

Utility Experience Computing Physical and Operational Margins: Part I – Basic Concept and Evaluation

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Abstract—This paper deals with the application of the concept of physical and operational margins to analysis of power system behavior. The approach offers fast and accurate determination of bottlenecks in the transmission network and optimal mitigation measures to alleviate the identified violations. The technical foundation of the approach and its practical benefits are discussed. The approach has been evaluated by the EPRI Probabilistic Reliability Assessment (PRA) User-Group members. Upon the evaluation of the approach, a variety of studies was performed, including System Planning and Reliability Studies, System Operations Studies, and Ranking Transmission Projects. The studies are described in the companion paper, *Part II*. The paper represents the collective effort of the PRA User-Group.

Index Terms—Physical and operational margins, optimal mitigation measures, reliability, project ranking, PRA.

I. INTRODUCTION

MAINTAINING reliable operation of the power grid is a fundamental aspect of electric utility operation. The deregulation of the electric utility industry has posed additional challenges to the reliability of the electric grid.

Electric power reliability problems have led to major blackouts in recent years in North America. Though major blackouts are relatively rare, they have serious economic and social impact.

To address the challenge of maintaining power system reliability and improve reliability of transmission grid during industry restructuring, Electric Power Research Institute (EPRI) launched the Power Delivery Reliability Initiative in late 1999 [1].

This Initiative was undertaken on behalf of the U.S. electric power industry and at the request of energy companies, the North American Electric Reliability Council (NERC), the Association of Edison Illuminating Companies, the IEEE Power Engineering Society, the Edison Electric Institute (EEI), and other organizations. The Initiative has 47 members.

The Initiative was a multi-year program to understand the root causes of recent power outages, identify underlying problems in utility systems, and recommend ways to improve system reliability. The Initiative consisted of two programs: Transmission and Distribution.

The Transmission Program of the Reliability Initiative assessed reliability of the transmission grid and provided new tools to improve system reliability. The Probabilistic Reliability Assessment (PRA) software, developed by the Transmission Program, offers energy companies an accurate and fast tool for assessing grid reliability under restructured market conditions. The PRA software consists of two software programs: Physical and Operational Margins (POM) licensed by V&R Energy Systems Research, Inc. (V&R) to EPRI and qualified EPRI members; and Probabilistic

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Reliability Indices (PRI), owned by EPRI. The PRA software provides the user with the ability to identify bottlenecks in the grid, evaluate their impact, and recommend effective mitigation alternatives.

The PRA User-Group, which includes users of POM and PRI programs, was established in early 2002.

The present paper concentrates on the theoretical background and evaluation studies performed using the POM software.

II. BASIC CONCEPT

In this section, the basic concept of physical and operational margins is presented.

A. Power System Model

Each generator bus that regulates its own real power and voltage (**pv** bus) is described by:

$$P_i'(V_i) - \sum_{\substack{j=1 \\ j \neq i}}^N [(V_{Ri} V_{Rj} + V_{Ii} V_{Ij})G_{ij} - (V_{Ri} V_{Ij} - V_{Rj} V_{Ii})B_{ij}] = 0 \quad (1)$$

$$V_{Ri}^2 + V_{Ii}^2 = V_{Si}^2 \quad (2)$$

Equation (1) defines real power balance in the system. Equation (2) defines constant voltage magnitude at **pv** buses.

At the point when the generator's reactive power reaches the limit, the generator model is switched from constant voltage (2) to limited reactive power (3).

Each load bus (**pq** bus) is described by equations for real (1) and reactive power balance:

$$Q_i'(V_i) + \sum_{\substack{j=1 \\ j \neq i}}^N [(V_{Ri} V_{Rj} + V_{Ii} V_{Ij})B_{ij} + (V_{Ri} V_{Ij} - V_{Rj} V_{Ii})G_{ij}] = 0 \quad (3)$$

where:
$$P_i'(V_i) = P_i(V_i) - V_i^2(G_{0i} + \sum_{\substack{j=1 \\ j \neq i}}^N G_{ij}) \quad i = 1, \dots, N-1.$$

$$Q_i'(V_i) = Q_i(V_i) + V_i^2(B_{0i} + \sum_{\substack{j=1 \\ j \neq i}}^N B_{ij})$$

V_i = Voltage magnitude at bus i .

V_{Si} = Scheduled voltage setpoint at bus i .

V_{Ri}, V_{Ii} = Real and imaginary components of bus voltage.

$P_i(V_i)$ = Real power balance for generation and load at bus i .

$Q_i(V_i)$ = Reactive power balance for generation and load at bus i .

G_{ij}, B_{ij} = Real and imaginary components of non-diagonal elements of admittance matrix.

G_{0i}, B_{0i} = Real and imaginary components of admittance matrix diagonal element for bus i .

B. Power Flow Solution

Physical and Operational Margins (POM) software application incorporates a nonlinear power system model. The full Newton method is used to solve nonlinear power flow equations. The contingency screening technique uses full AC analysis.

Power flow

$$f(x) = 0 \quad (4)$$

is solved using the Newton method:

$$x_{k+1} = x_k - J^{-1}f(x_k) \quad (5)$$

where: k = Number of iterations.

x = Real and imaginary components of bus voltage.

x_k = k -th iteration of x ; x_{k+1} = $(k+1)$ -th iteration of x .

J = The Jacobian matrix; $J(x) = \frac{\partial f}{\partial x}$; $f(x_k)$ = bus mismatch.

The proposed methodology allows for the Jacobian matrix to change on each iteration of the Newton method. Changes to the Jacobian matrix depend on:

- whether or not the enforced limits are reached.
- operation of control devices.

To solve large systems of nonlinear equations, sparse technique is usually employed. A fast and effective sparse technique is incorporated that is based on the following:

- The Jacobian matrix is sparse due to the fact that each bus is connected only to a small number of adjacent buses.
- The inversion of the Jacobian matrix is used on each iteration of the Newton method.
- The inversion of the Jacobian matrix is based on the Gaussian elimination method.

Optimal renumbering is performed very fast every time the new power flow case is loaded. Optimal renumbering is also performed every time network topology is changed. When working with same power flow case, optimal renumbering is not required.

C. Computation of Physical and Operational Margins

The methodology used for contingency screening has the capability to simultaneously monitor three constraints: voltage stability, voltage range/drop, and thermal [2].

The concept of physical and operational margins consists of a physical margin and an operational margin. Operational margin is a voltage stability margin. Physical margin incorporates voltage and thermal limits.

Physical and operational margins are defined as:

$$POM = \frac{Param_{max} - Param}{Param_{max}} \quad (6)$$

where:

$Param$ = The value of scaling parameter at the current operating condition.

$Param_{max}$ = The limit value of scaling parameter.

For example, if scaling parameter is real load:

$Param = P$ = The value of load at the current operating condition.

$Param_{max} = P_{max}$ = The value of load at the operating limit.

Various power system parameters, such as load at a bus, total load at a set of buses, generation at a bus or a set of buses, the value of power transfer may be considered as a parameter. The proposed methodology allows the user to

determine physical and operational margins while applying contingencies. Such margins are an important characteristic of each contingency.

D. Monitoring Constraints

Methodology incorporated in POM has the capability to simultaneously monitor three constraints:

1. Voltage stability.
2. Thermal overload of lines and transformers, and flowgate constraint.
3. Voltage violation (voltage range and/or pre-contingency to post-contingency voltage drop).

Voltage stability constraint is violated if power flow fails to converge within the specified number of iterations.

If power flow solution does not converge, POM is able to automatically adjust the number of iterations and the value of the acceleration factor. If power flow fails to converge after the adjustment, POM treats such non-convergence of power flow solution as voltage instability. This feature improves the convergence of the power flow equations.

POM also has the capability to build a set of PV, QV curves to estimate the proximity of the system to voltage collapse. To assess voltage stability, POM provides real and reactive margins at the critical buses (i.e., buses with low voltage level). For the purpose of voltage stability analysis the following computations may be performed for each contingency using PV, QV curves:

- Determine unstable operating conditions when the operating point is located on the lower part of the curve.
- Determine the margin (i.e., the distance between the nose point of the curve and the current operating point) and verify that it satisfies the reliability voltage stability criteria [3].
- Identify critical contingencies that result in the smallest margins.

Thermal violation occurs when the total power flow on a branch exceeds thermal limit:

$$S_{ij} > S_{ij}^{\max} \quad (7)$$

or if the current on a line exceeds the current limit

$$I_{ij} > I_{ij}^{\max} \quad (8)$$

Thermal constraint is monitored on each branch (or groups of branches) specified by the user.

Voltage range and/or pre-contingency to post-contingency voltage drop are considered as a voltage constraint.

If voltage at bus i falls below the specified low voltage limit or is above the specified high voltage limit, voltage level violation occurs:

$$V_i < V_i^{\min} \quad (9)$$

$$V_i > V_i^{\max} \quad (10)$$

If pre-contingency to post-contingency voltage drop at bus i exceeds the specified limit, voltage drop violation occurs:

$$\Delta V_i \geq \Delta V_i^{\max} \quad (11)$$

The voltage drop is entered in percentage of the pre-contingency value. Different voltage drop limits are allowed for N-1 and higher order contingencies.

Voltage constraint is monitored at each bus (or group of buses) specified by the user.

E. Methodology to Alleviate Violations

Methodology incorporated in POM determines bottlenecks in the system by identifying voltage, thermal and voltage stability violations in the power system network. Determining measures to alleviate these violations is the next step of analysis.

Methodology to alleviate thermal and voltage violations and mitigate voltage stability violations that are detected after a contingency is applied or a power system parameter is changed (for example, the load is scaled) has been incorporated as the basis of the Optimal Mitigation Measures (OPM) program.

OPM's fast and efficient solution algorithm provides the following solutions:

- Alleviates voltage and thermal violations.
- Alleviates voltage stability violations due to outages, load/generation scaling and power transfers.
- Provides diagnostics of stability violations.
- Performs optimal placement of capacitors.

The developed methodology provides diagnostics of stability violations and relieves these violations:

- Identifies causes of stability violations.
- Uses control devices to increase voltage stability margins after a contingency causing stability violation is applied.

The developed methodology incorporates the following mitigation measures:

- Capacitor and Reactor Switching
- Transformer Tap Change
- MW Dispatch
- MVAR Dispatch
- Line Switching (In and Out)
- Opening Not Affected (Non-Overloaded) Branches
- Optimal Capacitor Placement
- Load Curtailment
- Defined Operating Procedures

The solution algorithm works as follows:

1. Influence of each device employed for mitigation is computed based on the sensitivity analysis.
2. Devices which have the most influence on the identified violations are selected.
3. The objective function is the total amount of mitigation measures. Optimization procedures are used to minimize the total amount of mitigation measures while satisfying the monitored constraints.

Thus, the algorithm relieves thermal, voltage and voltage stability constraint violations while minimizing the amount of mitigation measures applied.

Any of the mitigation measures listed above may be combined based on the user-defined priority schedule. The

minimum number of devices that participate in each mitigation measure may be selected.

III. EVALUATING POM-OPM SOFTWARE

The concept of physical and operational margins is incorporated in the POM software application. The application has been evaluated by the PRA user-group members and implemented in their system studies. Results, observations and conclusions made by a number of member utilities are described in this paper.

A. Studies Performed during the EPRI Reliability Initiative

To improve reliability assessments, PRA methodology that calculates a measure of the probability of undesirable events and a measure of the severity or impact of the events was introduced. PRA methodology was demonstrated in three proof-of-concept studies in the Southern Control Area of the Southeastern Electric Reliability Council (SERC) [4], the American Electric Power (AEP) transmission system [5], and the Eastern Interconnection.

1) *Probabilistic Risk Assessment for the Southern Control Area in SERC*: The objectives of this study were:

- Develop a practical PRA methodology and apply it to the sizeable Southern Control Area of SERC.
- Demonstrate this methodology for identifying transmission bottlenecks.
- Demonstrate how to compute Relative Risk Measures that could be used for comparing the risks of various regions.

This effort was a collaboration between Southern Company Services (SCS) and EPRI. It used a new and powerful power flow and contingency analysis program developed by V&R, Physical and Operational Margins (POM).

During this study, POM results were compared against VSTAB and PSS/E for all 18 cases investigated in the study. The comparison of results was made by SCS. The comparison showed that the results of POM, VSTAB and PSS/E were very close while execution time for POM was significantly shorter.

SCS provided 18 loadflow cases representing different load levels and/or dispatch patterns. For each of the 18 cases under investigation, over 17500 N-1 and N-2 contingencies were applied to determine the list of critical contingencies. The security assessment simultaneously addressed voltage stability, voltage constraints, and thermal limits.

Critical contingencies (i.e., contingencies causing violation of monitored constraints) were identified for each case. Two types of violations were observed in the SCS control area: thermal overloads and voltage level violations. Then, a set of risk indices was computed for each case.

Fig. 1 displays zones with the worst voltage risk and zones with the worst overload risk. For each zone, there are two numbers displayed. For example, for voltage risk, the first index shows the number of buses that have post-contingency voltage limit violations. The second index shows the total

probability of the contingencies that result in a voltage limit violation in this zone. Thus, the first index tells us the severity of the risk, and the second index tells us the likelihood of encountering such an impact.

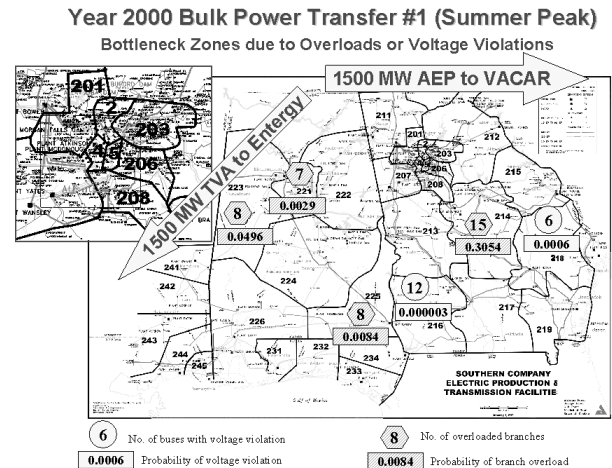


Fig. 1. Geographical Presentation of Bottlenecks and Risk Indices for the SERC Study of the Reliability Initiative

2) *Application of Probabilistic Reliability Assessment to a Part of the AEP System*: This was the second trial study conducted as a part of the Reliability Initiative.

The objectives of this second trial study were:

- Refine the PRA methodology and improve the PRI part.
- Demonstrate this methodology for identifying critical causes of reliability problems and the effect of mitigation alternatives.
- Apply this methodology to the AEP system to verify its practicality for the comprehensive study of the entire North American grid.

This effort was a collaboration between AEP and EPRI. It also used POM as a loadflow and contingency analysis program. PRI program was used to compute risk indices.

AEP supplied to V&R 9 power flow cases for this study. A set of 17 contingencies was selected by AEP. The reliability of the AEP study area has been tested according to the N-1 and N-2 combinations of these contingencies (about 150 examined situations). The security assessment simultaneously addresses voltage stability, voltage constraints, and thermal limits.

POM was used to determine a list of critical contingencies for each scenario and identify the bottlenecks.

Then, capacitors were added at a number of places where voltage violations occurred, and the base cases with capacitors were investigated. The effect of additional VAR compensation on alleviation of violations was analyzed.

For each load flow case investigated, the following computation results were obtained:

- Maximum power transfer from TVA to AEP
- Contingency analysis and bottlenecks
- Voltage limits

3) *Grid Reliability Study for Eastern Interconnection and ERCOT*: The objectives of this study [1] were to:

- Perform a reliability assessment study on an interconnection level.
- Demonstrate the use of PRA methodology to identify critical contingencies, represent probabilities of component failures, and identify mitigation measures.
- Verify the practical feasibility of applying this methodology to future regional studies.

During this study, two systems were investigated: Eastern Interconnection (EI) system and ERCOT system. The majority of the effort was dedicated to the EI study. The EI system studied consisted of more than 34000 buses and 42700 branches. During this study, over 700,000 contingencies were applied to the EI network. Seventeen scenarios were under investigation for EI system. For each of 17 scenarios under investigation for EI, N-1 and N-2 outages were simulated, and critical contingencies were ranked. For two of 17 scenarios, complex contingencies were also included in the contingency analysis. As a result, bottlenecks in the EI base case were identified. The effect of different transfer scenarios was analyzed, and bottlenecks appearing due to these transfers were also identified.

The ERCOT system studied consists of more than 4900 buses and 5800 branches. One case was investigated for the ERCOT system. As a result, bottlenecks were identified in the ERCOT grid.

The security assessment simultaneously addresses voltage stability, voltage constraints, and thermal limits.

The results of the study are available to the Reliability Initiative members.

B. Studies Performed by Member Utilities

1) Studies Performed by American Electric Power:

American Electric Power (AEP) is an electric utility that owns transmission and services customers in eleven states: Arkansas, Indiana, Kentucky, Louisiana, Michigan, Ohio, Oklahoma, Tennessee, Texas, Virginia, and West Virginia. AEP is one of the supporters for the EPRI Probabilistic Reliability Assessment (PRA) initiative, which includes V & R Energy's POM. AEP is evaluating POM to enhance the current analysis practices in both thermal and voltage analysis studies done by the East Bulk Transmission Planning department, which focuses on the AEP EHV transmission lines within ECAR. As part of the PRA process, AEP has used POM to determine critical contingencies for a thermal study done for the Canton, OH area. Based on the critical contingencies provided by POM, AEP investigated the possibilities of adding equipment in the area to alleviate the thermal concerns in the area.

AEP has also used POM in a voltage performance study in the central Ohio area. POM was used to provide PV curve analysis to investigate the effects of additional equipment in the area to reinforce the voltage in the central OH area. For example, Fig. 2 shows the voltage levels in the studied area before and after the improvements were implemented into the study case. Curve 1 represents the addition of 72 MVAR

shunt capacitor banks in the area, Curve 2 represents the voltage levels with the addition of a second 765/138 kV transformer at a 765 kV station and Curve 3 represents the voltage levels under extreme weather conditions without any area reinforcements in place. AEP is continuing its efforts to evaluate POM to enhance both probabilistic and deterministic techniques in its Transmission Planning Department.

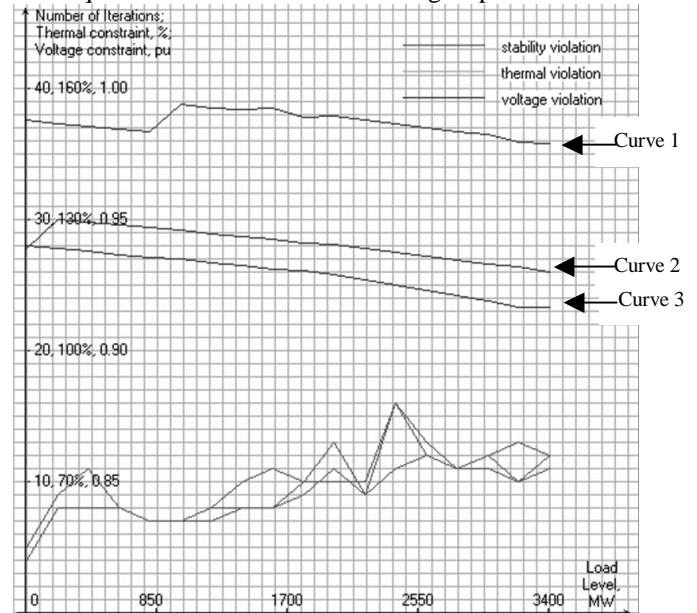


Fig. 2. AEP's POM Voltage Analysis

2) Studies Performed by Bonneville Power Administration:

One important measure of analytic capability is number of contingencies that can be run and analyzed per day. Using a 16-hour nighttime run and 8 hours for analysis, that number at the Bonneville Power Administration (BPA) was about 100,000. BPA is working to improve this capability by a factor of 100. First, POM is an easy choice because it is 2.5 times faster than our now retired in-house powerflow program and 10 times faster than a commercial powerflow that BPA is using. Next, our array of 38 computers looks like one computer to the user but each does a portion of the work. Finally, database analysis of results will replace the current practice of using spreadsheets. This is challenging, but necessary, if 10 million contingencies are to be processed each day. Probabilities for each contingency, will allow a better understanding of the risks involved the less likely but more numerous and devastating multi-element contingencies.

BPA is looking for ways to automate transient stability studies based on powerflow results. Perhaps these studies could be triggered by a specified change in angle for a generator output level or extreme reactive consumption. Again a database with the necessary information for fault location and clearing times is needed to make the process automatic.

3) Studies Performed by Kansas City Power & Light:

Over the past 6 months Kansas City Power & Light (KCPL) was evaluating the OPM concept.

Three sets of OPM results were obtained for 2003 summer peak case:

1. General OPM analysis.
2. OPM analysis restricted to mitigation measures through line switching and generation redispatch only.
3. OPM analysis with mitigation measures limited to maximum of two not affected lines being switched at a time.

OPM capability of switching not affected lines to alleviate thermal violations in downtown Kansas area is described here.

Switching not affected lines measure in OPM alleviates thermal overloads by switching not affected (i.e., non-overloaded) branches. Working very fast, this capability automatically selects lines that should be switched to effectively alleviate existing overloads without creating any new violations of the monitored constraints (see Fig. 3).

Switching Not Affected Lines				
Line switching measure alleviating all overloads				
Branch 1		Branch 2		
579XX 161.00 - 579XX 161.00 1				
579XX 161.00 - 579XX 161.00 1	579XX 161.00 - 579XX 161.00 1			
579XX 161.00 - 579XX 161.00 1	579XX 161.00 - 579XX 161.00 1			
579XX 161.00 - 579XX 161.00 1	579XX 161.00 - 579XX 161.00 1			
579XX 161.00 - 580XX 161.00 1	580XX 161.00 - 580XX 161.00 1			
579XX 161.00 - 580XX 161.00 1	580XX 161.00 - 580XX 161.00 2			
579XX 161.00 - 580XX 161.00 1	579XX 161.00 - 579XX 161.00 1			
Line switching measure decreasing overloads				
Branch 1	Branch 2	Number of violations	Sum overload(%)	Max overload(%)
580XX 161.00 - 580XX 161.00 2		1	11.1	11.1
580XX 161.00 - 580XX 161.00 1		1	12.3	12.3
579XX 161.00 - 579XX 161.00 1	579XX 161.00 - 580XX 161.00 1 2	12	12.9	10.5
579XX 161.00 - 579XX 161.00 1	579XX 161.00 - 580XX 161.00 1 2	12	13.2	10.9
579XX 161.00 - 579XX 161.00 1	579XX 161.00 - 580XX 161.00 1 2	12	13.3	11.1
579XX 161.00 - 580XX 161.00 1		2	13.4	11.4
579XX 161.00 - 579XX 161.00 1	579XX 161.00 - 579XX 161.00 1 2	14	14.8	9.2
Criteria				
<input checked="" type="radio"/> Sum of the overloads				
<input type="radio"/> Max overload				
<input type="radio"/> Number of the overloads				
<input checked="" type="button" value="OK"/>				

Fig. 3. Alleviating Post-Contingency Overloads Using the Switching Not Affected Lines Measure

Fig. 3 shows the output table of the line switching measure, when no more than 2 branches at a time may be switched. The top part of Fig. 3 lists one branch or combinations of two branches that completely alleviate post-contingency overloads. The bottom part of Fig. 3 lists combinations of branches that partially reduce post-contingency overloads. For each combination, the following information is provided:

- Number of remaining post-contingency overloads.
- Sum of all remaining overloads after the measure is applied (in %).
- Maximum remaining overload after the measure is applied (in %).

Combinations are sorted in the descending order by the sum of all overloads remaining after the measure is applied.

Recommendations made by KCPL during the PRA user-group meeting include:

- OPM program could be a valuable tool to be added to transmission planning software.
- It is especially valuable right now with transmission constraints and the transition phase in utility deregulation environment.

IV. CONCLUSION

In this paper, methodology and evaluation studies of the concept of physical and operational margins are presented. Based on this concept, two software applications, Physical and Operational Margins (POM) and Optimal Mitigation Measures (OPM), have been developed. Evaluation of POM program shows that it offers fast, robust and accurate solution for analyzing voltage, thermal and voltage stability problems. Evaluation of OPM program shows that this is a valuable tool for relieving voltage, thermal and voltage stability violations. Currently, POM and OPM programs are used by the EPRI PRA User-Group members to perform a wide range of studies for planning and operations environments.

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VI. BIOGRAPHIES

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