Utility Experience Computing Physical and Operational Margins: Part II – Application to Power System Studies

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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 has been evaluated by the EPRI Probabilistic Reliability Assessment (PRA) User-Group members as described in the companion paper, *Part I*. 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 approach offers fast and accurate determination of bottlenecks in the transmission network and optimal mitigation measures to alleviate the identified violations. 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

RESTRUCTURING in the electric power industry in North America has led to additional challenges in continuing to reliably operate power systems. Addressing challenges that power system planners and operators face, comprehensive analysis of power system operation, and measures required to maintain reliable power delivery are the focus of the Probabilistic Reliability Assessment (PRA) User-Group. The User-Group, which includes users of Physical and Operational Margins (POM) and Probabilistic Risk Indices (PRI) programs, was established in early 2002 as a part of the Transmission Program of EPRI Reliability Initiative.

The present paper concentrates on application of the POM software to power system studies.

Two programs were used in the studies described in the present paper: Physical and Operational Margins (POM) and Optimal Mitigation Measures (OPM).

1) Physical and Operational Margins (POM)

POM is a voltage stability and contingency analysis program that allows the user to effectively handle a wide range of problems in planning and operations environments. It uses full AC analysis for contingency screening and transfer studies and has an extremely fast optimal re-ordering technique [1]. Some of its capabilities are as follows:

- Performs contingency analysis for large power system models:
  - Automatically generates contingency lists.
  - Analyzes N-1, N-2 and complex contingencies.
  - Identifies critical contingencies and associated violations.
- Monitors user-defined constraints:
  - Simultaneously enforces voltage stability, and voltage and thermal constraints.
  - Monitors all buses and branches in the network on each iteration of power flow solution and shows the lowest bus voltages and the largest power flows on

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  - graphical display (includes capability to draw PV, QV curves).
  - Computes voltage stability margins.
  - Monitors flowgates.
- Simulates power transfers while monitoring constraints.
- Provides easy-to-use scripting language, fully integrated into POM.
- Features a flexible graphical editor.

2) Optimal Mitigation Measures (OPM)

OPM is a fast remedial action program used to relieve thermal, voltage and stability violations identified by POM.

Some of its capabilities are as follows:

- Applies a minimum number of remedial actions based on the user-defined priority schedule.
- Available remedial actions include:
  - MW Dispatch
  - MVAR Dispatch
  - Capacitor and Reactor Switching
  - Transformer Tap Change
  - Line Switching (In and Out)
  - Opening Not Affected (Non-Overloaded) Branches
  - Optimal Capacitor Placement
  - Load Curtailment
  - Defined Operating Procedures
- Automatically mitigates thermal, voltage and voltage stability violations after a contingency is applied, load is scaled, or power transfer is simulated.
- Identifies the causes of voltage stability violations.

II. Application of POM Software to System Studies

POM software has been evaluated by the PRA user-group members and implemented in their system studies.

POM is being used in system planning and reliability studies, ranking transmission projects and system operations studies. Results and conclusions obtained by a number of member utilities are presented in this paper.

A. System Planning and Reliability Studies

1) Studies Performed by Con Edison: Con Edison has been a supporter of EPRI's efforts in using the POM and developing the PRI programs for performing system planning and reliability analysis. The primary objectives in performing these analyses include:

1.Identifying single or multiple contingencies that have the potential to cause severe overloading or voltage problems.

2.Determining the consequences of exceeding emergency criteria that would require operating actions.

In addition Con Edison has been developing a component based transmission analysis program to perform probabilistic risk analysis. Briefly, the new approach can be described as predicting the frequency of the problems identified by POM so that alternative transmission system reinforcements or improvements can be evaluated.

The POM program is being used in performing not only N-1 analysis at a component level but also in addressing the consequences of multiple (N-2, N-3…) contingencies. The ability of the program to automatically perform N-1 and N-2 contingencies in any combination has been valuable.

It also has the capability to perform N-x contingencies that require manual input. The results of these studies identify which contingencies may lead to customer outages and are useful in determining the resiliency of the system.

The primary benefit of the POM program is in comparing alternative plans using a fast solution technique to identify weaknesses associated with a particular development and applying the results in performing transmission reliability analysis.

The objective of Con Edison's continuing efforts using the POM and Transmission Reliability Analysis (TRA) software to quantify case study inputs, is to develop a specific transmission system model, which can be used to support design decisions, operational decisions, including outage planning and scheduling.

The results of both POM and TRA studies are expected to provide loss of load expectations (LOLE) for each system state and provide comparable indices for alternative plans.

2) Studies Performed at LIPA/ KeySpan: POM was used to determine the maximum loadability in the eastern Long Island study area.

Three cases were analyzed:

1. With all generation out of service in the study area.
2. With all generation in service in the study area.
3. With all generation in service in the study area and an additional generator placed in service.

Then, OPM (including load shed) was applied to determine mitigation measures that increased the maximum load level in the study area for each case. The results are shown in Table I.

TABLE I
Maximum Load Level

	Base Case	With OPM Applied
Case #1	30 MW	150 MW
Case #2	80 MW	210 MW
Case #3	130 MW	300 MW

Table I shows a significant increase in area loadability after the OPM was used for each of the three cases under investigation. Increase of the maximum load level from 30 MW (prior to using mitigation measures) to 150 MW (after using mitigation measures) for Case #1 is shown in Fig. 1. The *x*-axis represents loadability in the study area. The curves represent monitored constraints: voltage, thermal and voltage stability.

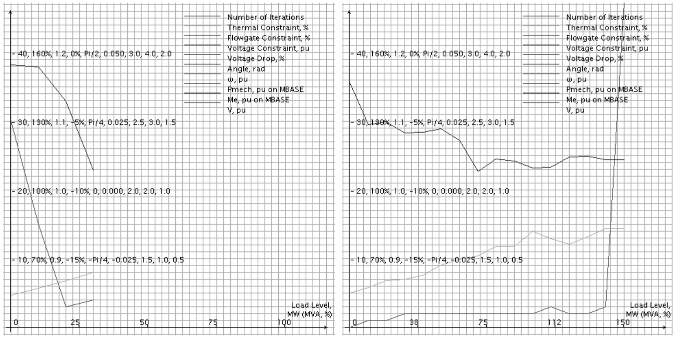


Fig. 1. Maximum loadability before (left) and after (right) using OPM.

In the study, POM was used to determine bottlenecks within the study area, and OPM was applied to improve the maximum loadability in the area.

3) Studies Performed at Midwest ISO: POM was used as a contingency analysis tool. Expansion planning studies are performed at Midwest ISO (MISO) in two stages:

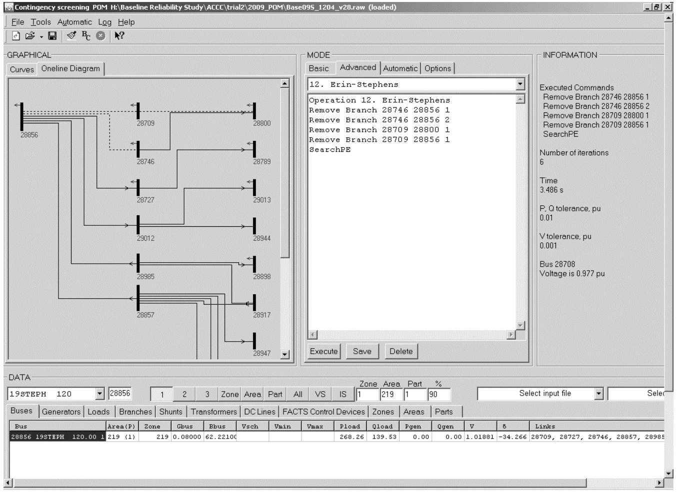
Stage 1

- Produce 5-year period expansion plan report by collecting transmission plans, proposing exploratory plans and analyzing economic impacts.

Stage 2

- Reliability Study to check whether currently planned system upgrades identified in Stage 1 are sufficient to achieve planned reliability requirements.

POM was tested to perform automatic N-1 AC contingency analysis for MISO 2007 summer peak model, and MISO 2003/2004 winter model. POM software was applied to perform AC contingency analysis for 2004 Baseline Reliability Study. Automatic mode is used to perform massive contingency analysis using PTI software MUST's contingency input files. POM was also used to perform transfer study and AC contingency analysis for Exploratory Studies. Advanced mode is used to analyze a particular scenario. In POM, contingencies may be also studied one by one (see Fig. 2) by making the massive contingency analysis input file as the Advance mode input file. Advanced mode provides an interactive panel, unique in POM to allow users to modify contingencies based on analysis results and hence to determine potential cascading risks by tripping overloading facilities one by one. POM has the function to find AC limits for a transfer scenario based on thermal constraints and voltage constraints, while MUST's AC Transfer Limit Analysis is based on thermal constraints only.



12. Erin-Stephens

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Operation 12. Erin-Stephens
Remove Branch 28746 28856 1
Remove Branch 28746 28856 2
Remove Branch 28709 28800 1
Remove Branch 28709 28856 1
SearchPE
```

Executed Commands
Remove Branch 28746 28856 1
Remove Branch 28746 28856 2
Remove Branch 28709 28800 1
Remove Branch 28709 28856 1
SearchPE

Number of iterations
6

Time
3.486 s

P, Q tolerance, pu
0.01

V tolerance, pu
0.001

Bus 28708
Voltage is 0.977 pu

19STEPH 120
28856

Zone: 1
Area: 219
Part: 1
%: 90

Bus	Area(P)	Zone	Gbus	Bbus	Vsch	Vmin	Vmax	Pload	Qload	Pgen	Qgen	V	δ	Links
28856 19STEPH 120.00 1	219 (1)	219	0.08000	62.2210				268.26	139.53	0.00	0.00	1.01881	-34.266	28709, 28727, 28746, 28857, 2898

Fig. 2. Using POM interactive panel in Advanced mode.

The POM output used for the studies was obtained in text format which is suitable for small scale AC contingency analysis, and in MS Access database format which is suitable for large scale AC contingency analysis.

B. System Operations Studies

1) Studies Performed at New York Power Authority: So far, NYPA has been using POM as a fast and convenient load flow analysis tool to study maintenance and emergency operating system conditions. It is also foreseen that it will be used as a very valuable voltage analysis tool (PV, QV curves) in transmission planning. Two specific applications are described here below:

a) FACTS Modeling and Testing: The Convertible Static Compensator (CSC) installed on the NYPA Marcy 345 kV substation is an innovative FACTS device that offers multiple voltage and power flow control functions. It can be operated in 4 basic configurations: STATCOM (shunt), SSSC (series), UPFC (shunt and series) and IPFC (series in two different lines). Depending on the configuration used, the CSC is able to regulate simultaneously the voltage on the Marcy 345 kV bus and the power flow in one or two 345 kV lines exiting the Marcy bus. As required by the NYISO, prior to the CSC commissioning tests which ended in January 2004, a study of the anticipated steady-state effects of the CSC on the New York power system was performed. POM Version 2.2 has the ability to model FACTS devices in STATCOM, SSSC and UPFC configurations. At NYPA, POM was used mainly to simulate the UPFC commissioning tests. In UPFC mode, the controlled parameters were Vref, the desired Marcy bus voltage (voltage regulation), and Vseries, the series injected voltage magnitude and phase angle in the Marcy-New Scotland 345 kV line (power flow regulation). Numerous combinations of Vref and Vseries were studied and the UPFC P-Q characteristics were analyzed. For example, it was determined that an incremental line power flow change of +/-110 MW was achieved when a series voltage of 1 pu, and +/- 60^0 phase angle, was injected in the line. In POM, the various UPFC parameters can be changed directly on a data table which is part of the POM interface, and the output results can be seen almost instantaneously on the same table. It was a repetitive task and with POM, it was accomplished faster and in a less cumbersome way than when using the PSS/E program.

b) Power Transfer with and without FACTS Device: Another NYPA application of POM was to determine the ability of the NYPA CSC device series configuration (UPFC) to increase the thermal operating limit of the UPNY (Upstate New York) – CONED interface during an identified limiting contingency. The limiting facility is one of two parallel 345 kV lines (Leeds –Pleasantville) when the second line goes out of service during a contingency. POM's Advanced Mode was used to limit the post-contingency power flow in the parallel line in service until it reaches its LTE rating, by reducing the power transfer from upstate to downstate New York. This was done with and without UPFC in service. It was concluded that by setting the UPFC so that it minimizes the flow in one of the 345 kV lines exiting the Marcy substation, it indirectly reduces the flow in the Leeds-Pleasantville line, and as a result the thermal limit of the UPNY-CONED power flow interface may increase by about 50 MW for this limiting contingency. The advantage of using POM for this study is that it simulates power transfers while simultaneously monitoring voltage stability, voltage and thermal violations. In Advanced mode, the power transfer and the contingency application were automated in one single run. The power transfer was reduced in steps (e.g. 10 MW) and the contingency was applied after each step, until there was no more thermal violation in the parallel line in question. The answer was obtained in a fraction of the time than when using PSS/E.

C. Ranking Transmission Projects

1) Studies Performed at Idaho Power Company: Studies performed at Idaho Power Company (IPC) include ranking alternative projects for the Treasure Valley (TV) part of the IPC system. The objectives of this study are:

- Identify transmission expansion plans that provide the most performance benefit to the TV Transmission system over a broadest range of possible future conditions, for the least cost (time frame 20 years).
- Perform detailed study of the three main supply options to the TV (time frame 10 years).
- Determine maximum served load to the TV, associated with major project additions over period of 20 years.
- Determine the best location of TS and generation projects in Western part of Idaho system.

The study approach is Incremental Simulation Approach based on ‘Per state Analysis’ (the best system expansion alternative determined at a given state was incorporated into the model and considered a part of the base case for the next state).

Tools used for the study are:

- GE-PSLF Power Flow Program.
- POM Contingency Program.

The following results were obtained:

- Transmission plans (2003-2012): impact of line additions; impact of station additions; comparison of supply options, comparison of system configurations.
- Transmission plans (2013-2023): finding the best location for future stations; finding the best location for future generation; results for maximum served load in TV associated with transmission project additions.

Table II illustrates a criterion used for prioritization of transmission station projects.

TABLE II
PRIORITY ORDER OF TV STATION PROJECTS USING FOUR DIFFERENT METRICS

Case	Max-over-load	Sum-over-load	Count of Viola-tions	Sum Voltage Violations	Prio-rity Order	Or-der	Project
xa	base	base	base	base			
xb	1	5	1	3	10	2	NMPA
xc	3	2	3	2	10	3	HPVL
xd	6	6	6	4	22	6	MORA
xe	5	1	2	1	9	1	NSTR
xf	2	3	5	5	15	4	GRNT
xg	4	4	4	6	18	5	CLVR

Criterion based on 4 metrics is used: maximum post-contingency overloads in the system, sum of overloads, sum of voltage violations and a total count of all violations. The approach shows that the priority order of stations in TV is: 1. NSTR, 2. NMPA, 3. HPVL, 4. GRNT, 5. CDAL, 6. MORA.

The maximum served TV load with NMPA station only is about 2100 MW. System with all projects is capable to serve the maximum TV load of 3580 MW in year 2023 as shown in Fig. 3.

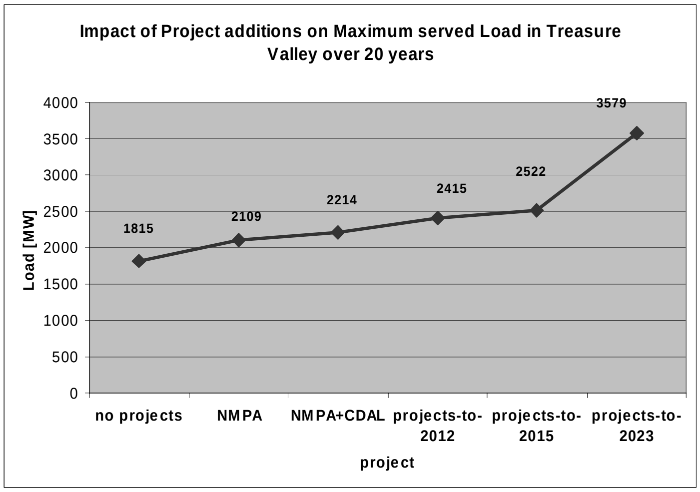


Fig. 3 Projects vs. Maximum served TV Load

2) Studies Performed at Entergy Services: The major steps used for a transmission system adequacy assessment performed at Entergy are as follows:

1. state enumeration,
2. power flow solution,
3. monitoring,
4. remedial actions,
5. reliability indices.

A state enumeration approach is used to simulate N-1 transmission outages. The power flow solution, monitoring and remedial actions are carried out for each outage contingency that is causing violation using POM-OPM program. The program POM-OPM uses an AC power flow model for contingency analysis and remedial actions. Thermal overloads, voltage and voltage stability violations are identified and these violations are relieved after taking a minimum number of remedial actions based on the user-defined priority schedule.

For the study presented in this paper, POM-OPM was used to calculate risk indices. The risk indices were calculated based on load curtailment to correct a post-contingency situation. The following system indices were calculated:

1. Probability of load interruption: This is the probability of load curtailment to quantify the risk due to either overloads or voltage violations.
2. Frequency of load interruption: This index represents the total number of times load may be curtailed in one year.
3. Amount of load interruption (MW per year): This is the amount of load curtailment in one year due to either overloads or voltage violations.
4. Amount of energy interruption (MWH per year): This is the amount of energy curtailment in one year due to either overloads or voltage violations. This is also called as EUE (Expected Unserved Energy).

The indices are used to compare the following three cases:

1. 2007 SUMMER PEAK CASE (ensum07_ver28)
2. 2007 SUMMER PEAK CASE with proposed reliability projects in Louisiana (ensum07_ver28_ELIprojects)
3. 2007 SUMMER PEAK CASE with proposed reliability projects in Mississippi (ensum07_ver28_EMIprojects)

EUE index is shown in Fig. 4.

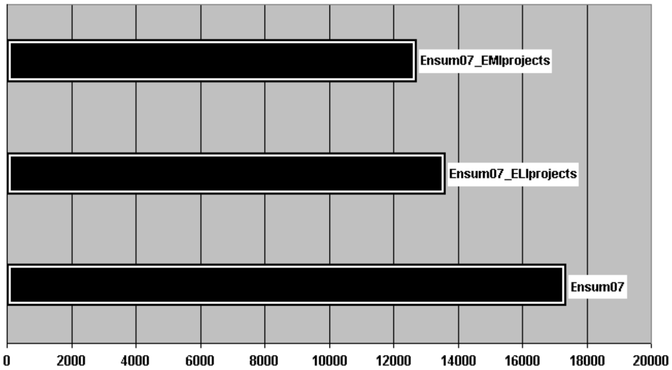


Fig. 4 Energy (MWh) Interrupted per year

Based on indices for each case, it is obvious that the addition of either of the projects provides better system reliability. The addition of proposed reliability projects in Mississippi is the comparatively better option as all indices are improved by approximately 25% when these projects are considered.

These indices are very useful to compare different alternatives and to quantify the impact of changes/ reinforcements/ modifications to the overall system reliability.

Entergy recommends that POM-OPM can be used as the network solution tools for ranking transmission projects [2]. Using the output from these programs, reliability indices are computed using the line outage data. The indices are used in successfully ranking the projects and in identifying the project that provides better reliability.

3) Studies Performed at American Transmission Company

a) Using Expected Unserved Energy (EUE) for Project Selection: While N-1 contingency analysis is a traditional and basic approach to plan future transmission system reinforcements, neglecting the multiple outage condition may result in widespread power outages that leave thousands of people in the dark.

Using the function for N-2 contingency analysis in POM-OPM, the future system model in American Transmission Company (ATC) is being analyzed to identify what the worst double contingencies are. In this pattern, it can be predicted how much benefit can be achieved from the potential transmission reinforcement and what the best alternatives are from the system performance point of view.

It is quite a complex idea to represent the existing system or the system with transmission reinforcement in terms of customer service. Calculating Expected Unserved Energy (EUE) would be one of the approaches to represent the customer impact under outage conditions. POM-OPM is intensively being used to compute EUE to measure what the customer impact is due to alternate solution and how good alternatives are by comparing the EUE of the existing system.

A system was tested using POM-OPM to obtain the amount of curtailed load for each critical contingency. The outage statistics for each critical contingency were applied to compute EUE for each option and the base case. Table III illustrates the EUE and construction cost for each option.

TABLE III
SUMMARY OF EUE FOR ALTERNATIVES

Name of Alternatives	Base Case	Option 1 (Constructing 138 kV lines)	Option 2 (Constructing 345 kV line A)	Option 3 (Constructing 345 kV line B)
EUE (MW.Hr/Yr)	17,092.19	12,284.82	6,742.93	6,277.30
Expected Unserved Demand (MW/Yr)	4,514.78	3,244.95	1,781.09	1,658.10
Rough Cost Estimation (Thousand $)	0	15000	25000	45000
Difference in EUE (Base Case - Option) (MW.Hr/Yr)	0.00	4,807.36	10,349.26	10,814.88

The result indicates that Option 3 is the best option in terms of EUE since the option provides the smallest EUE among those options. However, Option 2 is much better choice if the cost and EUE are compared together. It can be concluded that an option with the lower EUE may be better in terms of system performance while it may not be a good option because of higher construction cost. Finding the combination of alternatives with the lowest EUE and the lowest construction cost can be one of applications using POM-OPM.

b) Introducing the Concept of Transmission Capability Gap at ATC: ATC proposes a new measure for transmission system performance: Transmission Capability Gap (TCG). TCG is a measure of transmission system load capability deficit, the "gap" between MW demand and MW capability of the transmission system. TCG is the same as EUE when EUE is calculated as load interrupted plus the minimum load reduction necessary to alleviate thermal, voltage, and other criteria violations. However, "EUE" is not unambiguous because EUE is often calculated as a measure of load interruption only, which is more a measure of customer impact. TCG is intended as a measure of composite system performance rather than as a measure of customer impact only. The usefulness of TCG is:

- Multiple criteria, thermal, voltage, etc., reduce to one
- Enables comparisons between different types of violations
- Readily integrates across time
- Readily sums across locations
- More easily understood by customers, regulators
- Readily combines across scenarios (for planning)

OPM calculates TCG, which ATC proposes to use as the metric for:

- Real time grid performance measurement
- Project alternative value/benefit measures

Transmission planning involves evaluation of the future, which necessarily means consideration of things that cannot be known with certainty. The usual method for managing uncertainty is Scenario Analysis. POM generates alternative scenarios at ATC by constructing alternative scenarios from assumptions of various combinations of:

- Transmission line outages
- Generator outages
- Loads

POM will generate scenarios, OPM will calculate TCG for each scenario, and a probability weighted sum will combine these results into an expected value of future system performance. (Note the similarity to the Loss Of Load Expectation traditionally used in generation planning.) For planning purposes, the benefit of some proposed project, $\beta 1$, would be the difference between the probability weighted sum of TCG in a base case versus that same base case with project $\beta 1$ implemented. For project selection, prioritization, or reinforcement program optimization, an array of projects may be proposed as shown in Table IV, which includes both costs and benefits for each project. Structuring the decision problem this way makes it easy to answer questions such as: "What is the maximum benefit for $X investment?"

TABLE IV
COMPARING AN ARRAY OF PROJECT ALTERNATIVES USING MW GAP

Project Alternative	$\beta 1$	$\alpha 9$	$\lambda 5$	$\tau 9$	$\lambda 3$	$\mu 19$
Cost	$105	$125	$350	$525	$770	$980
Benefit (Gap)	37	42	122	130	185	209

D. *Use of Remedial Actions in Operations*

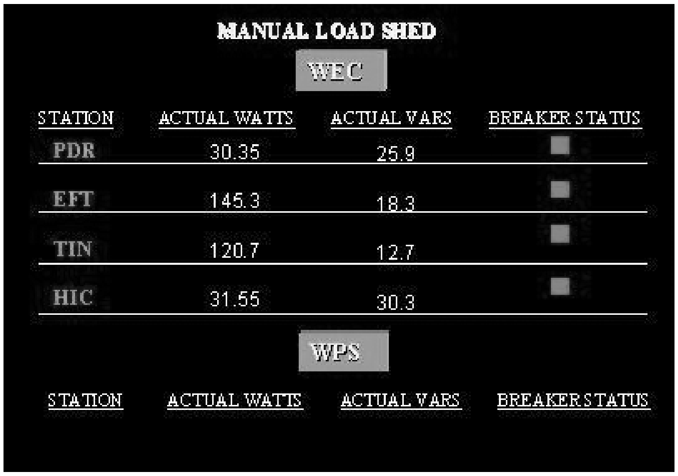
1) Studies Planned at ATC: The Load Shed Application will allow System Operations to quickly shed the load and restore loads in an emergency situation, when all other actions have failed and when shedding of firm load will be the last action to return the system to a reliable state. To achieve this objective, ATC will employ POM-OPM, which will instruct System Operator on where to effectively shed the load. POM-OPM will be run in an automatic mode, where load will be selected as the only remedial action scheme.

The application will perform the following functions:

- Run POM for Fast Contingency Analysis Screening in Automatic Mode every "X" minutes.
- Run OPM for Remedial Actions, which considers specific loads[1] as an only option, to alleviate thermal violations, voltage violations, and voltage stability problems.
- Visualize suggested load curtailment results, given by POM-OPM, for better Operators Interpretation.
- Have visualized output displayed in Control Room, and refreshed every "X" minutes.
- Develop EMS Load Shed Application that will allow System Operations to directly control loads that are provided to the POM-OPM.

POM Load Shed output will be customized to better-fit the System Operations needs.

In an emergency situation the System Operator will shed and restore load simply by pressing a button for the desired loads, and confirming the selection on the EMS Load display (see Fig. 5). Loads selected for shedding, after load survey was performed off-line, are grouped and listed by different Control Areas that are within ATC footprint. Please note that one button click will instantaneously trip multiple load circuit breakers, which will automatically take selected load off the system. Before any load can be shed, Load Shed Application must be armed by the System Operator. Load Shed will perform an important bookkeeping function by recording its actions.


MANUAL LOAD SHED

STATION	ACTUAL WATTS	ACTUAL VARS	BREAKER STATUS
PDR	30.35	25.9	■
EFT	145.3	18.3	■
TIN	120.7	12.7	■
HIC	31.55	30.3	■

STATION	ACTUAL WATTS	ACTUAL VARS	BREAKER STATUS

Fig. 5. Fast Load Shed Selection at ATC

III. CONCLUSION

In this paper, practical applications of Physical and Operational Margins (POM) and Optimal Mitigation Measures (OPM) are presented. These software applications are used by the EPRI PRA User-Group members to perform a variety of studies for planning and operations environments that include System Planning and Reliability Studies, System Operations Studies, and Ranking Transmission Projects. Some of the functions of these applications along with benefits of applying them to analysis of power systems have been described.

IV. REFERENCES

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[2] M. Nagle, S. Kolluri, S. K. Agarwal, "Implementation of Probabilistic Methods for Ranking Transmission Projects", Accepted at PMAPS-2004 Conference, Sept. 2004.

V. BIOGRAPHIES

Scott Lockwood is a Principal Engineer at American Electric Power (AEP). Roz Navarro is an Electrical Engineer at AEP East Bulk Transmission Planning group.

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[1] ATC is a multi-state Transmission only Company. Providing specific loads to the POM-OPM will allow System Operators to effectively shed the load from Transmission Level (50 kV and above), which they have control over.

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