , (). Submitted,

George Stefopoulos, A. P. Sakis Meliopoulos and George Cokkinides, "Probabilistic Power Flow with Non-Conforming Electric Loads", International Journal of Electrical Power & Energy Systems, p. 627, vol. 27, (2005). Published,

A. P. Sakis Meliopoulos and George Stefopoulos, "Characterization of State Estimation Biases", Probability in the Engineering and Informational Sciences, p. 157, vol. 20, (2006). Published,

Haibin Sun, Shi-Jie Deng and A. P. Sakis Meliopoulos, "Impact of Market Uncertainty on Congestion Revenue Right Valuation", Journal of Energy Engineering, p. 139, vol. 131, (2005). Published,

Books or Other One-time Publications

A. P. Meliopoulos, "Power System Modeling, Control and Operation", (). Book, manuscript, distributed to students freely.
Editor(s): manuscript form, about 1000 pages
Bibliography: not published yet

A. P. Meliopoulos and George J. Cokkinides, "Power System Relaying: An Introduction", (2007). Book, Manuscript used for teaching a class on Power System protection
Bibliography: This is a manuscript distributed to students via the internet.

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

Educational visualization and animation tools for power systems continue to be utilized by other universities in their curriculum.

The results of research in one of the five projects has been implemented within the program GEMI and distributed to practitioners.

The results of research from PSERC project S-19 have been utilized in the classroom for the purpose of visualizing and animating the operation of major power system equipment.

Analysis and visualization tools for power quality utilized in the course ECE6340, 'Electric Power Quality'.

Visualization and animation of state estimator performance. This work has been utilized in classes, seminars by Georgia tech researchers and other collaborators. The work in this area resulted in the SuperCalibrator approach, a fully distributed state estimator - see also below.

A new project spawn from the NSF/PSERC work that resulted in the development of the supercalibrator, a fully distributed state estimator. The supercalibrator was implemented on a five substation system, thus fully demonstrating the capabilities. It has been shown that state estimation can be performed as fast as four times per second, a remarkable achievement. An effort has been initiated to commercialize this idea.

A new method has been developed for monitoring the transient stability of a power system. The method is based on monitoring the system via GPS synchronized equipment and extracting the real time dynamic model of the system. This model is used to define a Lyapunov type function of the system which provides the stability properties of the system in real time.

Work by Professor Divan: Another project was involved with the design, fabrication and demonstration of a Distributed Series Reactance module. The project also explored the impact of deploying such modules on the IEEE 39 bus system, and quantifying the benefits in terms of system utilization, improved reliability and cost/benefit analysis. The project was also partially funded by TVA, ABB and Consolidated Edison.

Main Accomplishments ? Phase I:

? Design of 10 kVAR Distributed Series Reactance module suitable for use on 161 kV/1000 Ampere line, including control power supply and microprocessor controller.

- ? Development of model of DSR module for use in system simulation.
- ? Development of homeostatic control technique to control large number of DSR modules based only on local parameters.
- ? Operation of DSR modules in simplified 4 bus system, including quantification of improved system transfer capacity, performance index and contingency behavior.
- ? Fabrication and testing of prototype DSR module in laboratory.
- ? Testing of high voltage and fault current behavior of DSR module in NEETRAC laboratory.
- ? Simulation of IEEE 39 bus system with and without DSR modules, under normal and contingency conditions.
- ? Behavior of system with protection relays and other system level devices.
- ? Cost analysis and market impact of DSR modules in vertically integrated utilities and for ISO regulated power markets.

Several publications resulted from the project. These are listed below. Presentations were also made to over 30 utility groups, ISO's and industry partners. As a result of this project, Phase II of the project has been defined, and is being initiated. This will result in the deployment of at least one pilot full-scale demonstration project to validate performance of the modules. The project is being funded by a consortium of utilities, industry and institutional partners.

Selected Publications:

1. D. Divan and H. Johal, 'Distributed FACTS ? A New Concept for Realizing Grid Power Flow Control', IEEE Transactions on Power Electronics, V22, n6, Nov 2007, pp 2253-2260
2. H. Johal and D. Divan, 'Current Limiting Conductors ? A Distributed Approach for Increasing T&D System Capacity and Enhancing Reliability', Proc of IEEE Transmission and Distribution Conference, May 21-24, 2006, pp1127-1133.
3. D. Divan, H. Johal, M. Ingram, S. Ory, P. Springer and F. Lambert, 'Designing a Distributed Series Impedance and Impact on System Performance', IEEE T&D Conference & Exposition, Venezuela, Aug 15-18, 2006.
4. H. Johal and D. Divan, 'Calculating the Economic Impact of Congestion Mitigation Using DSI', PES Power System Conf., Oct 2006.

Another project was also completed on Optimal Allocation of reactive power sources. The Georgia Tech work in this project is summarized as follows: In recent years, new attention has been given to use of volt-amperes reactive (VAR) resources to support power system operation. In part, this attention has been motivated by the voltage problems experienced in the time before the U.S ? Canada blackout of 2003. An additional motivation arises from the evolution toward decentralized decision-making in power system markets. Of interest from a market design perspective is how to provide economic incentives for investment in and operational commitment of VAR resources. The engineering questions are how much VAR resources are needed, where should they be located, and what should the allocation be between static VARs that provide constant VARs and dynamic VARs that can be controlled in real-time. The engineering questions cannot be addressed separately, thus suggesting the need for an integrated assessment of optimal selection and placement of static and dynamic VAR resources in a power system.

The project's objectives were

- (a) to develop realistic models that accurately model system dynamics and capture voltage recovery phenomena,
- (b) to develop criteria for selection of the optimal mix and placement of static and dynamic VAR resources in large power systems based on modeling results using the tools developed part (a),
- (c) to create a unified optimization model for minimizing the deployment of static and dynamic VAR resources while meeting the criteria.

Examples of the criteria are:

- ? speed of voltage recovery
- ? avoidance of unnecessary relay operations
- ? avoidance of motor stalling and
- ? avoidance of voltage collapse.

The project was accomplished in five integrated steps described in the five volumes of this report. A test system provide by Entergy was used as a common platform to test the tools.

Work at Georgia Tech focused on developing an integrated optimization method capable of selecting the optimal mix of static and dynamic VAR resources for achieving fast voltage recovery under adverse system conditions.. The method models load dynamics while selecting critical contingencies as an integral part of the optimization procedure. The new methodology more accurately represents the dynamic behavior of loads and their impact on voltage recovery phenomena than previous work. The optimization methodology is based on successive dynamic programming.

Dynamic load models of induction motor loads were developed for various designs of induction motors. The dynamic load models were incorporated into a three-phase breaker-oriented model that accurately predicts the rate of voltage recovery for any specific contingency. In

addition, specific design criteria were developed by imposing the requirements that voltage recovery phenomena will not cause load disruption using modern protective relaying practices for motors and for general electric loads.

Another project initiated and completed in 2009 was a comprehensive study of the impacts of Pluggable Electric Vehicles on the electric power system. The findings of this research project are significant. The executive summary of the report is provided below:

Plug-in hybrid electric vehicles (PHEVs) offer an attractive solution to a growing dependence on imported foreign oil with potential benefits and issues to the electric power industry. The impact of PHEVs on the power grid is investigated. The methodology for this investigation is based on three procedures: (a) typical utilization of PHEVs that capture human habits and terrain on which cars are driven for the purpose of evaluating the energy consumption and split between electric and gas, (b) simulation of the electric infrastructure (distribution systems) and the loading patterns that results from PHEV deployment and the effects on the equipment and in particular the expected life of transformers, (c) impact of PHEV deployment on energy resource utilization in the power grid, and (d) impact of PHEV deployment on the operations and the security of the power grid. Proper models are utilized that capture all the interactions of the complex system that comprises the power grid, the distribution system and the PHEVs. The report consists of two volumes.

Volume I

First, four hybrid-electric vehicle (HEV) powertrain architectures are described. These architectures are commonly termed series, parallel, single-mode split-power, and dual-mode split-power. Conclusions suggest that either a parallel architecture or the GM 2-MT is the best choice. Second, calculations of the electric energy consumed by PHEVs under typical scenarios are performed using both an analytic approach and computer simulation. The analytic approach utilizes estimates for the efficiency of PHEV components. Simulations are run using the Powertrain System Analysis Toolkit (PSAT) v.6.2 program developed by DOE's Argonne National Lab. A comparison of results from both methods is provided. Sample results show that if 10% of the entire US vehicle fleet is replaced by PHEVs, and vehicles travel an average of 12,000 miles per year the added electric load due to PHEVs would be 3.3% of the installed 950 GW generation capacity in the US; a small increase in the added electric demand.

Third, the vehicle emissions including nitrogen oxides (NO_x) and the greenhouse gas carbon dioxide (CO₂) are described. It is found that if a PHEV control algorithm can operate a vehicle such that, on average, 62% of the energy supplied to the powertrain comes from the battery, then, with a standard spark-ignited IC engine the regulated emissions meet the latest standard (Tier2-Bin5).

Fourth, two infrastructure implications are described (1) the impact of typical household infrastructure on PHEV recharging, and (2) the vehicle to grid interface. The household circuit capacity (120V / 20A) is capable of recharging the required battery capacity needed to drive 40 miles in charge sustaining mode (70% of the required energy per mile is derived from onboard electric energy over the entire 40 miles) in 6 hours; further, the size of this battery pack is feasible in terms of weight and volume using battery technology available today. Additionally, four levels of vehicle to grid interface are defined, increasing in functionality and complexity.

Fifth, the impact of PHEV charging on distribution transformers is described. This impact is quantified through a loss-of-life (LOL) calculation. The LOL calculation is based on distribution transformer hot-spot temperature. This temperature is estimated using an electro-thermal distribution transformer model and is a function of the transformer winding currents. These currents are computed using a center-tapped single phase transformer model. Results of this research show that a measurable LOL can occur due to PHEV charging. Areas of high ambient temperature show larger LOL over areas of low ambient temperature and highly loaded transformers show higher LOL over transformers with excess capacity. The LOL of transformers is very sensitive on whether the combined residential load and PHEV is near or exceeds the rating of the transformer.

Sixth, the impact of PHEV charging in terms of (a) primary fuel utilization shifts, (b) pollution shifts, and (c) total fuel cost for yearly vehicle operation is described. Vehicle and power system simulations are used. The vehicle fleet simulations compute: the amount of added electric load demand to charge the PHEV fleet, amount of gasoline used by both IC vehicles and PHEVs, and the amount of environmental air pollution (EAP) generated by both IC vehicles and PHEVs. The power system simulations simulate how much fuel usage and subsequent EAP are generated by a specific power system. Results from this research indicate that PHEVs offer cleaner transportation (depending on the generation mix used to charge the vehicles) with decreased gasoline utilization at a lower cost to consumers. Specifically, three different power system generating mixes are simulated with varying levels of PHEV penetration (defined as the percentage of the light duty vehicle fleet in the power system area replaced by PHEVs). Two of the three power system generating mixes simulated show a decrease in total system NO_x EAP and all three showed a decrease in CO₂ EAP.

Seventh, the benefit of using a heavy penetration of PHEVs to act as support to the grid during contingencies and also the costs incurred with security constrained control is described. PHEVs provide a completely new way to store massive amounts of energy from the power grid. It is found that (1) PHEVs have a great potential to save grid operating costs and reduce critical contingencies and (2) PHEVs have a significant effect on unenforceable security constrained optimal power flow (SCOPF) contingencies and maximum line overloads.

Eighth, a comparison of vehicles powered from hydrogen fuel to PHEVs is described. The significant hurdles involving production, storage, distribution, and use of hydrogen are outlined. Conclusions drawn are that hydrogen use with a fuel cell or even injected directly into an IC engine is not a near-term prospect for reducing the use of petroleum-based fuels.

Ninth, a comparison of battery-electric ZEVs to PHEVs is described. The advantages of ZEVs over PHEVs are: a simpler less expensive powertrain, less maintenance with only an electric drivetrain, zero tailpipe emissions, electric energy that could be produced by renewable sources. The disadvantages of ZEVs are large battery packs to get a reasonable range, and very long recharging times. The advantages of

PHEVs over ZEVs are: that an appreciable amount of the driving energy comes from the electrical grid thus reducing the use of petroleum-based fuels and tailpipe emissions compared to conventional vehicles, range limitations are not limited as charge-sustaining operation is available, smaller battery packs can be used. The disadvantages of PHEVs are (a) more complex and costly powertrain, and (b) use of a petroleum-based fuel with some tailpipe emissions when driven longer distances.

Volume II

Two studies are presented quantifying the impact of plug-in hybrid vehicles (PHEVs) on the power grid. The first study quantifies this impact in terms of (a) primary fuel utilization shifts, (b) pollution shifts, and (c) total cost for consumers. The second study quantifies this impact on distribution transformers.

In the first study vehicle fleet and power system simulations are used. The vehicle fleet simulations compute the amount of added electric load demand to charge the PHEV fleet, the amount of gasoline used by both internal combustion (IC) vehicles and PHEVs, and the amount of environmental air pollution (EAP) generated by both IC vehicles and PHEVs. The power system simulations simulate how much fuel usage and subsequent EAP are generated by a specific power system.

In the second study the impact on distribution transformers is quantified through a loss-of-life (LOL) calculation that is based on the transformers hot-spot temperature. This temperature is estimated using an electro-thermal transformer model and is a function of the transformer currents. These currents are computed using a center-tapped single phase transformer model.

The results from this research indicate that PHEVs offer cleaner transportation (depending on the generation mix used to charge the vehicles) with decreased gasoline utilization at a lower operating cost to consumers. The impact to the utility infrastructure is favorable from the security point of view and additional revenues to the utility and unfavorable to the expected life of distribution transformers. The last issue can be addressed in a variety of ways, including monitoring of distribution transformers and replacing them with larger units if the loading from PHEVs results in substantial loss of life.

In general the impact of PHEVs on the power grid is favorable. The unfavorable effect on the expected life of distribution transformers is not much different than the effect of increasing loads in a household or commercial building. Power companies deal with this problem routinely. It is suggested as a follow up to this research project to develop transformer life expectancy monitor. The technology exists today to develop a smart monitoring device that will track the loading and thermal history of distribution transformers and compute the loss of life in real time. This technology can provide alarms that quantify the impact of increased loading on the transformer life which can be used by utilities to prioritize the replacement of transformers. The increase of total load on the power grid, assuming expected gradual penetration of PHEVs in the market, is at a level comparable to what utilities have experience under normal economic conditions, i.e. few percentage points annually. Therefore gradual penetration of PHEVs can be easily handled by typical power system planning scenarios.

Contributions to Other Disciplines:

There was no significant activity in this area.

Contributions to Human Resource Development:

A number of tutorials were provided. The list has been provided in the previous section.

Contributions to Resources for Research and Education:

PSERC research results were utilized to develop several tools for animation and visualization of power system operations for specific use in the classroom. Specific developments are: (a) animation and visualization of protective relays and used it to enhance the instruction of the short course on power system relaying. (b) analysis and visualization tools for power quality utilized in the course ECE6340, 'Electric Power Quality', (c) visualization and animation of power system spot prices, FTRs and FGRs, and (d) visualization and animation of state estimator performance.

The tools have been employed in the development of class notes for three classes: (a) electric power quality, (b) Power System protection and (c) Control and operation of power systems.

Contributions Beyond Science and Engineering:

Nothing yet to report

Conference Proceedings

Categories for which nothing is reported:

Any Web/Internet Site

Any Product
Any Conference



Power Systems Engineering Research Center

Final Report to the NSF Industry/University Cooperative Research Center Program

September 2009

PSERC has been an IUCRC since 1996. It has made noteworthy accomplishments in research, education, public service, and organization building as a collaborative research center. This report provides an overview of those accomplishments and its on-going work. This graduated Center that is still actively serving the electric power industry.

1. *Mission*

The Power Systems Engineering Research Center (PSERC) is drawing on university capabilities to creatively address challenges facing the electric power industry. Its core purpose is ***Empowering Minds to Engineer the Future Electric Energy System***. Under the banner of PSERC, multiple U.S. universities are:

- Pursuing, discovering and transferring knowledge
- Producing highly qualified and trained engineers
- Collaborating in all we do.

PSERC is working toward:

- An efficient, secure, resilient, adaptable, and economic electric power infrastructure serving society
- A new generation of educated technical professionals in electric power
- Knowledgeable decision-makers on critical energy policy issues
- Sustained, quality university programs in electric power engineering.

2. *Collaborating Universities and Site Directors*

Arizona State (Jerry Heydt)	Berkeley (Shmuel Oren)	Carnegie Mellon (Marija Ilic)
Colorado School of Mines (P.K. Sen)	Cornell (Tim Mount)	Georgia Tech (Sakis Meliopoulos)
Howard University (James Momoh)	Illinois (Peter Sauer)	Iowa State (Jim McCalley)
Texas A&M (Mladen Kezunovic)	Washington State (Anjan Bose)	Wisconsin (Chris DeMarco)
	Wichita State University (Ward Jewell)	

3. 2009 Industry Members

ABB	American Electric Power
American Transmission Company	AREVA T&D
Arizona Public Service	Bonneville Power Administration
British Columbia Transmission Co.	California ISO
CenterPoint Energy	Duke Energy
Entergy	EPRI
Exelon	FirstEnergy
GE Energy	Institut de recherche d'Hydro-Québec (IREQ)
ISO New England	ITC Holdings
MidAmerican Energy	Midwest Independent Transmission System
	Operator (MISO)
National Rural Electric Coop. Assn.	New York ISO
New York Power Authority	Pacific Gas and Electric
PJM Interconnection	PowerWorld Corp.
RTE - France	Quanta Technology
Salt River Project	Southern California Edison
Southern Company	Tennessee Valley Authority
Tri-State Generation and Transmission	U.S. Department of Energy
Cooperative	
Western Area Power Administration	

4. 2009 Personnel

Director: Vijay Vittal, Arizona State University (lead university)

Founding Director: Bob Thomas, Cornell University (previous lead university)

IAB Officers

- Floyd Galvan, Entergy, Chair
- Lisa Beard, TVA, Vice-Chair

Executive Committee: Site Directors (previous section)

Stem Committee Leadership

- Systems Stem
 - Jim McCalley, Iowa State University, Chair
 - Navin Bhatt, American Electric Power Co., Vice-Chair
- Transmission and Distribution Technologies Stem
 - Gerald Heydt, Arizona State University, Chair
 - Simon Chiang, Pacific Gas & Electric, Vice-Chair
- Markets Stem
 - Tim Mount, Cornell University, Chair
 - Jim Price, California Independent System Operator, Vice-Chair

Executive Director: Dennis Ray

PSERC Facilitator and Evaluator: Frank Wayno, Cornell University

Adjunct Researchers

- Ali Abur, Northeastern University
- Ross Baldick, University of Texas – Austin
- Judith Cardell, Smith College
- Yihsu Chen Univ. of California, Merced (junior adjunct researcher as assistant professor)

Administrative Assistant: Theresa Herr, Arizona State University

Financial Specialist: Laura DiPaolo, Arizona State University

5. Research Areas

PSERC's research program is divided into three research stems: power markets, power systems, and transmission and distribution technologies. Each year, PSERC funded 18-20 research projects. All publications (i.e., final reports, papers, and presentations) were posted to the PSERC website: www.pserc.org. Monthly hits on the website are on the order of 11,000 worldwide.

Power Markets Research Stem

Our primary research goal in this stem is to focus on short to medium term issues concerning the interaction between the technical and economic aspects of the restructured industry given the current technological landscape. In particular this stem focuses on a new market based paradigm that will replace the traditional functional timeline leading from years to cycles prior to real time, which includes long term demand forecasting, capacity planning and expansion, maintenance, short term forecasting, scheduling, dispatch, and real time control. The research under this stem emphasizes the design and analysis of market institutions, mechanisms and computational tools that will facilitate coordination, efficient investment, operational efficiency, and system reliability, while recognizing the economic and technical realities of the electric power industry.

Current Projects (projects in red are new projects in 2009; projects in green began in 2008; remaining projects are about to be completed)

- **Coupling Wind Generation with Controllable Load and Storage: A Time-Series Application of the SuperOPF (M-22)**
- **PHEVs as Dynamically Configurable Dispersed Energy Storage (T-40)**
- **Technical and Economic Implications of Greenhouse Gas Regulation in a Transmission Constrained Restructured Electricity Market (M-21)**
- Optimal Electricity Market Structures to Reduce Seams and Enhance Investment (M-9)
- Economic Impact Assessment of Transmission Enhancement Projects (M-14)
- Integrated Financial and Operational Risk Management in Restructured Electricity Markets (M-17)
- Improved Investment and Market Performance Resulting from Proper Integrated System Planning (M-18)
- Facilitating Environmental Initiatives While Maintaining Efficient Markets and Electric System Reliability (M-20)

Completed Projects (titles are linked to the final reports on the PSERC website)

- [Integrating Electric System Planning with Efficient Markets to Provide Adequate Investment \(2009, M-16\)](#)
- [Evaluation of Alternative Market Structure and Compensation Schemes for Incenting Transmission Reliability and Adequacy Related Investments \(2008, M-11\)](#)
- [Reliability, Electric Power, and Public Vs. Private Goods: A New Look at the Role of Markets \(2008, M-12\)](#)
- [Agent Modeling for Integrated Power System, Power and Fuel Market Simulation \(2008, M-13\)](#)
- [Tools for Assessment of Bidding into Electricity Auctions \(2008, M-15\)](#)
- [Modeling Market Signals for Transmission Adequacy Issues: Valuation of Transmission Facilities and Load Participation Contracts in Restructured Electric Power Systems \(2007, M-6\)](#)
- [Reliability Assessment Incorporating Operational Considerations and Economic Aspects for Large Interconnected Grids \(2007, M-8\)](#)
- [Uncertain Power Flows and Transmission Expansion Planning \(2007, M-10\)](#)

- [Electric Power Industry and Climate Change – Discussion Paper](#) (2007, M-19)
- [Market Redesign: Incorporating the Lessons Learned from Actual Experiences for Enhancing Market Design](#) (2005, M-4)
- [Software Agents for Market Design and Analysis](#) (2005, M-5)
- [Structuring Electricity Markets for Demand Responsiveness: Experiments on Efficiency and Operational Consequences](#) (2004, M-7)
- [Market Interactions and Market Power](#) (2003, M-3)
- [Market Mechanisms for Competitive Electricity](#) (2002, M-2)
- [Reactive Power Support Services in Electricity Markets](#) (2000, M-1)

Power Systems Research Stem

The work of the Systems Stem targets modeling, evaluation, decision, and control in power system operation, maintenance, and planning of generation, transmission, and distribution subsystems for more reliable & economic grid performance. The electric power industry is comprised of a large number of diverse organizations that together operate, maintain, and plan the infrastructure used to generate, transport, and distribute electric energy. These activities require continuous and intimate coordination among the various organizations while simultaneously satisfying information sharing needs and limitations associated with the economic systems (e.g., markets) used to facilitate energy trade. Regional coordinators for operations, reliability, and markets have needs driven by their functional complexity and by their large size. The complexity of systems problems increases with system size, new technology options, operational requirements, and environmental constraints. Advances in information technology, communications and mathematics demand that systems problems be reexamined and new approaches formulated. The Systems Stem supports development of new frameworks, approaches, advanced algorithms, and computational methods that will effectively cope with the complexity and large scale issues of the future electric power industry.

Current Projects (projects in red are new projects in 2009; projects in green began in 2008; remaining projects are about to be completed)

- [Toward a Systematic Framework for Deploying Synchrophasors and their Utilization for Improving Performance of Future Electric Energy Systems \(S-37\)](#)
- [Next Generation On-Line Dynamic Security Assessment \(S-38\)](#)
- [Special Protection Schemes: Limitations, Risks, and Management \(S-35\)](#)
- [Using PMU Data to Increase Situational Awareness \(S-36\)](#)
- [Techniques for the Evaluation of Parametric Variation in Time-Step Simulations \(S-17\)](#)
- [Development and Evaluation of System Restoration Strategies from a Blackout \(S-30\)](#)
- [Real-Time Security Assessment of Angle Stability and Voltage Stability Using Synchrophasors \(S-31\)](#)
- [Fast Simulation, Monitoring, and Mitigation of Cascading Failures \(S-32\)](#)
- [Implementation Issues for Hierarchical, Distributed State Estimators \(S-33\)](#)
- [Impact of Increased DFIG Wind Penetration on Power System Reliability and Consequent Market Adjustments \(S-34\)](#)

Completed Systems Stem Projects (titles are linked to the final reports on the PSERC website)

- [Optimal Allocation of Static and Dynamic VAR Resources](#) (2008, S-24)
- [Effective Power System Control Center Visualization](#) (2008, S-25)
- [Risk of Cascading Outages](#) (2008, S-26)
- [A Tool for On-Line Stability Determination and Control for Coordinated Operating between Regional Entities Using PMUs](#) (2008, S-27)

- [A Tool for On Line Stability Determination and Control for Coordinated Operating between Regional Entities Using PMUs: Expanded Testing](#) (2008, S-27G)
- [Preventing Voltage Collapse with Protection Systems that Incorporate Optimal Reactive Power Control](#) (2008, S-28)
- [Detection, Prevention and Mitigation of Cascading Events – Prototype Implementations](#) (2008, S-29)
- [Security Enhancement through Direct Non-Disruptive Load Control: Part I, Part II](#) (2006, S-16)
- [Enhanced State Estimators](#) (2006, S-22)
- [New System Control Methodologies](#) (2005, S-6)
- [Comprehensive Power System Reliability Assessment](#) (2005, S-13)
- [Extended State Estimation for Synchronous Generator Parameters](#) (2005, S-15)
- [Visualization of Power Systems and Components](#) (2005, S-18)
- [Detection, Prevention and Mitigation of Cascading Events: Part I, Part II, Part III](#) (2005, S-19)
- [New Implications of Power System Fault Current Limits](#) (2005, S-20)
- [On-Line Transient Stability Assessment](#) (2005, S-21)
- [Optimal Placement of Phasor Measurement Units for State Estimation](#) (2005, S-23G)
- [Integrated Security Analysis](#) (2003, S-7)
- [Risk-Based Maintenance Allocation and Scheduling for Bulk Transmission System Equipment](#) (2003, S-14)
- [Identification and Tracking of Parameters for a Large Synchronous Generator](#) (2002, S-1)
- [Voltage Collapse Margin Monitor](#) (2002, S-2)
- [Coordination of Line Transfer Capability Ratings](#) (2002, S-8)
- [Power System State Estimation and Optimal Measurement Placement for Distributed Multi-Utility Operation](#) (2002, S-10)
- [Steady State Voltage Security Margin Assessment](#) (2002, S-11)
- [Robust Control of Large-Scale Power Systems](#) (2002, S-12)
- [Impact of Protection Systems on Reliability](#) (2001, S-4)
- [Automated Operating Procedures for Transfer Limits](#) (2001, S-5)
- [Avoiding and Suppressing Oscillations](#) (2000, S-3)

Power Transmission and Distribution Technologies Research Stem

The transmission and distribution (T&D) technologies research stem addresses issues related to delivering electrical energy efficiently, safely, securely, and reliably. Improvements in the T&D infrastructure are achieved through innovations in software, hardware, materials, sensors, communications and operating strategies. Therefore, a central goal of this research stem is the improvement of transmission and distribution systems through the application of technological advances, particularly in the areas of (1) Data Integration and Enhanced Functions, (2) T&D Infrastructure Enhancements, (3) Distribution and Transmission Automation, (4) New Devices and Related Control Concepts, and (5) New Paradigms and Designs.

Current Projects (projects in red are new projects in 2009; projects in green began in 2008; remaining projects are about to be completed)

- [Communication Requirements and Integration Options for Smart Grid Deployment](#) (T-39)
- [PHEVs as Dynamically Configurable Dispersed Energy Storage](#) (T-40)
- [Implications of the Smart Grid Initiative on Distribution Engineering](#) (T-41)
- [The 21st Century Substation Design](#) (T-37)
- [Substation of the Future: A Feasibility Study](#) (T-38)
- [Overloading and Optimum Operation of Liquid Filled Power Transformers](#) (T-25)
- [Power System Level Impacts of Plug-In Hybrid Cars](#) (T-34)

- Comparative Characterization of Parallel Distribution Sensors Under Field Conditions (T-35)
- Integration of Asset and Outage Management Tasks for Distribution Applications (T-36)

Completed T&D Projects (titles are linked to the final reports on the PSERC website)

- [Satellite Imagery for the Identification of Interference with Overhead Power Lines](#) (2008, T-28)
- [Digital Protection System Using Optical Instrument Transformers and Digital Relays Interconnected by an IEC 61850-9.2 Digital Process Bus](#) (2008, T-29)
- [Transient Testing of Protective Relays: Study of Benefits and Methodology](#) (2008, T-30)
- [Massively Deployed Sensors](#) (2008, T-31)
- [Integration of Substation IED Information into EMS Functionality](#) (2008, T-32)
- [Characterization of Composite Cores for High Temperature-Low Sag Conductors](#) (2009, T-33, [for members only](#))
- [Reliability-Based Vegetation Management Through Intelligent System Monitoring](#) (2007, T-27)
- [Automated Integration of Condition Monitoring with an Optimized Maintenance Scheduler for Circuit Breakers and Power Transformers](#) (2006, T-19)
- [Novel Approach for Prioritizing Maintenance of Underground Cables](#) (2006, T-23)
- [Risk-Based Maintenance Resource Allocation for Distribution System Reliability Enhancement](#) (2006, T-24)
- [Prediction of Flashover Voltage of Insulators Using Low Voltage Surface Resistance Measurement](#) (2006, T-26G)
- [Distribution System Electromagnetic Modeling and Design for Enhanced Power Quality](#) (2005, T-12)
- [Voltage Sag Effect on Loads in Electric Power Systems](#) (2005, T-16)
- [Enhanced Reliability of Power System Operation Using Advanced Algorithms and IEDs for On-Line Monitoring: \[Part I\]\(#\), \[Part II\]\(#\)](#) (2005, T-17)
- [Control and Design of Microgrid Components](#) (2006, T-18)
- [Performance Assessment of Advanced Digital Measurement and Protection Systems: \[Part I\]\(#\), \[Part II\]\(#\)](#) (2006, T-22)
- [Intelligent Substation](#) (2004, T-5)
- [Evaluation of Critical Components of Non-Ceramic Insulators In-Service: Role of Seals and Interfaces](#) (2004, T-14)
- [Smart Sensor Development for Power Transmission and Distribution](#) (2004, T-20)
- [Distributed Electric Energy Storage and Generation](#) (2004, T-21)
- [Corona Discharge Caused Deterioration of All Dielectric Self-Supporting Fiber-Optic Cables](#) (2002, T-1)
- [Differential GPS Measurement of Overhead Conductor Sag and Software Implementation](#) (2002, T-2)
- [Condition Monitoring and Maintenance Strategies for In-Service Non-ceramic Insulators, Underground Cables and Transformers](#) (2002, T-6)
- [Investigation of Fuel Cell Operation and Interaction within the Surrounding Network](#) (2002, T-8)
- [Enhanced State Estimation via Advanced Substation Monitoring](#) (2002, T-9)
- [Accurate Fault Location in Transmission and Distribution Networks Using Modeling, Simulation and Limited Field-Recorded Data](#) (2002, T-10)
- [Power System Monitoring Using Wireless Substation and System-Wide Communications: \[Part I\]\(#\), \[Part II\]\(#\)](#) (2002, T-11)
- [Personnel Grounding and Safety Issues / Solutions Related to Servicing Telecommunications Equipment Connected to Fiber Optic Cables in Optical Ground Wire \(OPGW\)](#) (2002, T-13)
- [On-Line Peak Loading of Substation Distribution Transformers Through Accurate Temperature Prediction](#) (2001, T-3)

- [Electrical Transmission Line Insulator Flashover Predictor](#) (2001, T-4)
- [Redesign and New Interpretation of Power Acceptability Curves for Three Phase Loads](#) (2001, T-7)

6. Leveraged Research Projects

Industrial members' support is leveraged into other research initiatives, such as the Consortium for Electric Reliability Technology Solutions (CERTS), formed in 1998 to research, develop and commercialize new methods, tools and technologies to protect and enhance the reliability of the U.S. electric power system under the emerging competitive electricity market structure. CERTS is conducting research for the U.S. Department of Energy's Transmission Reliability Program and for the California Energy Commission's Public Interest Energy Research program. PSERC faculty are working with researchers at Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Sandia National Laboratories and Southern California Edison.

Also established a cooperative research arrangement with Concurrent Technologies Corp. for three projects by PSERC schools funded through D.O.E. in 2006/7.

7. Education, and Power and Energy Engineering Workforce Development

Accomplishments in advancing power engineering education and get students into the workplace:

- Disseminated PSERC student profiles and resumes for industry review and action
- Estimated production of bachelor's degrees in power engineering: 300-400 per year
- Estimated production of graduate degrees in power engineering: 300
- Approximate number of graduate students supported by PSERC funding: 60 per year
- Placing engineering students with PSERC industry members: 70 per year (est.)
- Advanced use of distance learning to achieve power engineering education
- Co-sponsor of NSF Workshop on the Future of the Power Engineering Workforce (November 2007)

Efforts to broadcast engineering workforce concerns and to form solutions:

- Worked with IEEE Power and Energy Society to create an on-line career service for the US and Canada (<http://www.ieee-pes/workforce/pes-careers/>), to start the Power & Energy Engineering Collaborative (<http://www.ieee-pes.org/workforce/workforce-collaborative/>), and to produce the report [Preparing the U.S. Foundation for Future Electric Energy Systems: A Strong Power and Energy Engineering Workforce](#).
- Worked with IEEE-USA to create and communicate a position statement on the use of \$100M in ARRA funds for worker training

8. Awards, Collaboration, Tech Transfer, and Public Service

A PSERC professor, Tom Overbye, University of Illinois-Urbana/Champaign, received the first Schwarzkopf Award.

Convened executive forums for senior managers from industry on timely topics. Academics also attended to offer perspectives. Topics included Smart Grid deployment, energy planning in a

competitive market environment, transmission infrastructure investment barriers, and issues facing independent system operators and regional transmission organizations.

Intellectual Property

- One small business formed based on PSERC research in visualization
- Three patent applications
- One patent awarded for microgrid controls

Communicating research perspectives and project results to PSERC members and to the broader engineering community

- Sponsor about nine public webinars on research and current industry topics each year, participated in by 150-250 engineers in industry and government, and faculty and students at universities. Publicly advertised via engineering listservs, PSERC listservs, and website notices
- Sponsor project webinars on each research project report to communicate research results to industry sponsors. Make archive of project webinars public available after the live webinar.
- Provided professional engineering education PDH certification to about 50 practicing engineers for each webinar

Provide information services

- Broadcast research news on power and energy engineering topics using PSERC listservs and the PSERC website
- Put publications and archived presentations on the PSERC website, www.pserc.org.

Selected activities in public service

- Participated on DOE Post Outage Study Team (POST) in 1999 to provide advice on how to avoid distribution failures
- Participated in DOE National Transmission Grid Study in 2002
- Participated in analyses of the 2003 Northeast Black
- Consulted with, provide training and presentations for state and federal officials
- Service on North American Electric Reliability Corp. Planning Committee Task Force: Reliability Impacts of Climate Change Initiatives
- Published white paper on [The Electric Power Industry and Climate Change: Power Systems Research Possibilities](#) (2007). Disseminating information through presentations.
- Sponsored for public executive forums for senior managers on critical industry issues such as transmission investment strategies, planning in a market environment, and Smart Grid deployment

9. Other Activities and Industrial Collaboration

Conduct PSERC Meetings

- Executive Committee Retreat with industry attendees in February
- Two IAB Meeting per year, one in May and the other in December
- Summer Planning Workshop in July or August to produce annual research solicitation

Collaborate on projects including meetings at PSERC events, conference calls and emails

Convene research stem meetings and conference calls attended by industry and universities



Cornell • Arizona State • Berkeley • Carnegie Mellon • Colorado School of Mines
Georgia Tech • Illinois • Iowa State • Texas A&M • Washington State • Wisconsin

Comprehensive Power System Reliability Assessment

Interim Project Report

Power Systems Engineering Research Center

A National Science Foundation
Industry/University Cooperative Research Center
since 1996

Comprehensive Power System Reliability Assessment

Interim Report

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PSERC Publication 03-xx

December 2003

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Additional Copies of the Report

Copies of this report can be obtained from the Power Systems Engineering Research Center's website, www.pserc.wisc.edu. The PSERC publication number is XX-XX. For additional information contact:

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1 Introduction

Advances in composite power system reliability assessment will be discussed. A framework for comprehensive reliability assessment has been developed based on Markov models of system components and identification methods of events that contribute to unreliability. Specifically, an improved wind-chime approach is discussed coupled with an improved power system model. The model is based on the single phase quadratic modeling approach that provides superior performance in two aspects: (a) faster convergence, (b) ability to model complex load characteristics, and classes of loads such as interruptible load, critical load, etc.. The same model has been extended for identifying events that contribute to the unreliability of the system. The method is integrated in the wind-chime scheme for the quick identification of critical events and effects analysis of the critical events. Since the methods are based on the Markov state space approach, probability, frequency and duration indices are computed, such as: (a) probability of customer interruption, (b) frequency of customer interruption and (c) duration of customer interruption. The advanced load modeling capability enables: (a) a realistic evaluation of industry practices such as load management programs on system reliability, and (b) a realistic evaluation of load characteristic on voltage problems and their impact on reliability. Examples illustrating the capabilities of the approach will be provided.

1.1 Project Description

The scope of this project is to advance the state of the art in reliability assessment and reliability optimization of electric power systems. These techniques will enable probabilistic risk assessment. This issue has become of the utmost importance as deregulation and competition is invading the power industry. The specific objectives of the project are to provide an integrated approach to reliability assessment addressing the issues of component reliability as well as system reliability. A useful feature is the proposed sensitivity analysis that identifies the components that limit system reliability. Byproducts of the proposed research will be a probabilistic methodology for available transfer capability. The proposed reliability analysis methods provide reliability indices at the customer site. Since the proposed methods are based on the Markov state space approach, probability, frequency and duration indices will be computed. Examples are: (a) probability of customer interruption, (b) frequency of customer interruption and (c) duration of customer interruption. Two approaches for the overall power system reliability have been considered: (a) the enumerative approach and (b) Monte Carlo simulation. We have made significant progress in developing an efficient enumerative approach. Specifically, an operating state of an electric power system (a contingency) is classified as "success" or "failure" via an effects analysis to determine whether the system will operate under normal conditions. Each "failure" state is further analyzed to determine how many customers will be affected, what are the limiting design parameters, etc. The reliability of the system is determined from the frequency and duration of the transitions from "success" operating states to "failure" operating states. The proposed

method is based on the efficient identification of boundary transitions, i.e. transitions from a successful operating state to a failure operating state and vice versa with a series of ranking/evaluation procedures. The success/failure of an operating system state will be determined with an improved contingency analysis method that takes into consideration the slow dynamics of the system, for example induction motor load retardation during a fault and subsequent acceleration after fault clearing. We have focused on the development of improved methodologies for these basic problems. The progress is reported here.

Project Progress Report

In reliability analysis, the majority of the computational effort is spent in the analysis of various system contingencies. The contingencies are selected on the basis of their effects on the reliability of the system. The selected contingencies are simulated to determine the effects of the contingency on system reliability, i.e. loss of load, abnormal conditions, possibility of cascading outages, etc. This simulation is performed with specialized power flow analysis methods. It is apparent that the efficiency of the power flow models plays a critical role in the efficiency of reliability analysis. In the first year of this project, the effort was focused in the development of efficient methods for the solution of these two basic problems. We report here a new approach that has led to the development of new and efficient method for these two problems. Both problems have been solved with a new formulation of the power system model. Specifically, the power flow model is expressed in terms of current balance equations at each bus. Control actions and other constraints that lead to nonlinear models are quadratized, i.e. with the introduction of additional variables, the resulting equations are of at most second order. The quadratized equations are solved via Newton's method. The new approach has been applied to the simulation of contingencies and the selection of contingencies. These two problems are presented here with some performance data.

1.2 Main Accomplishments

The main accomplishments of this project are:

1. Formulation of a comprehensive reliability assessment methodology.
2. An improved contingency selection.

1.3 Background on Reliability Assessment

Reliability assessment methods have appeared many decades ago. In the seventies the first comprehensive mathematical models were introduced, first for generation reliability and then for transmission reliability.

1.4 Summary Guide to this Report

Section 2 provides xxx.

Section 3 provides xxx.

1.5 Acknowledgements

The work described in this report was sponsored in part by the Power Systems Engineering Research Center (PSERC).

2 Reliability Assessment ñ Background Information

Considering a large-scale power system, the number of system states is enormous. As an instance, for a system with n components and each component with two states (up or down), there are totally 2^n states. When $n=2000$, the number of states is 2^{2000} , which is more than 10^{600} .

If all the possible states are analyzed one by one to identify the contingencies that contribute to the system unreliability, it requires too much computational effort and is not practical for a real large-scale system. As a result, some efforts have been dedicated to the reduction of state space, selection and evaluation of contingencies.

2.1 Truncation of the state space[1]

In this method, state space is reduced by considering the probabilities of the system states, i.e., states that are not likely to occur are omitted. Whether a state represents a system failure that leads to a significant service interruption or that is only a minor violation of the criteria for system success is not taken into account.

For instance, given a system with 300 units (FOR=0.05) and 2000 circuits (FOR=0.001), the cumulative probability and number of states are listed in Table 2.1 and 2.2.

Table 2.1 Cumulative Probabilities of States as a Function of Total Simultaneous Outages m for a System with 300 Units (FOR = 0.05) and 2000 Circuits (FOR = 0.001)

m	0	1	2	3	4	5	6
$\Pr[N_G \leq m]$	2.0753e-7	3.4843e-6	2.9268e-5	1.6406e-4	6.9083e-4	0.0023	0.0065
$\Pr[N_L \leq m]$	0.1352	0.4059	0.6767	0.8572	0.9474	0.9835	0.9955

The cumulative probability of having a maximum of m units/circuits out simultaneously, i.e. $\Pr(N_G \leq m) / \Pr(N_L \leq m)$ is given by the following recurrence:

$$\Pr(N_G \leq 0) = p_G^{n_G}$$

$$\Pr(N_G \leq m) = \Pr(N_G \leq m-1) + \frac{n_G!}{m!(n_G - m)!} p_G^{(n_G - m)} (1 - p_G)^m, \quad m = 1, 2, \dots, n_G$$

$$\Pr(N_L \leq 0) = p_L^{n_L}$$

$$\Pr(N_L \leq m) = \Pr(N_L \leq m-1) + \frac{n_L!}{m!(n_L - m)!} p_L^{(n_L - m)} (1 - p_L)^m, \quad m = 1, 2, \dots, n_L$$

Table 2.2 Cumulative Numbers of States as a Function of Total Simultaneous Outages m for a System with 300 Units and 2000 Circuits

m	0	1	2	3	4	5	6
$\#(N_G \leq m)$	1	301	45,151	4.5e6	3.35e8	1.99e10	9.827e11
$\#(N_L \leq m)$	1	2,001	2.0e6	1.3e9	6.66e11	2.66e14	8.85e16

The cumulative number of states having a maximum of m units/circuits out simultaneously, i.e. $\#(N_G \leq m) / \#(N_L \leq m)$ is given by the following recurrence

$$\#(N_G \leq 0) = 1 \quad \#(N_G \leq m) = \#(N_G \leq m-1) + \frac{n_G!}{m!(n_G - m)!}, \quad m = 1, 2, \dots, n_G$$

$$\#(N_L \leq 0) = 1 \quad \#(N_L \leq m) = \#(N_L \leq m-1) + \frac{n_L!}{m!(n_L - m)!}, \quad m = 1, 2, \dots, n_L$$

where

$$n_G = 300$$

$$n_L = 2000$$

N_G : number of simultaneous outages of units

N_L : number of simultaneous outages of circuits

$$p_G = 1 - \text{FOR of units} = 0.95$$

$$p_L = 1 - \text{FOR of circuits} = 0.999$$

It is easily seen that if the states that have seven or more circuits simultaneously down are neglected, whose associated probability is $\Pr[N_L \geq 7] = 1 - 0.9955 = 0.0055$, the number of states is dramatically reduced from 10^{600} to $8.85e16$. However the reduced state space is still too large to be evaluated state by state. In addition, some catastrophic rare events, such as cascading outages [10,13], may be reasonably excluded due to small probabilities.

2.2 Contingency selection and ranking [2]

The impact of states on the system is taken into consideration in contingency selection method. Reduction of the state space is based on the elimination of the states whose impact on the system is small, and the consideration of only those whose system effect is significant. Selected failure states are also ranked by their impact on the system.

Several approaches for the contingency selection and ranking have been achieved based on the traditional power flow (TPF) model.

(1) Performance index (PI) method

In this method, a variety of performance indices J , such as circuit current index, voltage index, reactive power index and so on, are defined to measure the normality of a system

[2]. When a contingency happens, the system operating conditions change, so do the associated PIs. The variations of PIs from pre-contingency to post-contingency, i.e., ΔJ , can be considered to indicate the impact of the contingency on system operating conditions. The contingencies are ranked in descending order of the projected PI changes.

A highly efficient computational method, which is called co-state method, has been developed to calculate the changes of PIs. The computational burden, as shown in the following procedure, is insignificant.

A brief description of this method is given below:

First, the concept of contingency control variable u is incorporated to system component models, such that

$$u = \begin{cases} 1 & \text{if component is in operation} \\ 0 & \text{if component is outaged} \end{cases}$$

The PI J is general a function of u and system states x , i.e. $J = f(x, u)$

The following linearized equation (first order approximation) is used to calculate PI after contingency ($u = 0$), based on the value of PI before contingency ($u = 1$).

$$J_{u=0} = J_{u=1} + \left. \frac{dJ}{du} \right|_{u=1} (u - 1) \quad (1)$$

Thus, the change of PI, ΔJ is derived:

$$\Delta J = J_{u=0} - J_{u=1} = - \left. \frac{dJ}{du} \right|_{u=1}$$

where $\frac{dJ}{du}$ is obtained by co-state method:

$$\frac{dJ}{du} = \frac{\partial f(x, u)}{\partial u} - x^T \frac{\partial g(x, u)}{\partial u}, \quad x^T = \frac{\partial f(x, u)}{\partial x} \left(\frac{\partial g(x, u)}{\partial x} \right)^{-1}$$

where $g(x, u) = 0$ is the power flow equations.

Additionally, contingency selection method can handle common mode failures [26]. For example, if a lightning strike happens to two parallel transmission lines, both transmission lines are outaged. By incorporating the same contingency control variables u to the two transmission line models, we can use the same procedure to obtain ΔJ , which is corresponding to this common mode contingency.

The main drawback of PI method is that it is vulnerable to misranking. This is mainly caused by the approximate method used to calculate PIs. As in the co-state method, $J_{u=0}$ is obtained by a linear approximation method. Because of the nonlinearities of power system, it will introduce errors to ΔJ . As shown in Figure 1, when u varies from 1 to 0,

the actual curve of J is nonlinear, the actual ΔJ ($\Delta J = J_{u=0} - J_{u=1}$) is larger than $\Delta J'$ ($\Delta J' = J'_{u=0} - J'_{u=1}$), which is calculated based on linear approximate model. This error may lead to misranking. Especially, when a contingency results in system abnormal, the difference between ΔJ and $\Delta J'$ may be large.

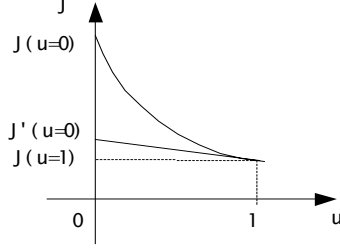


Figure 1. J -- Actual curve
vs approximate curve

Another reason that may result in misranking is the discontinuities of the system model caused by generator reactive limits and regulator tap limits [4].

(2) Screening methods

In this method, contingency ranking is based on approximate network solutions, such as Fast Decoupled Power Flow solutions [4,6]. It can take care of nonlinearities of the power system to some extent and be able to provide more accurate results than that of PI method.

However, the contingency analysis by screening method needs to spend time in solving post contingency cases, which is time consuming. Especially, the time may be wasted in solving contingencies that do not have much impact on system operation. Therefore, it is accurate but not efficient.

(3) Hybrid contingency selection and ranking method [3,4]

In order to achieve both efficient and accurate contingency selection and ranking, hybrid scheme combines the PI and screening methods. In such scheme, efficiency is achieved by employing PI method first to quickly identify the conceivable contingencies. Screening method is then utilized only for a subset of contingencies, which cannot rank with confidence by the PI method, to guarantee the accuracy of ranking.

The combination of the above two methods, such as Multiple contingency ranking scheme [3] and Hybrid contingency selection method [4], can take advantage of the best properties of both methods, i.e., to achieve efficient and accurate contingency selection.

2.3 Monte Carlo Simulation (MCS)

Previous methods focus on the use of analytical techniques in evaluating contingencies, which represent the system by analytical models and evaluate performance indices from these models using mathematical solutions. Monte Carlo simulation methods, however,

estimate the indices by simulating the actual process and random behavior of the system. This method, therefore, treats the problem as a series of experiments instead of studying the analytical models of systems [7].

It has been pointed out that the main shortcoming of MCS method is the enormous amount of experiments needed to run in order to obtain an acceptable level of the accuracy of the performance indices [1]. If the variance of an output random variable can be decreased without altering its expected value, a pre specified precision could be achieved with less simulation [17]. Several variance reduction techniques, such as control variates, importance sampling, stratified sampling and antithetic variates, have been developed [7,17].

3 Comprehensive Reliability Assessment Methodology

This section presents the overall methodology.

3.1 Component and Event Model

In the comprehensive reliability assessment, each component (circuit or unit) is modeled with a two state Markov Model, that is, the component is either working (up) or failed (down) as shown in Figure 3.1.

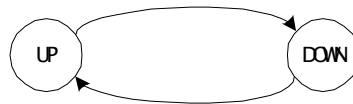


Figure 3.1 Two-state Markov model

Based on the two-state Markov model of each component, a Markov state of a power system is defined by a particular condition where every component is in a given operating state of its own. All the possible states of a system make up the state space. An event consists of a certain set of system states in the state space that are combined to form a single state.

3.2 Reliability Index Computations

Power system reliability can be described with a number of indices. A partial list of reliability indices are presented in Tables 3-1 and 3-2.

Table 3-1 List of System Reliability Indices

- A. Probability Indices
 - 1. Service Failure Probability

2. Unsupplied Energy Probability
- B. Expectation Indices
 1. Service Failure Occurrences
 2. Service Failure Duration
 3. Expected Unsupplied Energy
 4. Unserved Customer Hours
 5. Customer Interruptions
- C. Bulk System Reliability Indices
 1. Bulk Power Interruption Index
 2. Bulk Power Energy Curtailment Index
 3. Bulk Power Supply Average Curtailment Per Disturbance
- D. Customer Interruption Indices
 1. System Average Interruption Frequency Index
 2. System Average Interruption Duration index
 3. Customer Average Interruption Duration Index
 4. Average Service Availability Index
 5. Average Number of Customers Per Interruption

Table 3-2 Branch and Bus Reliability Indices

- A. Branch Reliability Indices
 1. On Peak Probability of Overload
 2. Annual Probability of Overload
 3. Annual Frequency of Overload
 4. Expected Duration of Overload
- B. Bus Reliability Indices
 1. Peak/Annual Probability of Loss of Load
 2. On Peak/Annual Frequency of Loss of Load
 3. On Peak/Annual Duration of Loss of Load
 4. On Peak/Annual Unserved Energy
 5. On Peak/Annual Customer Interruptions
 6. On Peak/Annual Unserved Customer Hours

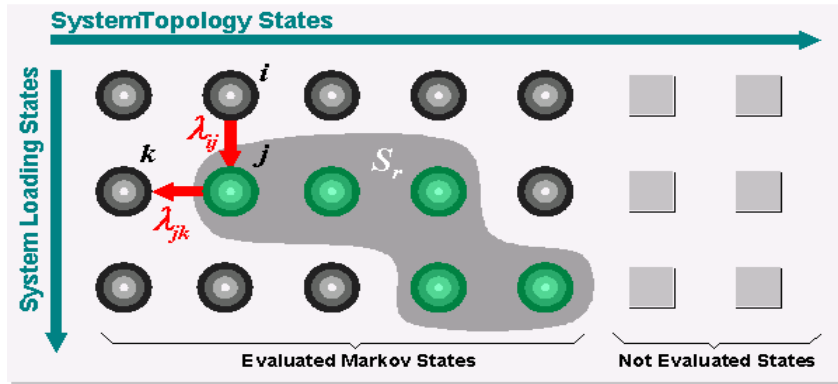


Figure 3.2 State-space Diagram

From the computational point of view, reliability indices can be classified into categories as follows:

- (1) Probability indices,

- (2) Frequency indices, and
- (3) Duration indices.

These reliability indices are computed directly from the Markov models. Considering the state space diagram shown in Figure 3.2, in which load levels are also modeled with a multi-state Markov model, if the load level or the state of any of the component changes, then the system enters another state. Figure 3.2 illustrates transitions from one load level to another (λ_{ij}) and transitions from one contingency to another λ_{jk} . Utilizing these models, a contingency at certain load level is characterized with a certain probability and transition rates to other system states, such as λ_{ij} and λ_{jk} . In Figure 3.2, S_r represents an event containing a set of states that possess some common features, such as system failure states.

The reliability indices related to the event S_r can be computed as follows:

(1) Probability index

The probability of S_r , $P_r[S_r]$ is obtained by adding all the probabilities p_j , that is:

$$P_r[S_r] = \sum_{j \in S_r} p_j$$

The probabilities $p_j, j \in S_r$ can be added because the events of being in any of the state j are mutually exclusive.

(2) Frequency index

The frequency of S_r , f_{S_r} , is the total of the frequency of leaving a state j for a state i outside S_r , therefore

$$f_{S_r} = \sum_{i \notin S_r} \sum_{j \in S_r} f_{ji} = \sum_{i \notin S_r} \sum_{j \in S_r} p_j \lambda_{ji} = \sum_{j \in S_r} (p_j \sum_{i \notin S_r} \lambda_{ji})$$

where

λ_{ji} is the transition rate from state j to state i

f_{ji} is the frequency of transfer from state j to state i , which is defined as the expected number of direct transfers from j to i per unit time. The relation between f_{ji} and λ_{ji} can be written as $f_{ji} = \lambda_{ji} p_j$.

(3) Duration index

The duration index of S_r , T_{S_r} , can be obtained using the probability index and frequency index given above by the following equation:

$$T_{S_r} = \frac{P_r[S_r]}{f_{S_r}}$$

3.3 Event Identification

A specific event can be identified with a search methodology that has evolved from the wind-chime method reported in earlier publications [13], [14].

Wind-chime scheme, as shown in Figure 3.3, is used to select contingencies (single independent outages or multiple (common mode) outages). This method has been extensively used for

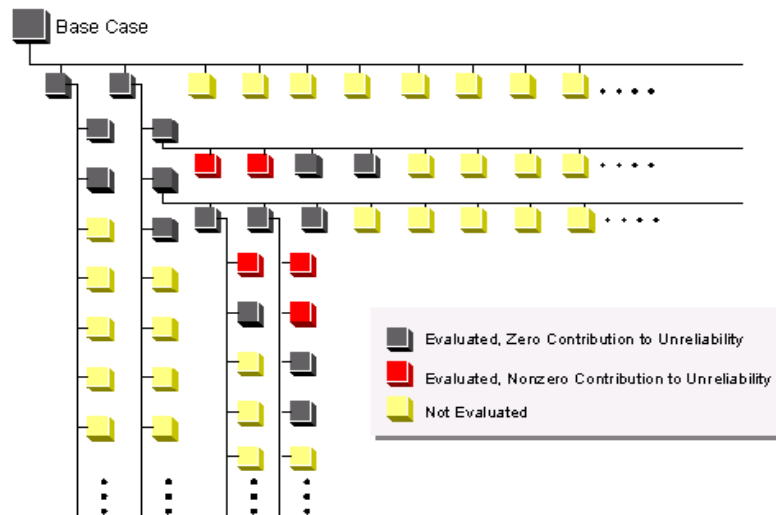


Figure 3.3 Wind-Chime Scheme

In wind-chime scheme, if a contingency is identified causing system problems, then all its combinative contingencies are immediately assumed to cause system problems

3.4 Effects Analysis

The impact of a contingency on the reliability of the system is evaluated with a comprehensive effects analysis methodology. This methodology recognizes the various effects following a contingency. These are:

- (a) inertial redispatch following a fault and tripping of a major piece of equipment.
- (b) operation of control devices such as capacitor/reactor switching, transformer tap changes, etc.
- (c) Economic redispatch in case of major generation-load imbalance.
- (d) Congestion management in case of emergencies following a contingency.
- (e) Reactive power rescheduling in case of emergencies following a contingency.

3.5 Overall Algorithm

Figure 3.4 illustrates the overall procedure of the reliability assessment. First, a load level is selected. For this load level, two kinds of effects analysis approaches can be applied, including a) Network Solution Approach, and b) System Simulation Approach. In the Network Solution Approach, the remedial action is also included in the effect analysis. The results of effects analysis are used as the input of defining feasible contingencies and contingency selection/enumeration. Subsequently, the system reliability indices are computed. The procedure is repeated for all selected contingencies and all load levels.

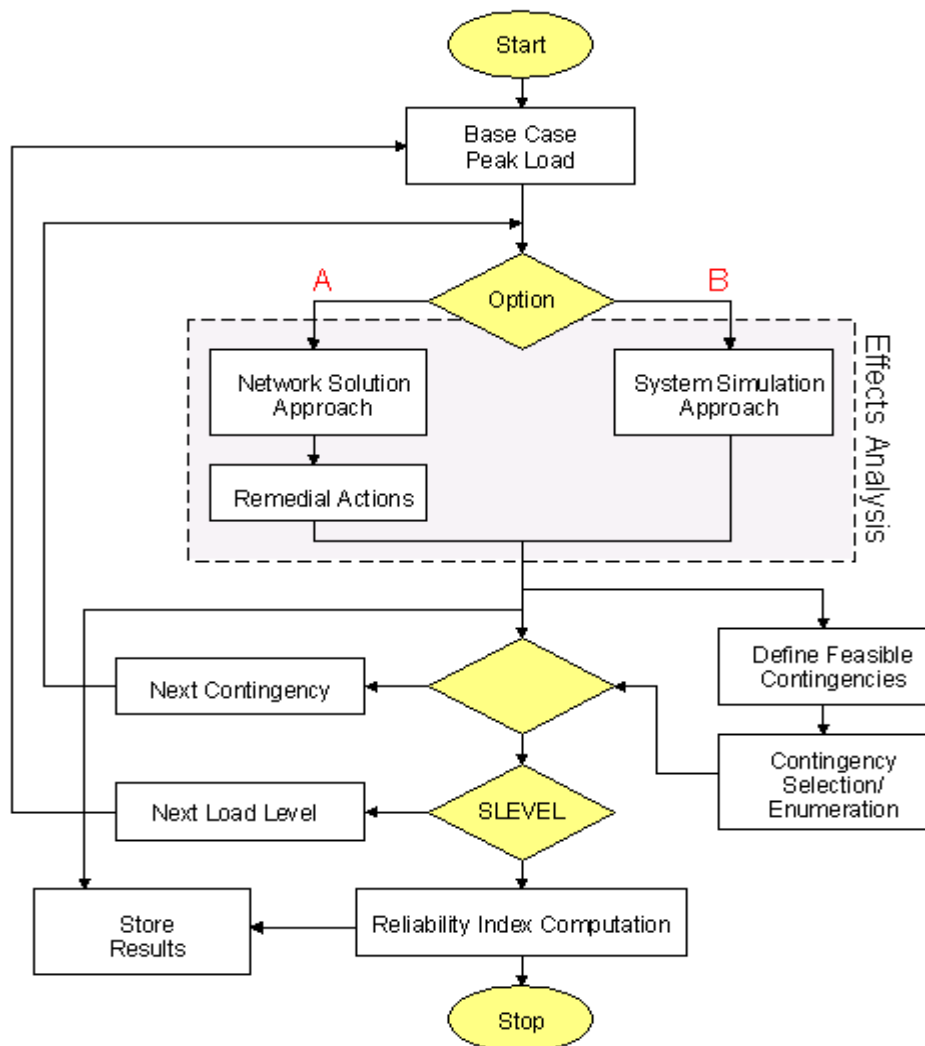


Figure 3.4 Flow Chart of the Overall Algorithm for the Reliability Assessment

4. Single Phase Quadratized Power Flow Problem

4.1 Introduction

Because of the importance of the power flow model as one of the basic analysis tools in the operations and planning of power systems, many attempts have been made to improve the efficiency and accuracy of power flow solutions. These attempts range from different formulations of the power flow problem to advanced sparsity methods and shortcuts for repeat solutions or even to attempts to obtain a direct non-iterative solution to the problem. In this section a method of reformulating the power flow problem in a way that will improve the efficiency of the solution method is presented. In this context it was observed in the early 70s that expressing the bus voltage phasors in Cartesian coordinates results in a formulation of the power flow problem that is less complex, since trigonometric functions are absent. Going one step further, an improved idea is not only to use Cartesian coordinates for the phasor expressions, but also to 'quadratize' the power flow equations, i.e. to express the power flow equations as a set of equations with order no greater than two. It turns out that this can be achieved very easily with the introduction of additional state variables as needed. The advantage of this formulation is that the resulting power flow equations are either linear or quadratic. Application of Newton's method is ideally suitable to quadratic equations. This results in the Quadratised Power Flow (QPF) formulation.

The traditional power flow model consists of the power balance equations at each bus of the system. Power flow equations are expressed in the polar coordinates in terms of the systems states (bus voltage magnitudes and angles). Therefore, trigonometric terms exist in the formulated power flow equations. In addition, induction machine load are very complicated and contain very high-order terms resulting from the complex load model. Consequently, the highest order of the TPF equations is more than two.

Quadratic power flow model, however, is set up based on applying the Kirchhoff's current law at each bus. In addition, the states variables are expressed in Cartesian coordinates. As a result, the power flow equations are quadratized as a set of equations that are linear or quadratic with order no more than two. Also trigonometric terms are absent, which makes the power flow equations less complex. The formulation of quadratic power flow provides superior performance in two aspects: (a) faster convergence, (b) ability to model complex load characteristics, and classes of loads such as interruptible load, critical load, etc.

In general, at a bus, there may be generation, loads (various types of loads), circuits, shunt devices, etc. The general bus of a system is illustrated in Figure 4.1. While the circuits and shunt terms are linear elements, the loads and generation may operate in such a way that imposes nonlinearities. Common loads models are: (a) constant power load, (b) constant impedance load and (c) induction motor load. Common operating modes of

generating units are: (a) constant voltage, constant real power operation, (b) constant real power constant power factor operation. The new QPF approach consists of writing the Kirchoff's current law at each bus of the system. The models of loads and generators are expressed in terms of their terminal current and additional equations in additional state variables that define their operating mode. The additional equations may be nonlinear but of order no higher than two. The resulting set of equations is consistent, i.e. the number of equations equals the number of unknowns. In addition, the set of equations are linear or quadratic in terms of the state variables. These equations are solved via Newton's method. The proposed model has two advantages: (a) the resulting power flow model is more accurate than usual load models and (b) the convergence characteristics of the proposed model are superior to conventional methods.

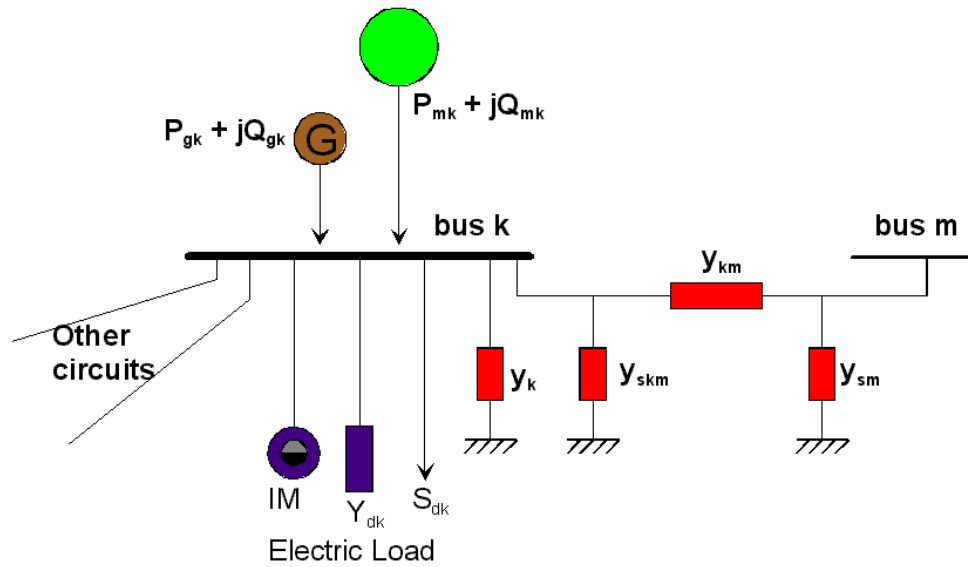


Figure 4.1: General Power System Bus

The new formulation of the power flow problem has been applied to a small test system. The performance characteristics of the solution have been compared to those of the traditional power flow problem. The results for a small five-bus system are given in Figure 4.2. Note how fast the new model converges. This is to be expected since the model is quadratic and Newton's method is best suited for quadratic models. We expect that this convergence characteristics carry to large systems.

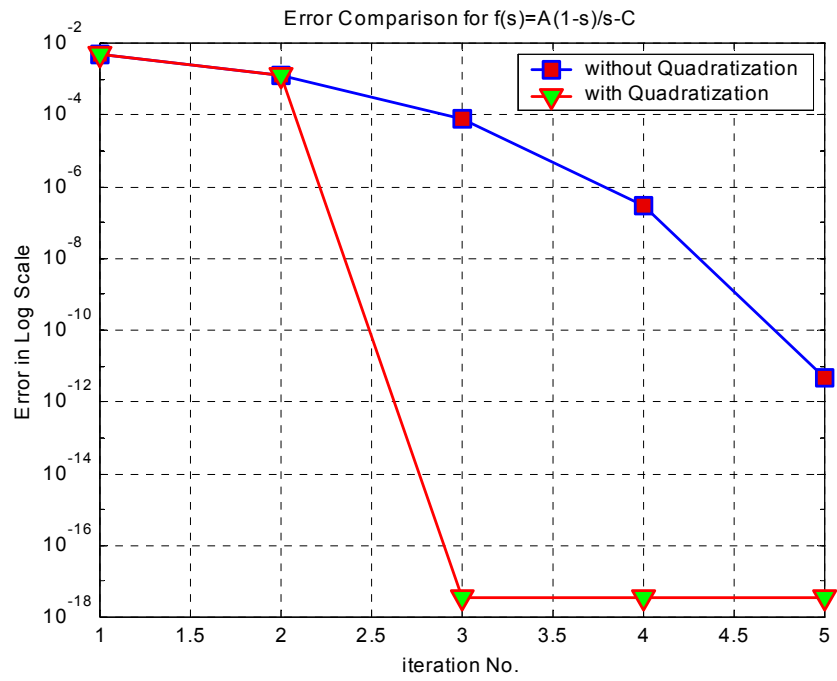


Figure 4.2: Performance Comparison of Quadratzated and Traditional Power Flow Method

4.2 Power Flow Equations using QPF

Consider again a bus of an electric power system as it is illustrated in Figure 4.1. The figure shows a generator, a constant impedance load, a constant power load, an induction motor load and a switched shunt capacitor/reactor load connected to the bus together with a transformed and a circuit (transmission line) to other buses. Each component of the power system illustrated in Figure 4.1 can be modeled with a set of linear and quadratic equations. As an example, the form of the models for a generator, a circuit, a switched shunt capacitor/reactor, a constant impedance load and a constant power load model is described next.

- **Generator Model:** Figure 4.3 illustrates the simplified equivalent circuit model of a single axis generator model. Assume a synchronous generator with admittance $\tilde{y}_{gk} = g_{gk} + jb_{gk}$ and internal emf $\tilde{E}_k = E_{kr} + jE_{ki}$, connected to bus k of voltage $\tilde{V}_k = V_{kr} + jV_{ki}$

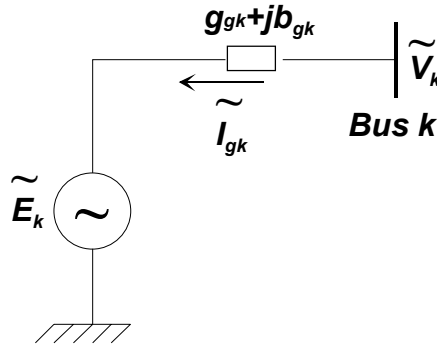


Figure 4.3: A Generator at Bus k

The electric current of the generator, in the direction from the bus into the generator, is given by the equation:

$$\tilde{I}_{gk} = (g_{gk} + jb_{gk}) \cdot (\tilde{V}_k - \tilde{E}_k) \quad (4.1)$$

where $(g_{gk} + jb_{gk})$ is the generator admittance.

Note here we use the single axis model of the generator for simplicity. The procedure can be applied to the two axes model of the generator as well. This is omitted to avoid the complexity of the two axes model equations.

The state vector for the generator model consist of the terminal voltage $\tilde{V}_k$ and the internal emf $\tilde{E}_k$. Expressing these quantities in Cartesian coordinates the state vector becomes:

$$x = [V_{kr} \quad V_{ki} \quad E_{kr} \quad E_{ki}]^T \quad (4.2)$$

where the subscripts "r" and "i" indicate real and imaginary part respectively.

The current equations in Cartesian coordinates are:

$$\begin{aligned} I_{gkr} &= g_{gk} V_{kr} - g_{gk} E_{kr} - b_{gk} V_{ki} + b_{gk} E_{ki} \\ I_{gki} &= g_{gk} V_{ki} - g_{gk} E_{ki} + b_{gk} V_{kr} - b_{gk} E_{kr} \end{aligned} \quad (4.3)$$

These expressions will be used in the Kirchhoff's voltage law applications when the connectivity constraints of the network are applied. In addition to the two current equations two additional internal equations are needed for the model to be consistent, i.e., the number of equations equals the number of unknown states. There are three control modes for the synchronous generator, i.e., a) Slack mode, b) PQ mode, and c) PV mode. Although the current equations are the same for each mode, the internal equations are the ones that make the model different for each mode. The model of each one of these cases is described next.

Slack mode: In the slack mode, the synchronous generator is controlled to maintain the specified voltage magnitude and zero phase angle. For the slack mode, we have the following equations.

$$\begin{aligned} I_{gkr} &= g_{gk} V_{kr} - g_{gk} E_{kr} - b_{gk} V_{ki} + b_{gk} E_{ki} \\ I_{gki} &= g_{gk} V_{ki} - g_{gk} E_{ki} + b_{gk} V_{kr} - b_{gk} E_{kr} \\ 0.0 &= V_{ki} \\ 0.0 &= V_{kr}^2 + V_{ki}^2 - V_{k,specified}^2 \end{aligned} \quad (4.4)$$

Note that the current equations force the phase of the generator terminal voltage to be zero. The last equation forces the magnitude of the generator terminal voltage to be equal to the specified.

PQ mode: In the PQ mode, the synchronous generator is controlled to maintain the specified real and reactive power. For the PQ mode, we have the following equations.

$$\begin{aligned} I_{gkr} &= g_{gk} V_{kr} - g_{gk} E_{kr} - b_{gk} V_{ki} + b_{gk} E_{ki} \\ I_{gki} &= g_{gk} V_{ki} - g_{gk} E_{ki} + b_{gk} V_{kr} - b_{gk} E_{kr} \\ 0.0 &= -\frac{P_{k,specified}}{3} + g_{gk} V_{kr}^2 + g_{gk} V_{ki}^2 - g_{gk} V_{kr} E_{kr} - g_{gk} V_{ki} E_{ki} + b_{gk} V_{kr} E_{ki} - b_{gk} V_{ki} E_{kr} \\ 0.0 &= -\frac{Q_{k,specified}}{3} - b_{gk} V_{kr}^2 - b_{gk} V_{ki}^2 + g_{gk} V_{kr} E_{ki} - g_{gk} V_{ki} E_{kr} + b_{gk} V_{kr} E_{kr} + b_{gk} V_{ki} E_{ki} \end{aligned} \quad (4.5)$$

Note that the two internal equations impose the requirement that the active and reactive power delivered by the generator equal their specified values.

PV mode: In the PV mode, the synchronous generator is controlled to maintain the specific real power and voltage magnitude. For the PV mode, we have the following equations:

$$\begin{aligned}
I_{gkr} &= g_{gk} V_{kr} - g_{gk} E_{kr} - b_{gk} V_{ki} + b_{gk} E_{ki} \\
I_{gki} &= g_{gk} V_{ki} - g_{gk} E_{ki} + b_{gk} V_{kr} - b_{gk} E_{kr} \\
0.0 &= -\frac{P_{k,specified}}{3} + g_{gk} V_{kr}^2 + g_{gk} V_{ki}^2 - g_{gk} V_{kr} E_{kr} - g_{gk} V_{ki} E_{ki} + b_{gk} V_{kr} E_{ki} - b_{gk} V_{ki} E_{kr} \\
0.0 &= V_{kr}^2 + V_{ki}^2 - V_{k,specified}^2
\end{aligned} \tag{4.6}$$

Note that the third equation imposes the requirement that the real power delivered by the generator is equal to the specified real power and the last equation imposes the requirement that the magnitude of the terminal voltage equals the specified value.

In each of the above cases we have an equation that describes the current at the terminal of the generator as a function of state variables and some additional equations expressing the control functions of the generator. All equations are linear or quadratic in terms of the state variables.

- **Circuit Branch Model:** Figure 4.4 illustrates the model of a circuit connecting buses k and m represented with its π -equivalent circuit.

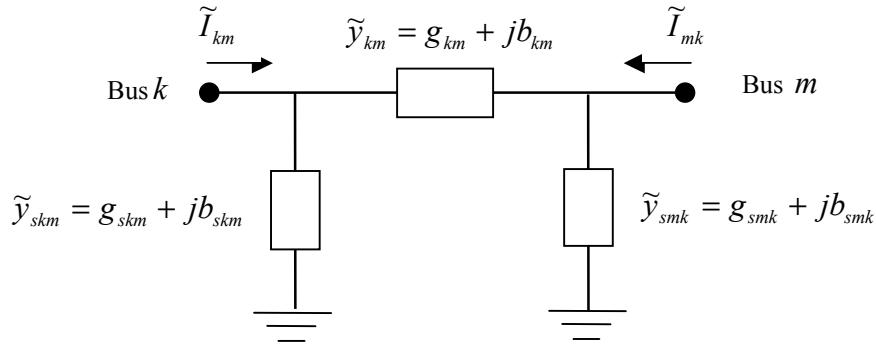


Figure 4.4: π -equivalent of circuit branch

The state vector for the circuit model consist of the bus voltages $\tilde{V}_k$ and $\tilde{V}_m$. Expressing these quantities in Cartesian coordinates the state vector becomes:

$$x = [V_{kr} \quad V_{ki} \quad V_{mr} \quad V_{mi}]^T \tag{4.7}$$

where the subscripts "r" and "i" indicate real and imaginary part respectively.

The circuit model is represented by the following equations:

$$\begin{aligned}
I_{kmr} &= (g_{km} + g_{skm})V_{kr} - (b_{km} + b_{skm})V_{ki} - g_{km}V_{mr} + b_{km}V_{mi} \\
I_{kmi} &= (b_{km} + b_{skm})V_{kr} + (g_{km} + g_{skm})V_{ki} - b_{km}V_{mr} - g_{km}V_{mi} \\
I_{mkr} &= -g_{km}V_{kr} + b_{km}V_{ki} + (g_{km} + g_{smk})V_{mr} - (b_{km} + b_{smk})V_{mi} \\
I_{mki} &= -b_{km}V_{kr} - g_{km}V_{ki} + (b_{km} + b_{smk})V_{mr} + (g_{km} + g_{smk})V_{mi}
\end{aligned} \tag{4.8}$$

where:

$\tilde{y}_{km} = g_{km} + jb_{km}$	is the circuit series admittance
$\tilde{y}_{skm} = g_{skm} + jb_{skm}$	is the k side shunt admittance
$\tilde{y}_{smk} = g_{smk} + jb_{smk}$	is the m side shunt admittance
$\tilde{V}_k$	is the voltage phasor at bus k
$\tilde{V}_m$	is the voltage phasor at bus m

Note that the equations are linear with respect to the state variables.

- **Switched Shunt Capacitor/Reactor Model:** Figure 4.5 illustrates the model of a switched shunt capacitor/reactor device of impedance $\tilde{y}_{Ck} = g_{Ck} + jb_{Ck}$, connected to bus k .

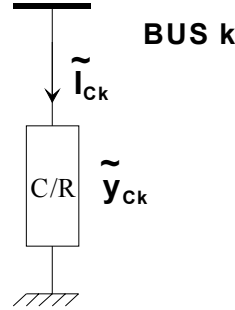


Figure 4.5: Capacitor or Reactor at Bus k

The state vector for the shunt capacitor/reactor model consist of the bus voltage $\tilde{V}_k$. Expressing this voltage in Cartesian coordinates the state vector becomes:

$$x = [V_{kr} \quad V_{ki}]^T \quad (4.9)$$

where the subscripts "r" and "i" indicate real and imaginary part respectively.

The shunt capacitor/reactor model is represented by the following equations:

$$\begin{aligned} I_{Ckr} &= g_{Ck}V_{kr} - b_{Ck}V_{ki} \\ I_{Cki} &= g_{Ck}V_{ki} + b_{Ck}V_{kr} \end{aligned} \quad (4.10)$$

Note that the equations are linear with respect to the state variables.

- **Constant Impedance Load Model:** Figure 4.6 illustrates the model of a constant impedance load of impedance $\tilde{y}_{Lk} = g_{Lk} + jb_{Lk}$, connected to bus k .

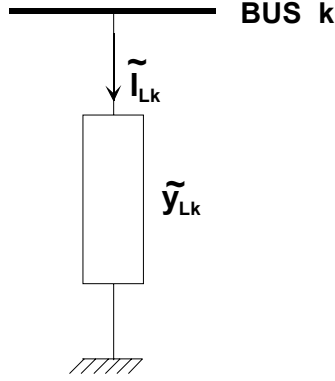


Figure 4.6: Constant Impedance Load at Bus k

The state vector for the constant impedance load model consist of the bus voltage $\tilde{V}_k$. Expressing this voltage in Cartesian coordinates the state vector becomes:

$$x = [V_{kr} \quad V_{ki}]^T \quad (4.11)$$

where the subscripts "r" and "i" indicate real and imaginary part respectively.

The constant impedance load model is represented by the following equations:

$$\begin{aligned} I_{Lkr} &= g_{Lk} V_{kr} - b_{Lk} V_{ki} \\ I_{Lki} &= g_{Lk} V_{ki} + b_{Lk} V_{kr} \end{aligned} \quad (4.12)$$

Note that the equations are linear with respect to the state variables.

- **Constant Power Load Model:** Figure 4.7 illustrates the model of a constant power load, connected to bus k . The constant power load is defined with the total complex power, $S_{dk} = P_{dk} + jQ_{dk}$ that is assumed to be constant, i.e. independent of the voltage magnitude at the bus.

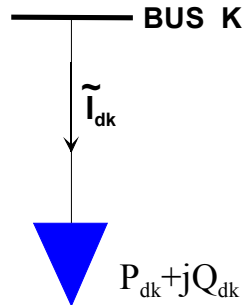


Figure 4.7: Constant Power Load at Bus k

Define the nominal admittance of the load to be:

$$\tilde{Y}_{dn,k} = \frac{1}{3V_{nk,ph}^2} (P_{dk} - jQ_{dk}) = g_{dn,k} + jb_{dn,k} \quad (4.13)$$

where $V_{nk,ph}$ is the nominal phase voltage at bus k .

Then the constant power load model can be expressed with the following set of equations.

$$\begin{aligned} I_{dkr} &= g_{dn,k}V_{kr} - b_{dn,k}V_{ki} + u_1g_{dn,k}V_{kr} - u_1b_{dn,k}V_{ki} = (1+u_1) \cdot (g_{dn,k}V_{kr} - b_{dn,k}V_{ki}) \\ I_{dki} &= g_{dn,k}V_{ki} + b_{dn,k}V_{kr} + u_1g_{dn,k}V_{ki} + u_1b_{dn,k}V_{kr} = (1+u_1) \cdot (g_{dn,k}V_{ki} + b_{dn,k}V_{kr}) \\ 0.0 &= u_2 - V_{kr}^2 - V_{ki}^2 \\ 0.0 &= g_{dn,k}u_2 + u_1u_2g_{dn,k} - P_{dk} \end{aligned} \quad (4.14)$$

The first two equations are the current equations; the last two are the internal equations of the model. The above equations force the complex power absorbed by the load to be equal to the specified load and constant.

The state vector for the constant impedance load model is:

$$x = [V_{kr} \quad V_{ki} \quad u_1 \quad u_2]^T \quad (4.15)$$

where the subscripts "r" and "i" indicate real and imaginary part respectively.

Note that the equations are at most quadratic with respect to the state variables.

The examples above show that each component of the system can be represented with an appropriate set of linear or quadratic equations. By expressing the voltage and current phasors with their Cartesian coordinates (i.e. $\tilde{I} = I_r + jI_i$ and $\tilde{V} = V_r + jV_i$) the following general form is obtained for any power system component:

$$\begin{bmatrix} I_r^k \\ I_i^k \\ 0 \end{bmatrix} = y_{eq_real}^k \begin{bmatrix} V_r^k \\ V_i^k \\ y^k \end{bmatrix} + \begin{bmatrix} x^{kT} f_{eq_real1}^k x^k \\ x^{kT} f_{eq_real2}^k x^k \\ \dots \end{bmatrix} - b_{eq_real}^k \quad (4.16)$$

$$\text{where: } x^k = \begin{bmatrix} V_r^k \\ V_i^k \\ y^k \end{bmatrix} \quad (4.17)$$

and $y_{eq_real}^k$, $b_{eq_real}^k$, and $f_{eq_real}^k$ are matrices with appropriate dimensions.

In this section the general quadratic models of five components of an electric power system were discussed, namely, generator, transmission line, switched shunt capacitor/reactor, constant impedance load and constant power load. It is emphasized that this procedure can be applied to any other component, i.e. transformer, variable tap

transformer, two axes generator model, etc. The end result will always be a model in the form of the equations (4.16).

4.3 Solution Method

The network solution is obtained with application of Newton's method to a quadratized form of the network equations. The quadratized network equations are generated as follows. Consider the general form of equations for any model of the system (linear or nonlinear), i.e. equation (4.16). Note that this form includes two sets of equation, which are named *external equations* or *current equations* and *internal equations* respectively. The electric currents at the terminals of the component appear only in the external equations. Similarly, the device states consist of two variable sets: *external states* (i.e. bus voltage $\tilde{V}^k = V_r^k + jV_i^k$) and *internal state variables* y^k (if any). The set of equations (4.16) is consistent in the sense that the number of external states and the number of internal states equal the number of external and internal equations respectively.

The entire network equations are obtained by application of the connectivity constraints among the system components, i.e. Kirchoff's current law at each system bus. Specifically, Kirchoff's current law applied to all buses of the system yields:

$$\sum_k A^k \tilde{I}^k = 0 \quad (4.18)$$

where $\tilde{I}^k = I_r^k + jI_i^k$ is the device k bus current injections, and A^k is a component incidence matrix with:

$$\{A_{ij}^k\} = \begin{cases} 1, & \text{if bus } j \text{ of device } k \text{ is connected to bus } i \\ 0, & \text{otherwise} \end{cases} \quad (4.19)$$

All the internal equations from all devices should be added to the above equation, yielding the following set of equations:

$$\begin{cases} \sum_k A^k \tilde{I}^k = 0 \\ \text{[internal equations of all devices]} \end{cases} \quad (4.20)$$

Let $\tilde{V} = V_r + jV_i$ be the vector of all bus voltage phasors. Then, the following relationship hold:

$$\tilde{V}^k = (A^k)^T \tilde{V} \quad (4.21)$$

where $\tilde{V}^k$ is device k bus voltage.

Equations (4.20) can be separated into two sets of real equations by expressing the voltages and currents with their Cartesian coordinates. Then the device currents can be

eliminated with the use of equations (4.16). This procedure will yield a set of equations in terms of the voltage variables and the internal device state variables. If all the state variables are represented with the vector x , then the equations can be written in the following form:

$$G(x) = Y_{real}x + \begin{bmatrix} x^T f_1 x \\ x^T f_2 x \\ \dots \end{bmatrix} - B_{real} = 0 \quad (4.22)$$

where x is the vector of all the state variables and Y_{real} , f , B_{real} are matrices with appropriate dimensions. The simultaneous solution of these equations is obtained via Newton's method described next.

Equation (4.22) is solved using Newton's method. Specifically, the solution is given by the following algorithm:

$$x^{v+1} = x^v - J_G^{-1} \left\{ Y_{real}x^v + \begin{bmatrix} x^{vT} f_1 x^v \\ x^{vT} f_2 x^v \\ \dots \end{bmatrix} - B_{real} \right\} \quad (4.23)$$

where v is the iteration step number; J_G is the Jacobian matrix of the equation (4.22). In particular, the Jacobian matrix takes the following form:

$$J_G = Y_{real} + \begin{bmatrix} x^{vT} (f_1 + f_1^T) \\ x^{vT} (f_2 + f_2^T) \\ \dots \end{bmatrix} \quad (4.24)$$

It is important to note that Newton's method is ideally suited for solution of quadratic equations.

4.4 Numerical Example

The quadratic power flow is demonstrated with an example.

Consider the power system of Figure 4.8. The generator controls the voltage magnitude at bus 1 to the value of 1.0 p.u.

Assume that the electric load at bus 2 is $S_{d2} = 0.85 + j0.36$ p.u. Formulate the traditional power flow problem as well as the quadratised power flow problem. Solve both problems starting from flat start, i.e. the voltage at bus 2 equal to 1.0 p.u. Record the mismatch at each iteration and tabulate the results.

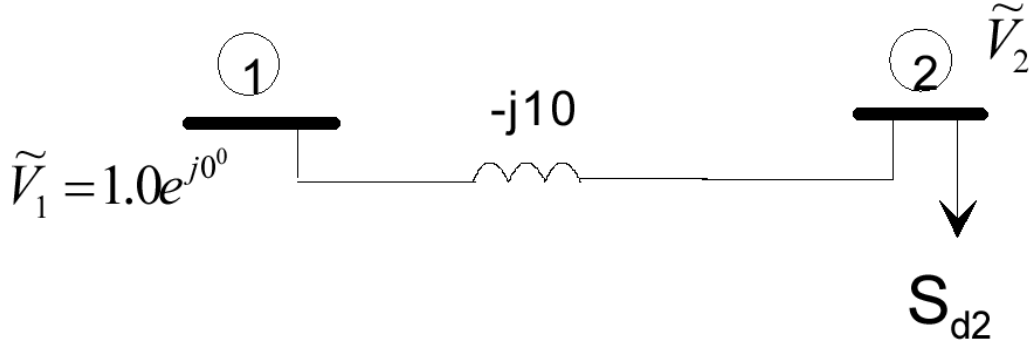


Figure 4.8: A simplified two-bus example power system

Solution: a) The traditional power flow problem for this system is defined with the following equations:

$$\begin{aligned} g_1(x) &= 10.0V_2 \sin \delta_2 + 0.85 = 0.0 \\ g_2(x) &= 10.0V_2^2 - 10.0V_2 \cos \delta_2 + 0.36 = 0.0 \end{aligned} \quad (4.25)$$

The iterative solution algorithm is:

$$x^{v+1} = x^v - J_g^{-1}(x^v)g(x^v) \quad (4.26)$$

where:

$$x = \begin{bmatrix} \delta_2 \\ V_2 \end{bmatrix}, \quad g(x^v) = \begin{bmatrix} g_1(x^v) \\ g_2(x^v) \end{bmatrix}, \quad J_g(x) = \begin{bmatrix} 10.0V_2 \cos \delta_2 & 10.0 \sin \delta_2 \\ 10.0V_2 \sin \delta_2 & 20.0V_2 - 10.0 \cos \delta_2 \end{bmatrix}$$

The quadratized power flow problem for this system is defined with the following equations:

$$\begin{aligned} -j10.0(\tilde{V}_2 - 1.0) + (1 + u_1)(0.85 - j0.36)\tilde{V}_2 &= 0.0 \\ 0.85u_2 + 0.85u_1u_2 - 0.85 &= 0.0 \\ u_2 - V_2^2 &= 0.0 \end{aligned} \quad (4.27)$$

Note that the first equation is complex while the second and third are real. Upon expressing the complex voltage for bus 2 with its Cartesian coordinates and conversion of the complex equation into two real equations yields:

$$\begin{aligned} G_1(y) &= -6.36V_{2r} + 0.85V_{2i} - 0.36V_{2r}u_1 + 0.85V_{2i}u_1 + 6.0 = 0.0 \\ G_2(y) &= 0.85V_{2r} + 6.36V_{2i} + 0.85V_{2r}u_1 + 0.36V_{2i}u_1 = 0.0 \\ G_3(y) &= 0.85u_2 + 0.85u_1u_2 - 0.85 = 0.0 \\ G_4(y) &= u_2 - V_{2r}^2 - V_{2i}^2 = 0.0 \end{aligned} \quad (4.28)$$

Note that the above equations are quadratic and include four unknowns. The iterative solution algorithm is:

$$y^{v+1} = y^v - J_G^{-1}(y^v)G(y^v) \quad (4.29)$$

where:

$$y = \begin{bmatrix} V_{2r} \\ V_{2i} \\ u_1 \\ u_2 \end{bmatrix}, \quad G(y^v) = \begin{bmatrix} G_1(y) \\ G_2(y) \\ G_3(y) \\ G_4(y) \end{bmatrix},$$

$$J_G(y) = \begin{bmatrix} -6.36 - 0.36u_1 & 0.85 + 0.85u_1 & -0.36V_{2r} + 0.85V_{2i} & 0 \\ 0.85 + 0.85u_1 & 6.36 + 0.36u_1 & 0.85V_{2r} + 0.36V_{2i} & 0 \\ 0 & 0 & 0.85u_2 & 0.85 + 0.85u_1 \\ -2V_{2r} & -2V_{2i} & 0 & 1.0 \end{bmatrix}$$

The iterations for both methods start from the same initial guess: $\tilde{V}_2 = 1.0e^{j0}$. The first three iterations of the algorithm are summarized in Table E6.1. To minimize the data, the table reports the solution at each iteration as well as the following norm:

$$\|g\| = \sqrt{\frac{1}{N} \sum_i g_i^2(x)}$$

Iteration	Newton-Rapston		Quadratized Power Flow	
	V	$\ g\ $	V	$\ g\ $
0	$1.0e^{j0^0}$	0.6525	$1.0e^{j0^0}$	0.4615
1	$0.964e^{-j4.870^0}$	0.4049×10^{-1}	$0.95894e^{-j5.129^0}$	0.7367×10^{-2}
2	$0.95854e^{-j5.086^0}$	0.2879×10^{-3}	$0.95850e^{-j5.088^0}$	0.5816×10^{-5}
3	$0.95850e^{-j5.088^0}$	0.15×10^{-7}	$0.95850e^{-j5.088^0}$	0.7997×10^{-11}

It is important to observe in this example that the convergence characteristics of the quadratized power flow are superior to those of the traditional power flow method. Specifically, the norm of mismatches of the quadratized power flow is consistently lower than that of the traditional method. For example, at the second iteration, the norm of mismatches of the quadratized power flow is two orders of magnitude lower than that of the traditional method. The quadratized power flow formulation appears to be more complicated than the usual formulation in terms of the polar form of voltages. However, the advantage of the quadratized power flow formulation is the improved convergence

characteristics that lead to an overall algorithm that is more efficient than the traditional formulation. This property carries to large scale systems.

5. Advanced Contingency Selection

5.1 Security Assessment

Security assessment is defined as the real time analysis procedures by which the security of the system is measured (assessed). Security assessment procedures are classified into steady state and dynamic depending on whether the transients following the disturbance are neglected or not. Most of transmission line and transformer outages cause a rather fast rerouting of power flow in such a way that the transients following the disturbance are not of great consequence. The same is true for generating unit outages when the unit is small compared to the system or operating at low power points prior to the event. These cases represent the majority of outage events. Cases of major generation unit outages or major tie lines may cause transients with major effects on security. In this case, the transients must be studied and their effect on security must be assessed. This process is called dynamic security assessment.

In general, considering the power system as a nonlinear dynamic system, we can say that the steady state security assessment should evaluate if after a contingency (or a number of contingencies) occurs there will be a new equilibrium state for the post-contingency system and how secure this state is. The dynamic security assessment will, in addition to that, also show if there will in fact be a transient trajectory in the state space from the original pre-contingency equilibrium point to the post-contingency equilibrium point (thus, if the system will actually reach that equilibrium point) and what will be the security level of the system during this transition. It is therefore possible, for some severe disturbances, that even if a post-contingency equilibrium point exists the system may not be able to reach it, because there is no transient path from the one equilibrium to the other one. Or the final equilibrium state may be reached and may be a secure state, however, some of the transient states the system went through during the transition may have not been acceptably secure. This can only be investigated using transient analysis. However, in this report we are interested only in steady state or static security assessment. The purpose of this part of the project is simply to use security assessment techniques for contingency screening and ranking (not analysis) in order to reduce the size of the space of system states, to the few ones that worth to be further analyzed from the system reliability point of view. Dynamic security assessment is therefore beyond the scope of this report.

Steady state security assessment, i.e. assessment of the effects of equipment outages on system security, requires the analysis of the post-contingency steady state conditions. In other words, steady state security assessment involves the analysis of the steady state post-contingency conditions for any foreseeable and probable outage. Since the number of such contingencies may be extremely large for practical systems, the basic problems in static security assessment are: (a) identification of contingencies which may cause system problems or adversely affect security (contingency selection) and (b) techniques for

contingency simulation to assess the effects of the contingency. These problems will be discussed next.

5.2 Contingency Ranking/Selection

Contingency analysis is necessary to determine the level of security and/or reliability of a given system following a disturbance (contingency). Because of the large number of possible contingencies, this analysis can be extremely costly from the computational point of view. Fortunately for practical power systems, only a small number of contingencies are potentially critical to system security and/or reliability. If these contingencies can be identified, then only these contingencies should be analyzed to determine their effect. The problem of identifying the critical contingencies is known as contingency ranking. That is, contingencies are ranked in terms of their severity

Contingency ranking methods can be divided into two categories: Performance index (PI) methods and screening methods based on approximate power flow solutions. In the first case, the contingency ranking is facilitated by the use of performance indices which provide a measure of system 'normality'. These methods are computationally simple and efficient, however, they are prone to misranking. On the other hand the methods based on approximate power flow solutions are in generally less efficient and require more computation; their accuracy depends on the level of approximation used. In this study we are interested only in PI methods and we use them to evaluate the system state after certain disturbances, therefore, estimate the severity of each disturbance. The more sever disturbances are to be further analyzed using reliability analysis methods.

Several different performance indices can be defined and used, depending on then network quantities that are considered more important for the specific study. Some of the most commonly used indices are listed below:

- **Current Based Loading Index:**

$$J_C = \sum_j w_j \left(\frac{I_j}{I_{N,j}} \right)^{2n}$$

I_j : current magnitude in circuit j

$I_{N,j}$: current rating of circuit j

w_j : appropriate circuit weight, $0 < w_j \leq 1$

n : integer parameter defining the exponent

- **Apparent Power Flow Based Loading Index:**

$$J_T = \sum_j w_j \left(\frac{T_j}{T_{N,j}} \right)^{2n}$$

T_j : apparent power flow in circuit j

- $T_{N,j}$: apparent power flow rating of circuit j
- w_j : appropriate circuit weight, $0 < w_j \leq 1$
- n : integer parameter defining the exponent

• **Active Power Flow Based Loading Index:**

$$J_P = \sum_j w_j \left(\frac{P_j}{P_{N,j}} \right)^{2n}$$

- P_j : active power flow in circuit j
- $P_{N,j}$: current rating of circuit j
- w_j : appropriate circuit weight, $0 < w_j \leq 1$
- n : integer parameter defining the exponent

• **Voltage Index:**

$$J_V = \sum_k w_k \left(\frac{V_k - V_{k,mean}}{V_{k,step}} \right)^{2n}$$

- V_k : voltage magnitude at bus k
- $V_{k,mean}$: nominal voltage value (typically 1.0 p.u.)

It is in general the mean value in the desired range, i.e. $\frac{1}{2}(V_k^{\max} + V_k^{\min})$

$V_{k,step}$: voltage deviation tolerance (i.e. $\frac{1}{2}(V_k^{\max} - V_k^{\min})$)

- w_k : appropriate bus weight $0 < w_k \leq 1$
- n : integer parameter defining the exponent

• **Generation Reactive Power Index:**

$$J_Q = \sum_{j=1}^L w_j \left(\frac{Q_j - Q_{j,mean}}{Q_{j,step}} \right)^{2n}$$

w_j : real number representing generator weight $0 < w_j \leq 1$

$Q_{j,mean}$: real number representing the expected generated reactive power value

This is the mean value is the allowable range for each generator, i.e.,

$$\frac{1}{2}(Q_j^{\max} + Q_j^{\min})$$

$Q_{j,step}$: reactive power deviation tolerance

This is half of the allowable range, i.e., $\frac{1}{2}(Q_j^{\max} - Q_j^{\min})$

Q_j : reactive power generated by unit j

n : integer parameter defining the exponent

Note that the quantities inside the parenthesis express normalized circuit power flow, circuit current, voltage magnitude and generator reactive power respectively. The normalization is with respect to equipment capability or allowable limits. Thus, values of the quantities in the parenthesis in the range (-1.0 to 1.0) indicate normal operation while values outside this range indicate abnormal operation. When these quantities are raised to the $2n$ power, they will produce a large number for abnormal conditions and a very small number for normal conditions. Specifically, large values of the performance indices J_C , J_T , J_P indicate that one or more circuits are overloaded. Similarly, large values of the performance index J_V indicate that one or more voltage magnitudes are outside the permissible range for voltage magnitude. Large values of the performance index J_Q indicate that one or more generating unit produces reactive power outside its limits. A contingency will cause a change in system operating conditions which will be accompanied by a change in the performance indices J_C , J_T , J_P or J_Q .

The security indices provide a quantitative way to access the security of the system. Contingencies that may impact system security can be recognized by the change of the performance indices. Thus in order to rank contingencies on the basis of their impact on security, we can use the changes in the performance indices due to the contingency. In general, the exact change of the performance indices J_C , J_T , J_P or J_Q due to a contingency can be computed by first obtaining the system post contingency solution (power flow solution) and then computing the performance index by direct substitution. This procedure is computationally demanding and negates the objectives of a contingency ranking algorithm. Specifically, the objective of contingency ranking is to compute the approximate change of the security indices due to a set of postulated contingencies with a highly efficient computational method. Such methods were introduced in the late 70s.

In this work the Quadratized Power Flow (QPF) model has been applied towards the development of a contingency selection method using as metric performance indices. It is well known that performance index approaches lead to misrankings because of the nonlinearities of the model involved. The idea here is to use the quadratized power flow model that is expected to have milder nonlinearities and therefore should performed better. This is indeed the case. In addition, the quadratized power flow model is better suited to use current based ratings of circuits as opposed to power based ratings of circuits. It is pointed out that most capacity limitations of circuits are thermal limitations, i.e. electric current limitations. Thus using current limits, results in a more realistic approach.

The described approach has been applied to contingency selection using a variety of performance indices, circuit current index, voltage index, reactive power index, etc. In this report we present the methodology of the new method for some of these performance indices.

The contingency selection is based on the computation of the performance index change due to a contingency and subsequent ranking of the contingencies on the basis of the change. Mathematically one can view the outage of a circuit as a reduction of the admittance of the circuit to zero. We introduce a new control variable, the outage control variable, u_c , as illustrated in Figure 5.1. Note that the contingency control variable, u_c , has the following property:

$$u_c = \begin{cases} 1.0, & \text{if the component is in operation} \\ 0.0, & \text{if the component is outaged} \end{cases}$$

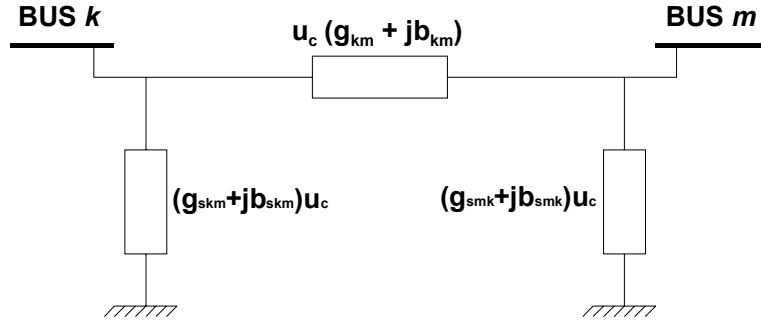


Figure 5.1. Definition of the outage control variable u_c .

The current flow in the circuit km is now a function of the contingency control variable, u_c .

$$I_{kmr} = [(g_{km} + g_{skm})V_{kr} - (b_{km} + b_{skm})V_{ki} - g_{km}V_{mr} + b_{km}V_{mi}] \cdot u_c = I_{kmr}^0 \cdot u_c$$

$$I_{kmi} = [(b_{km} + b_{skm})V_{kr} + (g_{km} + g_{skm})V_{ki} - b_{km}V_{mr} - g_{km}V_{mi}] \cdot u_c = I_{kmi}^0 \cdot u_c$$

where

V_{kr} is the real part of the voltage at bus k ,

V_{ki} is the imaginary part of the voltage at bus k .

V_{mr} is the real part of the voltage at bus m ,

V_{mi} is the imaginary part of the voltage at bus m .

and

I_{kmr}^0 is the real part of the base case current value from bus k to bus m .

I_{kmi}^0 is the imaginary part of the base case current value from bus k to bus m .

Similarly, consider the outage of a generating unit. Following the outage, the system will experience a generation deficiency which will result in frequency decrease. The outage will be also followed by transient. At the same time, the output of other generators will increase accordingly to their inertia initially. The net interchange (power import export) will also change. In the post contingency steady state the output of the remaining units will be increased by the action of the AGC and the net interchange will return to its scheduled value. The change of the remaining generating unit outputs at the steady state is determined by economic factors. In other words, the lost generation will be made up by increasing the output of the remaining generators according to their economic participation factors. This is shown in Figure 5.2. Specifically, considering the outage of unit i , we introduce again a contingency control variable u_c which is defined as follows:

$$P_{gi} = u_c P_{gi}^0$$

where

P_{gi}^0 is the precontingency output of the generating unit i

P_{gi} is the generating unit i output

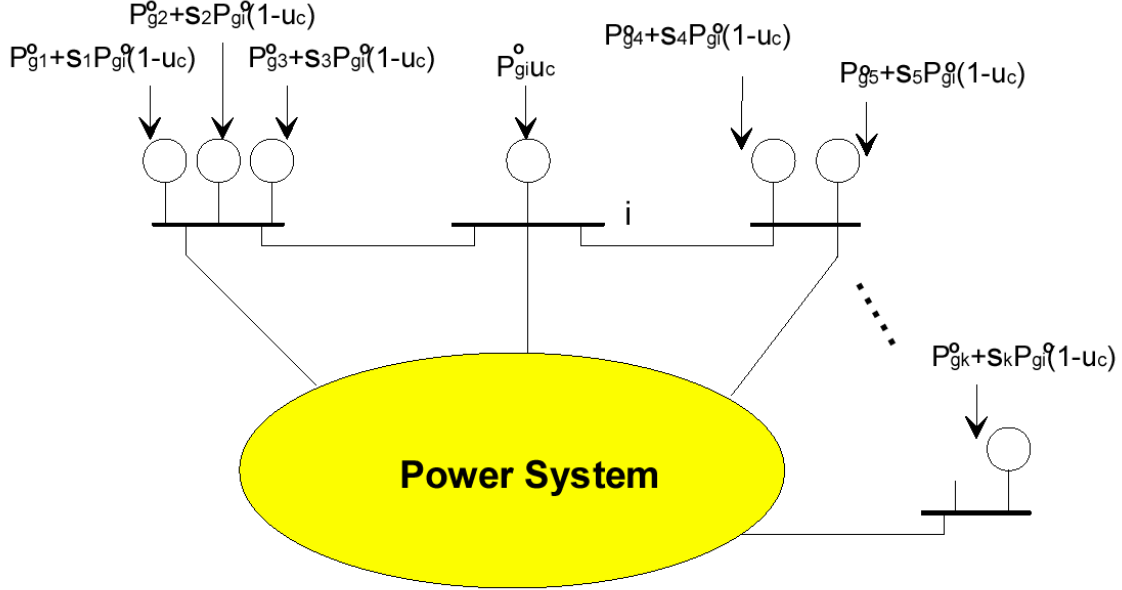


Figure 5.2. Illustration of a Unit Outage Model with the Contingency Control Variable u_c

Note again that

$$u_c = \begin{cases} 1.0, & \text{if the unit is in operation} \\ 0.0, & \text{if the unit is outaged} \end{cases}$$

The generation deficiency P_{gi}^0 caused by the outage of this unit is absorbed by the other units. Consider the generating unit j . The output of this unit will be controlled by the automatic generation control loop to the value:

$$P_{gj} = P_{gj}^0 + (1 - u_c) \sigma_j P_{gi}^0$$

where σ_j is the unit economic participation factor. Note again that the generating unit outputs are expressed as a function of the contingency control variable.

In summary, any circuit or generating unit outage can be modeled with a control variable, the contingency control variable. Using these control variables, the power flow equations can be written as a function of the control variables. Specifically, the quadratic power flow equations are written in the usual compact form:

$$G(x, u) = 0.0$$

where u is a vector of all contingency control variables. The contingency control variable, u_c , completely defines a contingency. $u_c = 1$ defines the precontingency system and $u_c = 0$ defines the postcontingency system. The security indices are in general complicated functions of the contingency control variables. Let J be anyone of the performance indices discussed earlier. Linearization of the performance index around the precontingency condition ($u_c = 1$) yields:

$$J(u_c) \cong J(u_c = 1) + \frac{dJ}{du_c}(u_c - 1.0)$$

The first order change of the security index ΔJ due to a contingency is given by:

$$\Delta J = J(u_c = 0) - J(u_c = 1) = -\frac{dJ}{du_c}$$

The above equation provides the basis of contingency ranking algorithms: The first order approximation of the effect of a contingency on security indices is determined by the derivative of the security index with respect to the contingency control variable.

Thus, the central computational problem in contingency ranking is the computation of the sensitivities $\frac{dJ}{du_c}$. For this purpose, observe that, in general, the performance index is a function of the system state, x , and the contingency control variables u .

$$J = f(x, u)$$

On the other hand, the state of the system must obey the power flow equations:

$$G(x, u) = 0$$

The costate method (previously developed by the authors) is applied to perform sensitivity analysis of the system state with respect to the control variable:

$$\frac{dJ}{du_c} = \frac{df}{du_c} = \frac{\partial J}{\partial u_c} - \dot{\lambda}^T \left[\frac{\partial G(x, u)}{\partial u_c} \right]$$

where

$$\dot{\lambda}^T = - \left[\frac{\partial J(x, u)}{\partial x} \right] \left[\frac{\partial G(x, u)}{\partial x} \right]^{-1} \text{ is the costate vector.}$$

Note that the costate is precomputed at the present operating condition and remains invariant for all contingencies. Thus for each contingency we have to only compute the partial derivatives of the power flow equation $G(x, u)$ with respect to the contingency control variable. This vector has only few nonzero entries and therefore the computations are extremely fast.

5.3 Improvements in Performance Index Contingency Ranking Methods

Performance index contingency ranking methods are very efficient and fast, however, they are susceptible to misrankings, mainly due to the highly nonlinear nature of the power flow equations. In this report, besides from transforming the power flow problem using the QPF formulation, several techniques are investigated to achieve less misranking.

In order to reduce the error introduced by the approximation in PI method, one approach is to include higher order terms to reduce the error. Another method is to do the proper control variable transformation such that the resulting $J - u$ curve has less nonlinearity. Both methods based on the quadratic power flow model are described below:

(1) QPF Sensitivity Method [14,16]

The described approach has been applied to contingency selection using a variety of performance indices, circuit current index, voltage index, reactive power index, etc. In this report we present the methodology and comparison of the new method for one of these performance indices.

In this method, instead of linearizing the performance indices directly, the system states of the QPF model are linearized with respect to the control variable, the performance index J is then calculated as following:

$$J = J(x^0 + \frac{dx}{du}(u - 1), u)$$

where

- x^0 : present operating condition
- x : system state of the QPF problem
- u : control variable

The utilization of the linearized system states in calculating the system performance index provides the higher order terms in Taylor's series. The unique potential of this method has been proven in the simulation of an example power system given in [14]. Three indices, the quasi-linearized indices by the QPF sensitivity method, the linearized indices based on TPF, and the original index, have been computed and compared. The QPF sensitivity method provides the traces of indices with curvature, which can follow the highly nonlinear variations of the original indices to some extent. While the TPF method provides only the straight line. Therefore, the QPF higher order sensitivity method is superior to the PI method based on TPF.

The contingency selection is based on the computation of the performance index change due to a contingency and subsequent ranking of the contingencies on the basis of the change. Mathematically one can view the outage of a circuit as a reduction of the admittance of the circuit to zero. We use again the outage control variable, u_c , as illustrated in Figures 5.1 and 5.2.

Consider the performance index, J . The change of the performance index due to the contingency is:

$$\Delta J = J\left(x^0 + \frac{dx}{du_c}(u_c - 1), u_c\right) - J(x^0, u_c = 1.0),$$

where x^0 is the present operating condition. The sensitivity of the state with respect to the control variable can be easily computed as:

$$\frac{dx}{du_c} = -\left[\frac{\partial G(x, u)}{\partial x}\right]^{-1} \left[\frac{\partial G(x, u)}{\partial u_c}\right]$$

Note that $\frac{\partial G(x, u)}{\partial x}$ is the Jacobian of the system and therefore it is precomputed at the present operating condition and remains invariant for all contingencies. Thus for each contingency we have to only compute the partial derivatives of the power flow equation $G(x, u)$ with respect to the contingency control variable. This vector has only few nonzero entries and therefore the computations are extremely fast. It should also be noted that $\frac{dx}{du_c}$ is a vector of the same size as the state vector each element of which is the derivative of the corresponding state with respect to the control variable. Once the new state is computed via this linear approximation, the calculation of the new value of the performance index is a straightforward operation.

The method has been applied to a small power system and compared to the traditional contingency selection algorithms (based on the traditional power flow formulation). The results for both methods are shown in Tables 1 and 2. Note that the proposed method predicts much better the changes of the performance index due to the outage (Table 1). Note also that the proposed method provides the correct ranking of the outages, as compared to the traditional method which results in severe misrankings for this system (Table 2).

Table 1. Performance Index Change Computed Directly, with the Traditional Method and with the Proposed Method

Contingency	Before Contingency	After Contingency					
	Original Index	Original Index		Linearized Index (TPF)		Linearized Index (QPF)	
		Value	Change	Value	Change	Value	Change
u_{12}	0.30392	0.30395	0.00003	0.30394	0.00002	0.30394	0.00002
u_{13}	0.3039	5.6357	5.3318	0.1917	-0.1122	0.5403	0.2364
u_{14}	0.3039	4.9665	4.6626	0.4910	0.1871	0.9684	0.6645
u_{24}	0.3039	2.7788	2.4749	0.3046	0.0007	0.3284	0.0245
u_{34}	0.3039	0.2921	-0.0118	0.2977	-0.0062	0.2994	-0.0045

Table 2. Ranking Results

Contingency	Ranking				
	u_{c12}	u_{c13}	u_{c14}	u_{c24}	u_{c34}
Original Index	4	1	2	3	Improved
Linearized Index (Pbase)	2	improved	1	Improved	Improved
Linearized Index (TPF)	3	improved	1	2	Improved
Linearized Index (QPF)	4	2	1	3	Improved

(2) Reducing the nonlinearity of the variations of performance indices

In the formulation of QPF model, the control variable transformation is introduced to reduce the nonlinearity of the changes of performance indices. As shown in Figure 5.3, the curve, which represents the relation between the performance index and the control variable, is generally nonlinear due to the inherent nonlinearity of power systems. If proper control variable transformation is applied, such that the curve of the performance index via the new control variable is more close to a straight line, then the prediction of post-contingency performance index based on the new curve can provide more accurate information by the linearized model. The proper control variable transformation is still being investigated. Several transformation means have been tried in reference [27,28].

6. Remedial Actions

This section presents the methodology for remedial action computations using the quadratized power flow model.

Remedial actions (RAs) provide the means of correcting the abnormal conditions, such as alleviating circuit overloads, abnormal voltages, and etc. These abnormal conditions usually result from scheduled or random events, especially the system contingencies.

A list of system typical remedial actions is given in Table 6.1. The table provides an indication of the relative cost associated with each remedial action. According to the cost, the remedial actions can be divided into three hierarchical levels, i.e., low, moderate and high cost levels. From the viewpoint of power system economic operation, the low cost level remedial actions should be considered first in the case of abnormal conditions, if the available low cost remedial actions can not improve the situation to the required level, the moderate and even high cost remedial actions are then applied. Table 6.1 also provides comments on the complexity to achieve and the influence to equipments of each remedial action.

Remedial actions greatly affect reliability and to a lesser degree economics of the power system operation. Depending on the objectives of remedial actions, different mathematical problems can be defined to address the problem, i.e., objectives can be (a) minimum control action, (b) minimum deviation of economic operation, (c) maximization of system security, etc. These problems will be defined next.

Table 6.1 List of Possible Remedial Actions

	Remedial Action	Associate Cost	Comments on Complexity/Influence
1	Shunt Capacitor Switching	Low	Simple / Small
2	Shunt Reactor Switching	Low	Simple / Small
3	Phase Shifter Adjustment	Low	Moderate / Large
4	MVAR Generation Adjustment	Low	Moderate / Large
5	Generation Bus Voltage	Low	Moderate / Large
6	Transformer Taps	Low	Moderate / Large
7	FACTS Controls	Low	Complex / Large
8	Load Transfer	Low	Simple / Small
9	MW Generation Adjustments	Moderate	Moderate / Large
10	Area Interchange	High	Complex / Large
11	Interruptible Load	High	Simple / Small

12	Firm Load	High	Simple / Small
13	Critical Load	High	Simple / Small

6.1 Quadratized Remedial Action Models

The quadratized remedial action models are illustrated in this section in an effort to analyze the effect of remedial actions on the power system operation. The control variable u_i is integrated to each remedial action model to represent the availability and magnitude of these control actions.

1. Shunt Capacitor/Reactor Switching

Figure 6.1 shows a switched capacitor/reactor model that is connected at a bus k . The switched capacitor/reactor model is characterized with admittance $\tilde{y}_k$ and control variable u_1 .

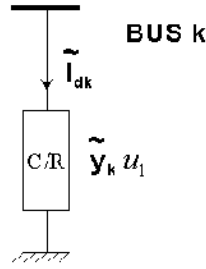


Figure 6.1 Shunt Capacitor or Reactor at Bus k

The control variable u_1 is defined as:

$$u_1 = \begin{cases} 1 & \text{capacitor / reactor is switched in} \\ 0 & \text{capacitor / reactor is switched out} \end{cases}$$

From Figure 6.1, we can extract the current flow equation:

$$\tilde{I}_{dk} = \tilde{y}_k u_1 \tilde{V}_k$$

The real and imaginary equations are given separately:

2. Phase Shifter Adjustment

Figure 6.2 illustrates a regulating transformer connected to buses k and m. The transformer model is characterized with series admittance $2\tilde{y}$, shunt admittance $\tilde{y}_s$, phase shift α and tap setting t. This model assumes that the tap is on the k bus side. The regulating transformer can regulate both voltage magnitude and phase. The control variable u_2 and u_3 are introduced to the transformer model to represent the two kinds of control actions separately.

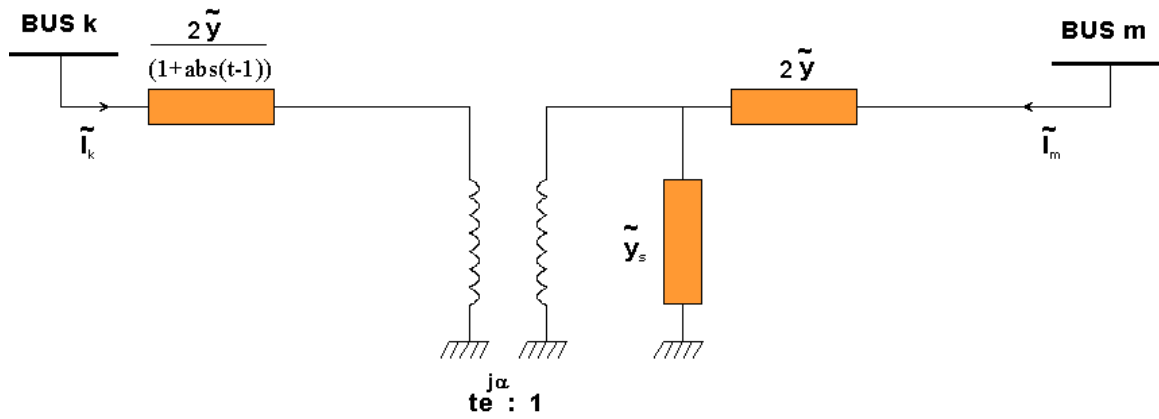


Figure 6.2 Regulating Transformer Model (Tap side = Bus k)

(1) Phase shift adjustment

Figure 6.3 illustrates a phase shifter connected to buses k and m. Two control variables u_{2r} and u_{2i} are defined to describe the phase shift control:

$$u_{2r} + ju_{2i} = e^{j\alpha}$$

where

$$u_{2r} = \cos \alpha$$

$$u_{2i} = \sin \alpha$$

The constraints for control variables u_{2r} and u_{2i} are given:

$$u_{2r}^2 + u_{2i}^2 = 1$$

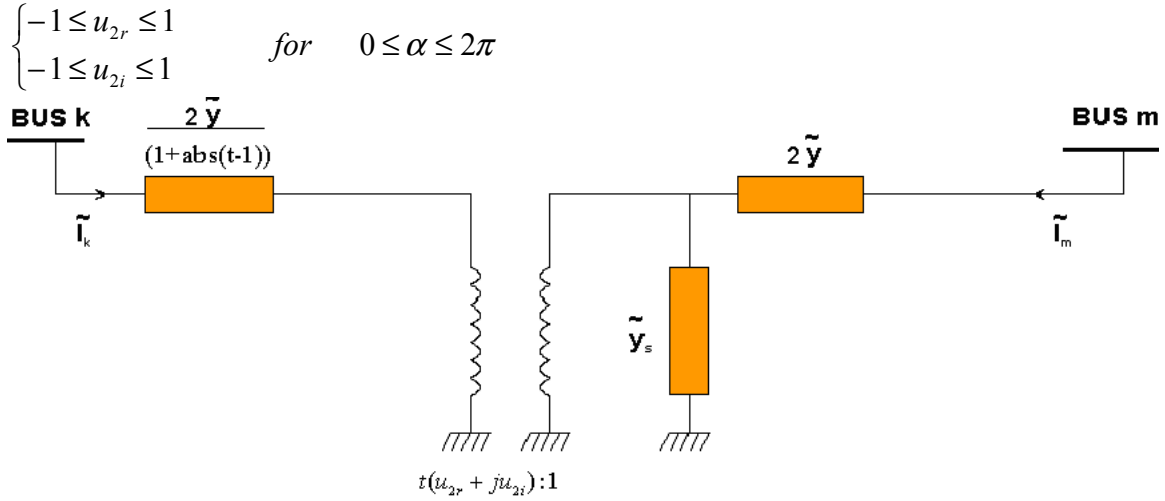


Figure 6.3 Regulating Transformer Model (Tap side = Bus k)

The current flow equations are:

$$\tilde{I}_k = 2\tilde{y}T_1(\tilde{V}_k - t(u_{2r} + ju_{2i})\tilde{E})$$

$$\tilde{I}_m = 2\tilde{y}(\tilde{V}_m - \tilde{E})$$

$$0 = (\tilde{y}_s + 2\tilde{y} + 2\tilde{y}T_1t^2)\tilde{E} - 2\tilde{y}T_1t(u_{2r} - ju_{2i})\tilde{V}_k - 2\tilde{y}\tilde{V}_m$$

where:

$$T_1 = \frac{1}{1 + \text{abs}(t-1)}$$

t is tap of the transformer.

The real and imaginary equations are given separately:

(2) Voltage magnitude adjustment

In the Figure 6.4, control variable u_3 is defined as follows to describe voltage magnitude control:

$$u_3 = t$$

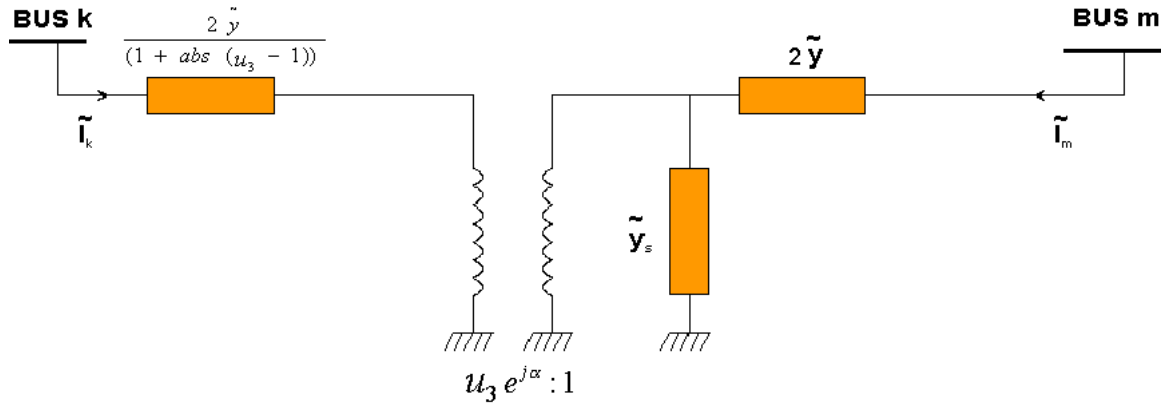


Figure 6.4 Regulating Transformer Model (Tap side = Bus k)

In this case the transformer tap varies to control the voltage at a point of the system to a specified value. The equations for this model are:

$$\begin{aligned}\tilde{I}_k &= 2\tilde{y}T_1(\tilde{V}_k - u_3 e^{j\alpha} \tilde{E}) \\ \tilde{I}_m &= 2\tilde{y}(\tilde{V}_m - \tilde{E}) \\ 0 &= (\tilde{y}_s + 2\tilde{y} + 2\tilde{y}T_1 u_3^2) \tilde{E} - 2\tilde{y}T_1 u_3 e^{-j\alpha} \tilde{V}_k - 2\tilde{y} \tilde{V}_m \\ 0 &= V_m - V_{m, given} \\ T_1 &= \frac{1}{1 + abs(u_3 - 1)}\end{aligned}$$

The real and imaginary equations are given separately:

3 Transformer tap adjustment

In the Figure 6.5, the regulating transformer simply regulates voltage magnitude. Control variable u_4 is defined to describe voltage magnitude control:

$$u_4 = t$$

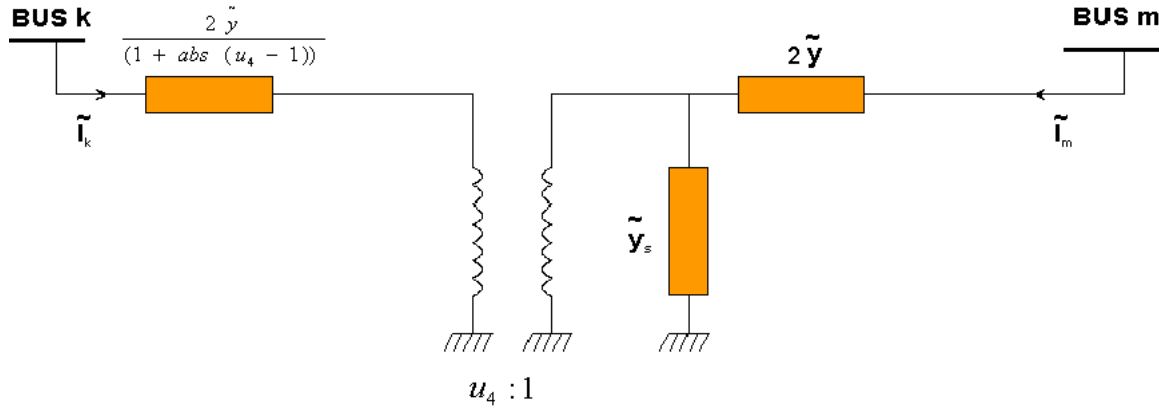


Figure 6.5 Regulating Transformer Model (Tap side = Bus k)

In this case the transformer tap varies to control the voltage at a point of the system to a specified value. The equations for this model are:

$$\tilde{I}_k = 2\tilde{y}T_1(\tilde{V}_k - u_4\tilde{E})$$

$$\tilde{I}_m = 2\tilde{y}(\tilde{V}_m - \tilde{E})$$

$$0 = (\tilde{y}_s + 2\tilde{y} + 2\tilde{y}T_1u_4^2)\tilde{E} - 2\tilde{y}T_1u_4\tilde{V}_k - 2\tilde{y}\tilde{V}_m$$

$$0 = V_m - V_{m,given}$$

where

$$T_1 = \frac{1}{1 + abs(u_4 - 1)}$$

The real and imaginary equations are given separately:

4 MVAR Generation / Bus Voltage Adjustments

Since bus voltage adjustment is very sensitive, usually it is achieved by the MVAR generation adjustment.

Figure 6.6 shows a generator connected at bus k . The generator is characterized with a current injection from the bus k to the generator, i.e. $\tilde{I}_k$. The total complex power generation is $P_k + jQ_k$.

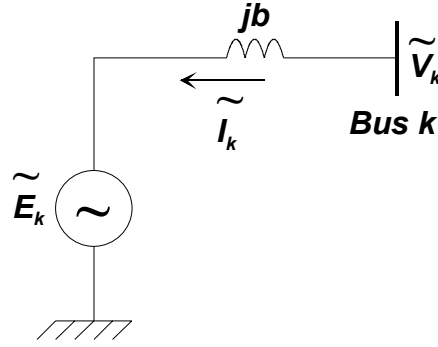


Figure 6.6 A Generator at Bus k

The current equation from bus k to the generator is:

$$\tilde{I}_k = jb(\tilde{V}_k - \tilde{E}_k)$$

There are three control modes for the synchronous generator, i.e., a) Slack mode, b) PQ mode, and c) PV mode. MVAR generation adjustment is related with the PQ mode:

PQ mode

In the PQ mode, the synchronous generator is controlled to maintain the specified real and reactive power. For the PQ mode, we have the following real and imaginary equations.

$$I_{kr} = -bV_{ki} + bE_{ki}$$

$$I_{ki} = bV_{kr} - bE_{kr}$$

$$0.0 = bV_{kr}E_{ki} - bV_{ki}E_{kr} + \frac{P_{k,specified}}{3}$$

$$0.0 = -bV_{kr}^2 + bV_{kr}E_{kr} - bV_{ki}^2 + bV_{ki}E_{ki} + \frac{Q_{k,specified}}{3}$$

Introducing the control variable u_5 to the MVAR generation adjustment, the above equations are modified as follows:

$$I_{kr} = -bV_{ki} + bE_{ki}$$

$$I_{ki} = bV_{kr} - bE_{kr}$$

$$0.0 = bV_{kr}E_{ki} - bV_{ki}E_{kr} + \frac{P_{k,specified}}{3}$$

$$0.0 = -bV_{kr}^2 + bV_{kr}E_{kr} - bV_{ki}^2 + bV_{ki}E_{ki} + \frac{Q_{k,specified} + u_5}{3}$$

The control variable u_5 is defined as:

$$u_5 = \begin{cases} 0 & \text{the remedial action is not available} \\ \text{others} & \text{the remedial action is available} \end{cases}$$

5 MW generation adjustments

For the three control modes for the synchronous generator, i.e., a) Slack mode, b) PQ mode, and c) PV mode. MW generation adjustment is related with both PV and PQ modes:

PQ mode

In the PQ mode, the synchronous generator is controlled to maintain the specified real and reactive power. For the PQ mode, we have the following real and imaginary equations.

$$I_{kr} = -bV_{ki} + bE_{ki}$$

$$I_{ki} = bV_{kr} - bE_{kr}$$

$$0.0 = bV_{kr}E_{ki} - bV_{ki}E_{kr} + \frac{P_{k,specified}}{3}$$

$$0.0 = -bV_{kr}^2 + bV_{kr}E_{kr} - bV_{ki}^2 + bV_{ki}E_{ki} + \frac{Q_{k,specified}}{3}$$

Introducing the control variable u_6 to the MW generation adjustment, the above equations are modified as follows:

$$I_{kr} = -bV_{ki} + bE_{ki}$$

$$I_{ki} = bV_{kr} - bE_{kr}$$

$$0.0 = bV_{kr}E_{ki} - bV_{ki}E_{kr} + \frac{P_{k,specified} + u_6}{3}$$

$$0.0 = -bV_{kr}^2 + bV_{kr}E_{kr} - bV_{ki}^2 + bV_{ki}E_{ki} + \frac{Q_{k,specified}}{3}$$

The control variable u_6 is defined as:

$$u_6 = \begin{cases} 0 & \text{the remedial action is not available} \\ \text{others} & \text{the remedial action is available} \end{cases}$$

PV mode

In the PV mode, the synchronous generator is controlled to maintain the specified real power and voltage magnitude. For the PV mode, we have the following real and imaginary equations.

$$\begin{aligned} I_{kr} &= -bV_{ki} + bE_{ki} \\ I_{ki} &= bV_{kr} - bE_{kr} \\ 0.0 &= bV_{kr}E_{ki} - bV_{ki}E_{kr} + \frac{P_{k,specified}}{3} \\ 0.0 &= V_{kr}^2 + V_{ki}^2 - V_{k,specified}^2 \end{aligned}$$

Introducing the control variable u_7 to the MW generation adjustment, the above equations are modified as follows:

$$\begin{aligned} I_{kr} &= -bV_{ki} + bE_{ki} \\ I_{ki} &= bV_{kr} - bE_{kr} \\ 0.0 &= bV_{kr}E_{ki} - bV_{ki}E_{kr} + \frac{P_{k,specified} + u_7}{3} \\ 0.0 &= V_{kr}^2 + V_{ki}^2 - V_{k,specified}^2 \end{aligned}$$

The control variable u_7 is defined as:

$$u_7 = \begin{cases} 0 & \text{the remedial action is not available} \\ \text{others} & \text{the remedial action is available} \end{cases}$$

6 Interruptible / Firm / Critical Load

We use the constant power load as an example to illustrate the remedial action model of shedding loads. Figure 6.7 shows the constant power interruptible, firm and critical loads, i.e., S_{dki} , S_{dkf} and S_{dkc} , that are connected at a bus k.

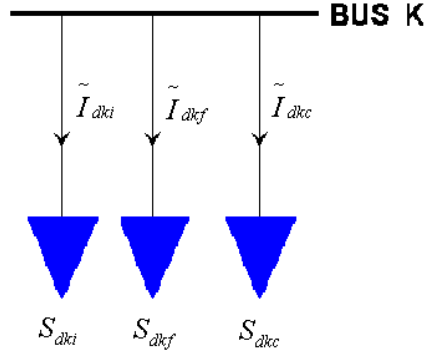


Figure 6.7 Constant Power critical Load at Bus k

Introducing the control variable u_8 , u_9 and u_{10} related to the interruptible, firm and critical Load model separately, the load at bus k is expressed as:

$$S_{dk} = u_8 S_{dki} + u_9 S_{dkf} + u_{10} S_{dkc}$$

The control variable u_8 , u_9 and u_{10} are defined as:

$$u_i = \begin{cases} 1 & \text{the remedial action is not available} \\ \text{others} & \text{the remedial action is available} \end{cases} \quad i = 8, 9, 10$$

7 Load Transfer

Figure 6.8 illustrates the load transfer. Originally the total load at bus m is P_{dm} and the total load at bus k is P_{dk} , if any disturbance occurs to bus m or feeder circuit m, some or all of P_{dm} can be transferred to bus k through the operation of circuit breaker CB1 and CB2. The control variable u_{11} is introduced to represent the transferred load. After load transfer, the load at bus m is $P_{dm} - u_{11}$ and the load at bus k is $P_{dk} + u_{11}$, where $-P_{dk} \leq u_{11} \leq P_{dm}$.

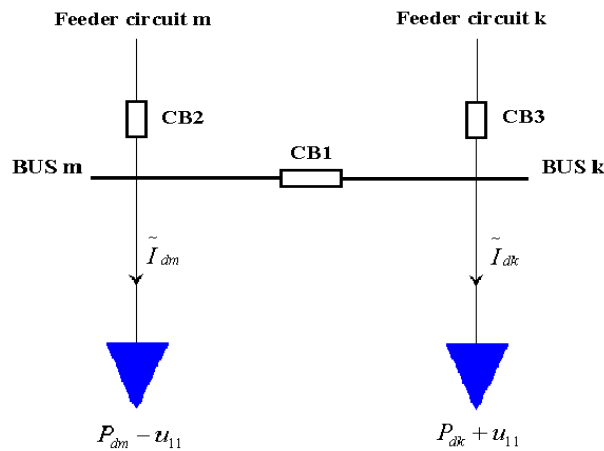


Figure 6.8 Load transfer

8 FACTS Controls

9 Area Interchange

6.2 Problem Formulation --- Nondivergent Optimal Power Flow Approach

Different mathematical problems can be formulated depending on various objectives of remedial actions. For example, if the minimum control action is the objective, an optimization problem is formulated as follow:

Objective function

$$\text{Min } f(x,u) = \sum_{i=1,8\sim 10} |u_i - 1| + \sum_{i=2\sim 4} |n_i(u_i - u_{i0})| + \sum_{i=5\sim 7,11} |n_i u_i| \quad (6.1)$$

Subject to

$$g(x,u) = 0 \quad (6.2)$$

$$h(x,u) \leq 0 \quad (6.3)$$

$$u_{i,\min} \leq u_i \leq u_{i,\max} \quad i = 1, \dots, 11 \quad (6.4)$$

where

$$u \text{ is the control variable vector and } u = \begin{bmatrix} u_1 \\ \vdots \\ u_{11} \end{bmatrix}$$

n_i is the normalization coefficient for the control variable u_i

u_{i0} is the original equipment setting before the remedial action i

Equ. 6.1 objective function which takes into account the magnitude of the remedial actions

Equ. 6.2 quadratized power flow equation of the power system

Equ. 6.3 operating constraints

Equ. 6.4 control variable constraints

If the minimum deviation of economic operation is the objective, an optimization problem is formulated as follow:

Objective function

$$\text{Min } f(x,u) = \sum_{i=1}^p c_i(u_i) \quad (6.5)$$

Subject to

$$g(x,u) = 0 \quad (6.6)$$

$$h(x,u) \leq 0 \quad (6.7)$$

$$u_{i,\min} \leq u_i \leq u_{i,\max} \quad i = 1, \dots, p \quad (6.8)$$

where

$$u \text{ is the control variable vector and } u = \begin{bmatrix} u_1 \\ \vdots \\ u_{11} \end{bmatrix}$$

p is the number of available control actions

Equ. 6.5 objective function which takes into account the operation costs of the remedial actions

Equ. 6.6 quadratized power flow equation of the power system

Equ. 6.7 operating constraints

Equ. 6.8 control variable constraints

In the following sections, the minimum deviation of economic operation is considered as the objective in the analysis.

Nondivergent Optimal Power Flow Approach

In this section, a special optimal power flow model, i.e., the nondivergent optimal power flow approach is utilized to solve the optimization problem formulated above, which combines the quadratized power flow model, remedial actions and optimal power flow algorithm in one unified approach. The new model also leads to a non-divergent power flow algorithm.

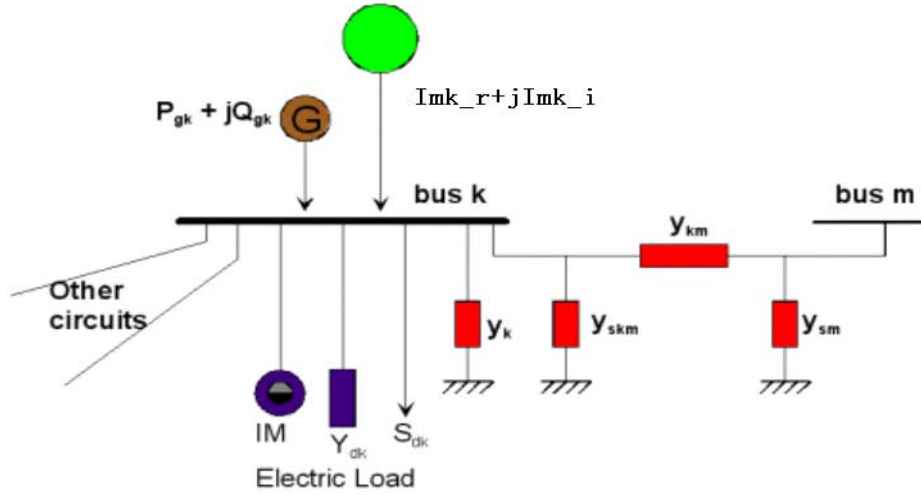


Figure 6.7 Illustration of a general bus I of an electric power system with a fictitious current source

Consider an electric power system comprising n buses. Let the state of the system be represented with the vector x (x contains bus voltage real and imaginary parts). Let the vector u represent the control variables of available remedial actions. Assuming a given operating state x^0 and settings of controls u^0 . Further, consider bus k as is illustrated in Figure 6.7. Unless x^0 and u^0 represent a power flow solution, there will be a current mismatch at bus i equal to $I_{mk_r}^0 + jI_{mk_i}^0$. Now place a fictitious current source at bus i , the output of it is $I_{mk_r}^0 + jI_{mk_i}^0$. In this case, x^0 and u^0 represent the present operating condition of the system. The actual operating condition of the system can be obtained by gradually reducing the output of the fictitious current sources at each bus to zero and computing the system variables x and u which will make the mismatch $dI_{mk_r} + jdI_{mk_i}$ equal to zero. This transition can be achieved along a trajectory which maintains feasibility and optimality with respect to a postulated objective. Mathematically, by modifying the objective function (6.5), this procedure is formulated as follows:

Objective function

$$\text{Min } f(x,u) = \sum_{i=1}^p c_i(u_i) + \mu \sum_k (|dI_{mk_r}| + |dI_{mk_i}|) \quad (6.9)$$

$$\text{Subject to } g(x,u) = 0 \quad (6.10)$$

$$h(x,u) \leq 0 \quad (6.11)$$

$$u_{i,\min} \leq u_i \leq u_{i,\max} \quad i = 1, \dots, p \quad (6.12)$$

where

u is the control variable vector and $u = \begin{bmatrix} u_1 \\ \vdots \\ u_{11} \end{bmatrix}$

p is the number of available control actions

Equ. 6.9 objective function which takes into account the operation costs of the remedial actions

Equ. 6.10 quadratized power flow equation of the power system

Equ. 6.11 operating constraints

Equ. 6.12 control variable constraints

The last term of the objective function is a penalty function weighted with μ , which tends to reduce the fictitious mismatches to zero, thus reaching feasibility.

The defined optimization problem is a large-scale problem. The size of this problem can be drastically reduced with simple transformations. That is, the incremental mismatch variables can be substituted with one control variable v as follow:

$$dI_{mk_r} = I_{mk_r}^0 v \quad k = 1, 2, \dots, n$$

$$dI_{mk_i} = I_{mk_i}^0 v \quad k = 1, 2, \dots, n$$

where the variable v represents the normalized change of the mismatch variables ($0 \leq v \leq 1$). This transformation replaces all the mismatch variables (a total of $2n$) with a single variable v . So the above formulation becomes:

Objective function

$$\text{Min } f(x, u) = \sum_{i=1}^p c_i(u_i) + \mu \sum_k (|I_{mk_r}^0| + |I_{mk_i}^0|)v \quad (6.13)$$

Subject to

$$g(x, u) = 0 \quad (6.14)$$

$$h(x, u) \leq 0 \quad (6.15)$$

$$u_{i,\min} \leq u_i \leq u_{i,\max} \quad i = 1, \dots, p \quad (6.16)$$

where

u is the control variable vector and $u = \begin{bmatrix} u_1 \\ \vdots \\ u_{11} \end{bmatrix}$

p is the number of available control actions

Under the initial condition, the variable v is 1. The decreasing step size of the variable v is controlled so that at each step, the number of failed operating constrains is relative small and appropriate remedial actions can be applied. In this way, a feasibility and optimality transition with respect to the objective function can be achieved until v finally reaches zero.

6.3 Solution Methodology

The solution methodology for the above problem involves mainly two steps: (1) linearizing objective function and operating constraints in each iteration, (2) solving the obtained linear programming model by LP algorithm.

1. Linearization of objection function and operating constraints

Linearization of the optimization problem requires the computation of sensitivities of the objection function and operating constraints with respect to the control variable u_i and v . A co-state method is applied in the sensitivity analysis. The computation of sensitivities is achieved by direct differentiation of the quantity of interest. The resulting general expression of the sensitivity of a quantity f with respect to a control variable u is

$$\frac{df}{du} = \frac{\partial f}{\partial u} - \hat{x}^T \frac{\partial g}{\partial u}$$

$$\hat{x}^T = \frac{\partial f}{\partial x} J^{-1}$$

where

f is the quantity of interest (objective function or operating constraints)

u is the control parameter of interest (u_i or v)

g represents the quadratized power flow equations

J Jacobian matrix of Equ. (6.18)

$\hat{x}^T$ is the co-state vector

Linearization of the quantity f with respect to the u involves the computation of $\frac{\partial f}{\partial u}$, $\frac{\partial g}{\partial u}$, and $\hat{x}^T$. The computation of $\frac{\partial f}{\partial u}$ and $\frac{\partial g}{\partial u}$ is straightforward. With respect to the computation of co-state vector $\hat{x}$, the Jacobian matrix J is a constant matrix that can be obtained from the last iteration step in solving quadratic power flow equation (6.18). $\frac{\partial f}{\partial x}$ is a constant vector at the nominal operating condition. Therefore, the co-state vector $\hat{x}^T = \frac{\partial f}{\partial x} J^{-1}$ is a constant vector that can be calculated using the result of power flow solution at nominal operating condition. Based on the above analysis, linearization procedure by the co-state method is efficient and only requires minor computation effort.

Using the co-state method, the objective function and operating constraints are linearized as follows:

Linearized objective function:

$$\text{Min } f(x, u) = f(x^0, u^0) + \sum_{i=1}^p a_i (u_i - u_i^0) + a_v (v - v^0) \quad (6.17)$$

where $a_i = \frac{df}{du_i}$, $i = 1, 2, \dots, p$ and $a_v = \frac{df}{dv}$ are sensitivity values of objective function to the variable u_i and v , which can be computed by the co-state method

Linearized operating constraints:

$$h(x^0, u^0) + \sum_{i=1}^p b_i (u_i - u_i^0) + b_v (v - v^0) \leq 0 \quad (6.18)$$

$$u_{i,\min} \leq u_i \leq u_{i,\max} \quad i = 1, \dots, p \quad (6.19)$$

where $b_i = \frac{dh}{du_i}$, $i = 1, 2, \dots, p$ and $b_v = \frac{dh}{dv}$ are sensitivity values of operating constraints to the variable u_i and v , which can be computed by the co-state method.

2. LP Solution

The above optimization problem is linearized with the use of co-state method. The procedure results in a large linear program in terms of the control variable u_i and v . The interior point method can be used to solve such problem [].

To increase efficiency, the size of the linear program is decreased (model reduction). The model reduction methodology developed is based on sensitivity information and does not affect the solution. A brief description of the method is as follows: based on the sensitivity values, the remedial action which is most effective to correct a failed constraint is identified. Next the remedial actions which have sensitivities below a predetermined cutoff value (typically 0.1 of maximum sensitivity) are flagged as ineffective to correct the failed constraints. The procedure is repeated for all failed constraints. Then the remedial actions which are ineffective for all failed constraints are eliminated from the model. It should be emphasized that the model reduction procedure does not affect the accuracy of the final result.

In summary, the problem formulation and linearization are listed below, and this procedure together with the LP algorithm is repeated in every iteration.

Problem formulation:

Objective function

$$\text{Min } f(x,u) = \sum_{i=1}^p c_i(u_i) + \mu \sum_k (|I_{mk_r}^0| + |I_{mk_i}^0|)v \quad (6.20)$$

Subject to

$$g(x,u) = 0 \quad (6.21)$$

$$h(x,u) \leq 0 \quad (6.22)$$

$$u_{i,\min} \leq u_i \leq u_{i,\max} \quad i = 1, \dots, p \quad (6.23)$$

where

$$u \text{ is the control variable vector and } u = \begin{bmatrix} u_1 \\ \vdots \\ u_{11} \end{bmatrix}$$

p is the number of available control actions

Linearization of the model:

Linearized objective function

$$\text{Min } f(x,u) = f(x^0, u^0) + \sum_{i=1}^p a_i(u_i - u_i^0) + a_v(v - v^0) \quad (6.24)$$

where

$$a_i = \frac{df}{du_i}, \quad i = 1, 2, \dots, p$$

$$a_v = \frac{df}{dv}$$

Linearized operating constraints

$$h(x^0, u^0) + \sum_{i=1}^p b_i (u_i - u_i^0) + b_v (v - v^0) \leq 0 \quad (6.25)$$

$$u_{i,\min} \leq u_i \leq u_{i,\max} \quad i = 1, \dots, p \quad (6.26)$$

where

$$b_i = \frac{dh}{du_i}, \quad i = 1, 2, \dots, p$$

$$b_v = \frac{dh}{dv}$$

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ANNUAL NSF GRANT PROGRESS REPORT

NSF Program: I/UCRC

NSF Award Number: EEC-0080012

PI Name: A. P. Meliopoulos

Period Covered By This Report: 9/01/03-Present

PI Institution: Georgia Institute of Technology Date: May 1, 2004

PI Address: School of ECE
Atlanta, GA 30345

☒ Check if Continued Funding is Requested

Please include the following information:

1. Brief summary of progress, including results obtained to date, and their relationship to the general goals of the grant;
2. A brief summary of work to be performed during the next year of support if changed from the original proposal; and indication of any current problems or favorable or unusual developments; and any other significant information pertinent to the type of project supported by NSF or as specified by the terms and conditions of the grant.
3. Statement of funds estimated to remain unobligated--if more than 20%--at the end of the period for which NSF currently is providing support;
4. Proposed budget for the ensuing year in the NSF format, only if the original award letter did not indicate specific incremental amounts or if adjustments to a planned increment exceeding the greater of 10% or \$10,000 are being requested;
5. Information about other current and pending research support of senior personnel, if changed from the previous submission;
6. A statement describing any contribution of the project to the area of education and human-resource development, if changed from any previous submission; and
7. Updated Information on animal care and use, Institutional Biohazard Committee and Human Subject Certification, if changed substantially from those originally proposed and approved.

Item #1: See attached sections 1-3

Item #2: See attached sections 1, 2 and 4

Item #3: There will be no funds unobligated by the end of the current funding period.

Item #4: Budget per original proposal

Item #5: Current/Pending support is per original proposal

Item #6 See attached section 6

Item #7: This project does not involve animal care, biohazards, or human subjects.

I certify that to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinions) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or individuals working under their supervision. I understand that the willful provision of false information or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001.)

PI Signature: *A. P. Meliopoulos*

A. Report on Goals and Accomplishments

Georgia Tech University has maintained full participation in all PSERC activities. A description of the research projects and accomplishments of the past period (June 2003 to present) follows.

1. *Areas of research*

Georgia Tech's activities share the PSERC vision to provide new or improved solutions to power industry problems arising from restructuring and technological changes as well as operational collapse such as the blackout 2003. Georgia Tech researchers participated or lead in the following PSERC research projects.

Current Markets Projects

- Modeling Market Signals for Transmission Adequacy Issues: Valuation of Transmission Facilities and Load Participation Contracts in Restructured Electric Power Systems
- Reliability Assessment Incorporating Operational Considerations and Economic Aspects for Large Interconnected Grids (approved for 2004)

Current T&D Projects

- Automated Integration of Condition Monitoring with an Optimized Maintenance Scheduler for Circuit Breakers and Power Transformers

Completed T&D Projects

- Personnel Grounding and Safety Issues / Solutions Related to Servicing Telecommunications Equipment Connected to Fiber Optic Cables in Optical Ground Wire (OPGW)
- Distribution System Electromagnetic Modeling and Design for Enhanced Power Quality (final report under review)

Current Systems Projects

- Enhanced State Estimators (approved for 2004)
- New Implications of Power System Fault Current Limits
- On-Line Transient Stability Assessment
- Visualization of Power Systems and Components

Completed Systems Projects

- Risk-Based Maintenance Allocation and Scheduling for Bulk Transmission System Equipment
- Comprehensive Power System Reliability Assessment (final report under review)

2. *Leveraged Research Projects*

Georgia Techg participated in research sponsored by the Consortium for Electric Reliability Technology Solutions (CERTS). This work is focused on the microgrid project and on the Eastern Interconnection Phasor project.

3. Major accomplishments

PSERC reports distributed in draft or final form in 2003:

- Risk-Based Maintenance Allocation and Scheduling for Bulk Transmission System Equipment, Jim McCalley (Project Leader), Tim Van Voorhis, A.P. Meliopoulos and Yong Jiang

Papers prepared by PSERC researchers and made available on the PSERC web site:

- Risk-Based Maintenance Allocation and Scheduling for Bulk Transmission System Equipment, Jim McCalley, Tim Van Voorhis, A.P. Meliopoulos and Yong Jiang

Industry/University Seminars given by PSERC researchers (most including web casts available on the PSERC web site):

- Valuation of Congestion Revenue Rights Based on Power Market Simulation Models; Shijie Deng, School of Industrial and Systems Engineering, Georgia Tech
- Role of GPS-Synchronized Measurements on Power Grid Visibility; A. P. Meliopoulos, Georgia Institute of Technology

Papers prepared by Georgia Tech PSERC researchers:

- Deok Young Kim and A. P. Sakis Meliopoulos, "Comparison of Small Signal Stability Analysis Methods in Complex Systems with Switching Elements", Proceedings of IFAC 2003, pp 1292-1296, Seoul, Korea, September 15-19, 2003.
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- A. P. Sakis Meliopoulos, George Cokkinides and Andras M. Dan, "Statistical Evaluation of Voltage Variations via Physically Based Modeling and Simulation", Proceedings of the NSF Caribbean Colloquium on Power Quality, Dorado, Puerto Rico, June 24-27, 2003.
- A. P. Sakis Meliopoulos, George J. Cokkinides, Haibin Sun, Shi-Jie Deng and George Contaxis, "Impact of Uncertainty on Flow-Gate and Financial Transmission Rights", Proceedings of the ISAP 2003, Lemnos, Greece, August 31-September 3, 2003.

4. Research goals

In addition to our primary goal of continuing a strong participation in all PSERC activities, we will continue to make contribution to the existing five major research projects that are funded or approved. Our goal is to expand our collaboration with PSERC universities as well as with universities in Europe. The collaborative efforts will result in higher quality of research.

5. Activities and Industrial Collaboration

The faculty and students at Georgia Tech participated in the following PSERC and PSERC related activities during the previous grant period:

- Participated in the PSERC IAB meetings in Pullman, WA (May 2003) and Scottsdale, AZ (December 2003), presenting project updates.
- Organized, attended and participated in the PSERC sessions at the 2003 Hawaii International Conference on System Sciences.
- Contributed to the IEEE Power Engineering Society 2003 General Meetings
- Participated in multi-university PSERC tele-seminar exchanges (presented two of them).
- Participated in PSERC industry/university collaboration meetings on PSERC research, education and management activities: Executive Management Retreat (San Antonio, February 2003) and Summer Research Planning Retreat (Lake Delton, WI, August 2003).

6. Contributions to Education and Human Resources

PSERC research results were utilized to develop several tools for animation and visualization of power system operations for specific use in the classroom. Specific developments are: (a) animation and visualization of protective relays and used it to enhance the instruction of the short course on power system relaying. (b) analysis and visualization tools for power quality utilized in the course ECE6340, "Electric Power Quality", and (c) visualization and animation of power system spot prices, FTRs and FGRs.