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Identifying Optimal Remedial Actions for Mitigating Violations and Increasing Available Transfer Capability in Planning and Operations Environments

E. Bajrektarevic, P. Burke, S. W. Kang, *ATC*; V. Kotecha, *ConEd*; S. Kolluri (CIGRE Member), M. Nagle, S. Datta, *Entergy*; M. Papic, *IPC*; J. Useldinger, P. C. Patro, *KCPL*; L. Hopkins, D. Le, *NYPA*; M.Y. Vaiman (CIGRE Member)*, M.M. Vaiman, M. Povolotskiy, *V&R Energy*
United States of America

SUMMARY

The present paper describes utility experience in identifying and optimizing mitigation measures based on a user-defined priority schedule to alleviate voltage, thermal and voltage stability violations. Four types of studies were performed by participating utilities:

1) Determining maximum loadability in the power system
   First, power system loadability for present conditions was computed. Then, mitigation measures were used to increase the system loadability by determining mitigation measures needed to alleviate thermal, voltage or voltage stability violations.
2) Comprehensive contingency analysis
   Optimal mitigation measures were automatically determined for each contingency during the comprehensive AC contingency analysis. Thus, bottlenecks identified in the power system network were rapidly alleviated.
3) Available transfer capability computations
   The transfer capability limits on studied interfaces were determined while monitoring voltage, thermal and voltage stability constraints, and the most limiting facilities were identified. The effect of different operating measures on the transfer capability limits was analyzed.
4) Determining the secure operating region
   The boundary of secure operating region was plotted and limiting constraints were determined while simulating simultaneous transfers. Optimal mitigation measures that increase the size of the secure operating region were determined for each contingency, and the effect of remedial actions on the size of the secure operating region was then analyzed.

The studies were performed using Physical and Operational Margins (POM), Boundary of Operating Region (BOR), and OPtimal Mitigation Measures (OPM) software applications.

This paper is a joint effort of six US utilities: American Transmission Co. (ATC), Con Edison, Entergy, Idaho Power Co. (IPC), Kansas City Power & Light (KCPL), and New York Power Authority (NYPA). Each utility describes their experience using POM-OPM-BOR, summarizes studies performed utilizing the applications, and shares the obtained results. The capabilities and advantages of using POM-OPM-BOR are also discussed in this paper.

KEYWORDS

Optimal mitigation measures, alleviating post-contingency violations, increasing transfer capability.

Michael Vaiman is with V&R Energy Systems Research, Inc. (V&R Energy); e-mail: mvaiman@vrenergy.com

1. INTRODUCTION

Performing security assessment and assessing that there is adequate transfer capability margin on the system are critical aspects of maintaining reliable operation of electric power system [1]. As interconnected power networks become more stressed due to interregional transfers, the area of the regions affected by voltage, thermal and voltage stability violations is expected to increase. Thus, the need has arisen in more effective and robust tools for fast and reliable power system assessment.

Based on various studies, POM-OPM-BOR applications proved to be a fast, robust and user-friendly approach for analyzing and graphically representing power system behavior.

Physical and Operational Margins (POM) is a very fast AC loadflow and contingency analysis program that solves a 45,000-bus case in approximately 0.6 sec [2, 3]. POM allows the users to simultaneously monitor three constraints during contingency analysis and transfer simulation: (1) Voltage stability, (2) Thermal overload of lines and transformers, and flowgate constraint, and (3) Voltage violation (voltage range and/or pre contingency to post contingency voltage drop).

POM capabilities include:

- Perform contingency analysis for large power system models:
    - Automatically generate contingency lists.
    - Automatically apply and analyze N-1, N-2, N-3 and complex contingencies.
    - Identify critical contingencies and associated violations.
- Simulate power transfers while monitoring voltage, thermal, flowgate, voltage stability constraints
- Determine maximum loadability in the loads of interest while monitoring voltage, thermal, flowgate and voltage stability constraints

Optimal Mitigation Measures (OPM) is fast, powerful and efficient remedial actions or transmission expansion planning program to maintain and increase power system reliability. It is fully integrated into POM and BOR applications. OPM relieves thermal, voltage and voltage stability violations identified by POM:

- Determines the minimum actions needed to alleviate violations, based on user-specified priorities
- Determines the causes of stability violations and increases voltage stability margins
- Increases transfer capability and loadability
- Relieves base case violations

OPM applies a minimum amount of mitigation measures based on a user-defined priority schedule. Available remedial actions include: (1) MW Dispatch; (2) MVAR Dispatch; (3) Capacitor and Reactor Switching; (4) Transformer Tap Changing; (5) Phase Angles Regulator Adjustment; (6) Line Switching (In and Out); (7) Opening Not Affected (Non-Overloaded) Branches; (8) Optimal Capacitor Placement; (9) Load Curtailment; and (10) Defined Operating Procedures.

Boundary of Operating Region (BOR) is a powerful AC tool that identifies and illustrates the region within which the system operation is secure [4, 5]. BOR finds AC limits for transfer scenarios based on voltage stability, voltage and thermal constraints. The tool has the ability to automatically generate nomograms for planning and real-time environments.

2. USING POM – OPM AT AMERICAN TRANSMISSION CO. (ATC)

2.1 Real Time Applications of POM – OPM at ATC

The changes of the Midwest Regional Transmission Organization entering the Market Day-Ahead Operation introduced new variables and different challenges for American Transmission Co. (ATC) as a transmission operator. ATC was traditionally a net importer of energy. With the advent of the Day 2 Market, ATC saw non-conventional power flows on many occasions, especially in the summer of 2005, when power flows made ATC essentially a net exporter.

To continue to operate reliably while implementing scheduled outages, ATC is investigating the tools including POM-OPM to address this challenge. There is a need for better tools and methods in System Operations that will deliver fast and efficient answers to the following:

- Easier, more efficient sharing of reliability information between ATC and the RTO when coordinating transmission and generation outages or addressing the real time operations issues such as automatically generating N-1 and N-2 contingency lists while running cases of 42,000 buses; performing contingency screening, while taking into account thermal and voltage constraints, as well as voltage stability.

Based on ATC's preliminary experience, POM proved to be an adequate tool for easier sharing and benchmarking the contingency results between ATC and the RTO.

- Develop mitigation plans by implementing remedial measures and providing guidelines to System Operators for contingencies evaluated. This can be divided into three categories:
  1. Pre-contingent (Preventive)
     - Estimating the security margin with respect to a credible contingency.
     - Enhancing the process of monitoring transmission interfaces. POM-OPM was used to analyze sensitivity of the interfaces to the different transfer levels.
     - Enhancing the estimation and determination of the voltage support requirements and Mvar requirements. ATC is investigating POM's robust process in computing P-V curves for specific interfaces in its footprint that are susceptible to voltage collapse.
  2. Post – contingent (Corrective)
     - Developing plans for emergency system conditions, such as when load shedding becomes imminent as a last action to return the system to a reliable state.
  3. Pre-contingent (Preventive) and/or Post – contingent (Corrective)
     - Modeling the consequence of implementing the remedial action plan for contingency in real time which would require Operator's pre-contingent or post – contingent action. The V&R's OPM tool is used at ATC to deliver the load shed recommendations in system operations for the credible contingencies. The load shed recommendations provide system operators with the locations of where load needs to be curtailed as well as the estimate the amount of load shedding that removes the contingent problem.

<u>ATC's Operating Example. Identification of South Imports Limit while simulating power transfer by using POM-OPM</u>

The POM – OPM tool was used to provide answers to the following:

- Determine the most credible N-1 and N-2 contingencies;
- Establish the south imports limit for N-1 and N-2 system conditions.

The study was performed by simulating a power transfer from a particular direction on ATC's system. The power transfer was simulated by increasing the generation in area defined as South, and increasing the load in the ATC system. The increase in flows was observed by calculating the flows on five lines that connect ATC's system to other transmission systems operated by other parties. An EMS-based snapshot of real time system conditions was converted to PSSE raw file and used as a base case for study. The following runs were performed (see Table 1):

- Base case run where the worst N-1 and N-2 contingencies were identified.
- Increased power transfer until the base case violation is reached.
- Increased power transfer with remedial actions implemented (generation dispatch) until the base case violation is reached.
- Increased power transfer with critical contingency taken out of service in base case.

Table 1. Summary of Power Transfer Limits for Each Identified Run With Remedial Actions Applied to The Base Case

EMS Case Snapshot of Real System Conditions converted to POM Case (raw file)				
	(N-0)	**(N-0)**	**(N-0)**	**(N-1)**
	MW Flows			
Southern Ties	**Base Case**	**+ Increased Imports**	**+Remedial Actions Applied Generation Dispatch**	**+ Critical Contingency**
	Run 0	**Run 1**	**Run 2**	**Run 3**
	No violations	Thermal Violation (Critical Contingency 1)	Thermal Violation (Critical Contingency 1)	Thermal Violation (Critical Contingency 2) +Voltage Violations
Subsystem 1	**SOUTH to (ATC - ALTE)**			
South Import Line 1	678	826	860	784
South Import Line 2	327	417	440	392
Subsystem 2	**SOUTH to (ATC - WEC)**			
South Import Line 3	475	608	631	771
South Import Line 4	621	929	1094	275
South Import Line 5	95	139	156	95
Total Subsystem 2	1191	1676	1881	1141
Total South Import	**2196**	**2919**	**3181**	**2317**
Critical Contingency 1	898 <em: 1096	1097 > em.1096	1112 > em. 1096	0

Voltage, thermal and voltage stability constraints were simultaneously monitored during power transfer analysis.

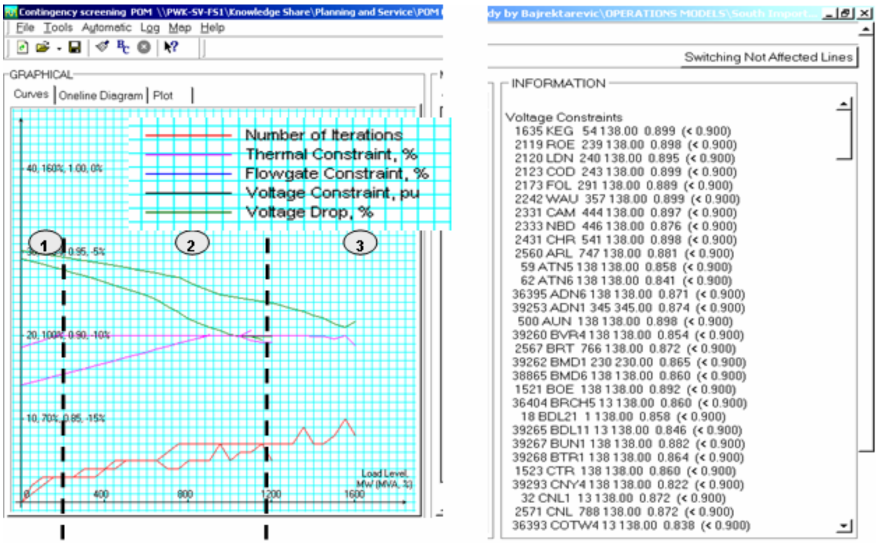


Figure 1. ATC's South Imports Power Transfer Analysis.

Figure 1 shows the following runs:

1. (N-1) Critical Contingency Trip. Transfer Limit <<
2. (N-1) Critical Contingency 1 Outage + Remedial Actions. Transfer Limit >
   (N-0) Intact System + Increased Imports. Transfer Limit >
3. (N-0) Intact System + + Increased Imports + Remedial Actions. Transfer Limit >>

The study showed that the real-time limit from the area designated South is 2919 megawatts and that the limit is thermally constrained. Study results revealed that, by applying the generation dispatch, the limit could be increased from 2919 MW to 3181 MW. Furthermore, after the worst contingency was taken out of service, the security limit was drastically lower (as anticipated) and the new limit of 2317 MW was established to protect for the next worst contingency (observe the lower P-V curve, Figure 1, with the critical contingency applied in the base case).

To continue to operate the system reliably, the complexity introduced by creation of a real time and day ahead energy market in the Midwest RTO requires better and more efficient tools. POM-OPM, because of its flexibility and quick computations, has a potential to be used as a network solution tool for addressing the reliability needs previously listed in system operations.

2.2 Introducing the Concept of Transmission Capability Gap at ATC

One of ATC's future applications using POM-OPM is measuring 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:

- 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 for: (1) Real time grid performance measurement and (2) 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. For planning purposes, the benefit of some proposed project, β1, would be the difference between the probability weighted sum of TCG in a base case versus that same base case with project β1 implemented. For project selection, prioritization, or reinforcement program optimization, an array of projects may be proposed as shown in Table 2, 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 2. Comparing an Array of Project Alternatives Using MW Gap

Project Alternative	β1	α9	λ5	τ9	λ3	μ19
Cost	$105	$125	$350	$525	$770	$980
Benefit (Gap)	37	42	122	130	185	209

3. CON EDISON EXPERIENCE

The primary objectives in performing planning and reliability analyses at Con Edison 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.
3. Developing mitigation measures for severe contingencies

Con Edison has been developing a component based transmission analysis program to perform probabilistic reliability analysis. Briefly, the new approach can be described as predicting the frequency of the problems identified by POM program 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, N-2 and N-3 contingencies in any combination has been valuable. It also has the capability to perform analysis for 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 and 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.

Using OPM along with POM alleviates post-contingency violations. Optimal mitigation measures are automatically determined by OPM for selected contingencies during the comprehensive AC contingency analysis, and bottlenecks identified in the power system network can be rapidly alleviated with appropriate reserves or available operating actions.

4. USING POM-OPM-BOR TO DETERMINE AND INCREASE SECURE OPERATING REGION FOR ONE OF THE LOAD POCKETS IN ENTERGY CONTROL AREA

A POM-OPM-BOR study was performed on Entergy's summer peak load flow case with approximately 43,000 buses and 55,000 branches to illustrate the capability of this software application.

Voltage, thermal and voltage stability constraints were simultaneously monitored during the transfer analysis. Two power transfers were simulated by increasing the import to the load pocket in Entergy control area. A secure operating region was constructed in BOR (see Figure 2, left plot).

Then, the boundary of secure operating region was simulated with OPM enabled. OPM applied the mitigation measures at the transfer levels where violations of the monitored constraints have been identified. The following three actions have been recommended by OPM: (1) Capacitor Placement; (2) Shunt Switching, and (3) Line Switching. Figure 2 (right plot) summarizes the effect of different mitigation measures on the size of the secure operating region.

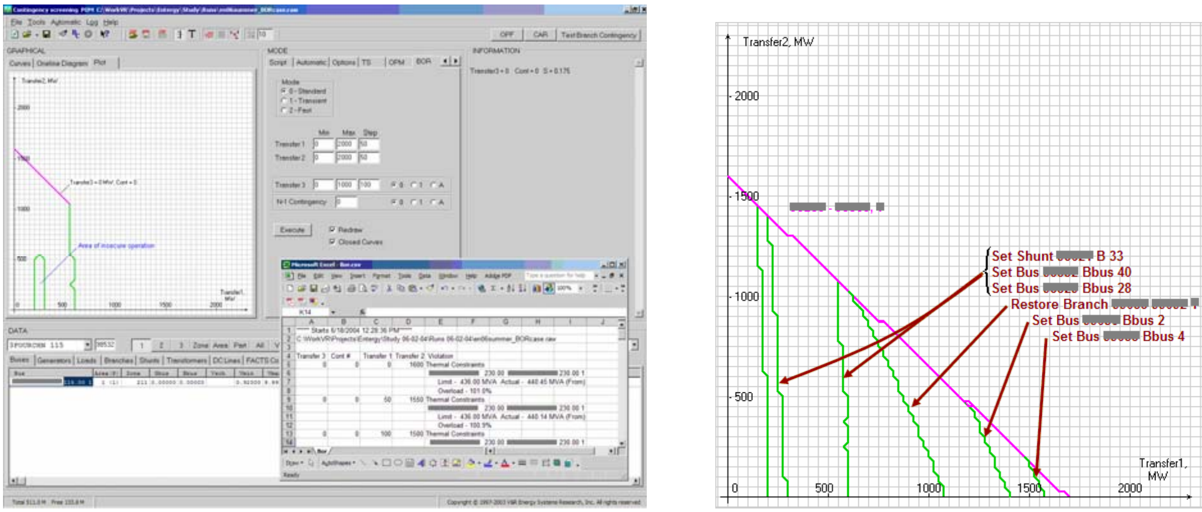


Figure 2. BOR Interface. *Using OPM to Increase the Size of the Secure Region*

The study showed the effectiveness of OPM in increasing both the maximum transfer capability and the size of the secure operating region.

5. USING POM-OPM-BOR TO DETERMINE AND INCREASE POWER TRANSFER CAPABILITY AND SECURE OPERATING REGION FOR IPC

POM application was used to determine power transfer capability across WECC Path 17. BOR was utilized to compute the secure operating region. OPM was used to increase the size of the secure operating region. Two cases were analyzed. Case 1 is the case that represents the present state; Case 2 corresponds to a future state with new projects included.

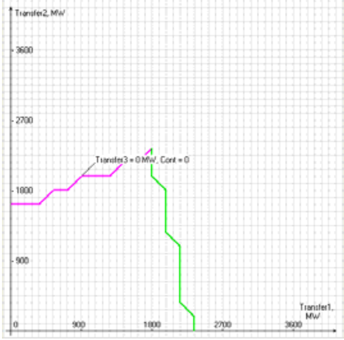
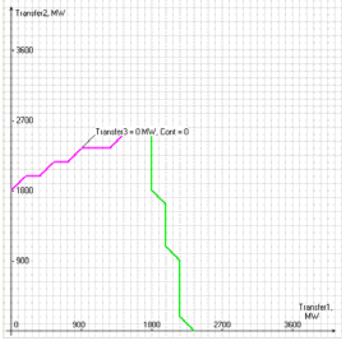
The following constraints are simultaneously monitored within WECC system during power transfer and contingency analyses: voltage stability, thermal and voltage constraints.

A power transfer is simulated in POM by increasing generation in several WECC areas (14- Arizona, 26- LADWP, 65- PACE, 30- PG&E and 73- WAPA RM) and decreasing generation in areas (40 – NW and 60 - Idaho). The results show power transfers that can be simulated in addition to the transfers present in the base cases. The maximum value of power transfer is 2000 MW for Case 1 and 2400 MW for Case 2. Both transfers are limited by thermal overload on the same 230/161 kV transformer. OPM was then used to increase the maximum transfer capability. After OPM was enabled, the maximum transfer capability was increased from 2000 MW to 2600 MW for Case 1 and from 2400 MW to 2800 MW for Case 2.

POM was also utilized to simulate the same transfer with N 2 BORAH-ADELAIDE-MIDPOINT 345.00 contingency applied. For Case 1, this contingency is already critical (i.e., causes constraint violation) in the base case. For Case 2, the maximum value of transfer with the contingency applied is 1400 MW. OPM was then used to increase the maximum transfer capability when the contingency is applied. After OPM was enabled, the maximum transfer capability was increased from 0 MW to 2200 MW for Case 1 and from 1400 MW to 2700 MW for Case 2.

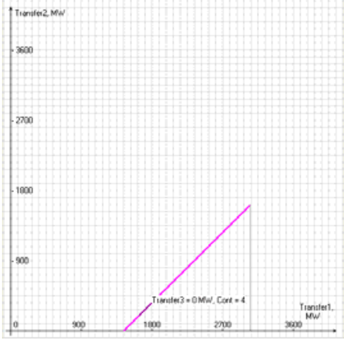
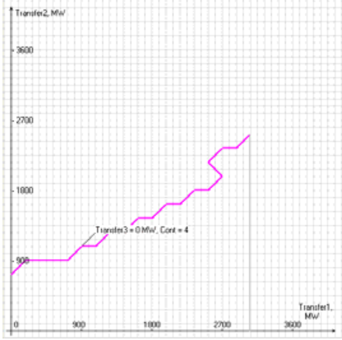
BOR was used to construct secure operating region for both cases. The initial transfer was represented as two simultaneous independent transfers. Transfer 1 was simulated from the same source areas to area 60; Transfer 2 was simulated from the same source areas to area 40. The size of the secure operating region is 0.450 pu for Case 1 and 0.516 pu for Case 2, see Table 3.

Table 3. . BOR Results for IPC Cases 1 and 2

	Case 1	Case 2
Secure Operating Region without a Contingency Applied	 S = 0.450 pu	 S = 0.516 pu

Then, BOR was constructed for the same contingency while simulating Transfers 1 and 2 for Case 1 with and without OPM. The size of the secure operating region is 0.101 pu prior to using OPM. It was increased over 3 times to 0.338 pu after OPM was used (see Table 4).

Table 4. . BOR-OPM Results for IPC Case 1

	OPM Disabled	OPM Enabled
Secure Operating Region with a Contingency Applied	 S = 0.101 pu	 S = 0.338 pu

6. USING POM-OPM FOR A SUMMER PEAK OPERATING STUDY AT KCPL

Transmission Planning has performed a 2005 Summer Peak Operating Study. A 2005 summer peak case from the SPP 2005 Load Flow Model Series was used as the initial case. Single and more probable contingency analyses were performed on all KCPL facilities (345kV, 161kV, 69kV) and all KCPL ties. Branch loadings were monitored for ninety percent of normal ratings and above. Voltage limits were monitored above 1.05 V PU and below 1.00 V PU. Mitigation measures include changes in system configuration, changes in generation, and implementing operating guides. All overloads caused by single contingencies can be eliminated using one or more of these mitigation measures. For the first time, new POM/OPM software was utilized as part of this years operating study to help determine the appropriate mitigation procedures.

7. NYPA OPM APPLICATIONS

7.1 Relieving Thermal Overloads

In New York 50% of the approximately 34,000 MW total load is concentrated in the south-eastern part of the State. Approximately 300 MW of new wind generation is being added in the northern area of the State. In addition, 500 MW of load will eventually be removed from that same area resulting in a net Northern area generation increase of 800 MW. POM/OPM software was utilized to analyze whether there is sufficient transmission capacity to carry the additional 800 MW of generation out of the Northern area of the State, as well as to alleviate thermal and voltage violations which occur during pre-specified contingencies.

The first step was to study the new operating state of the system with the added wind generation and load removed. POM gave no violations for this operating state. The next step was to analyze pre-specified contingencies. Using POM's Advanced Mode, the most severe contingency resulting in thermal overload was determined. Finally, OPM Mode was enabled to alleviate the post-contingency thermal overload, using Capacitor and Reactor Switching and MW Dispatch as remedial actions.

7.2 Increasing Loadability

OPM may be used by transmission planners to determine the system maximum loadability by alleviating voltage, thermal or voltage stability violations. Using POM's Basic Mode, the load in all New York control areas was increased in steps of 100 MW with constant power factor. Voltage violations occurred at 700 MW load increase, thus it was concluded that for normal operating conditions, the present New York State maximum loadability is 600 MW above the base load. Then OPM Mode was enabled with the following mitigation measures selected in order of priority: MVAR Dispatch, Capacitor and Reactor Switching, Optimal placement of additional capacitors and MW Dispatch. Voltage violations occurred at 2300 MW, thus maximum loadability is 2200 MW (see Figure 3). This level is the highest load level at which OPM can determine mitigation measures. Therefore, the New York power system maximum loadability increased from 600 MW (OPM not used) to 2200 MW (OPM used) above a base case load of 34,000 MW.

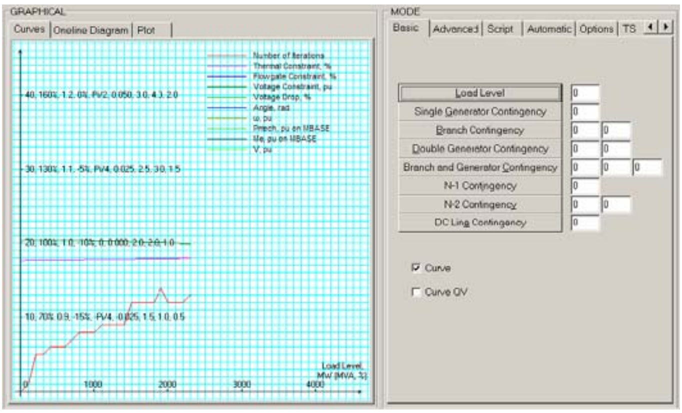


Figure 3. Increasing Power System's Loadability

An additional step would be to account for contingencies as the load is being increased. System loadability increase is a very useful application in transmission planning, especially in New York, since it is predicted that the New York load will increase by at least 10% in the next five years.

8. CONCLUSION

The present paper describes utility experience with Optimal Mitigation Measures (OPM) software application. A number of studies have been performed in planning and operations environment. As a result of applying optimal mitigation measures in OPM, bottlenecks in the power system network were alleviated. Mitigation measures identified by OPM allowed the users to eliminate pre- and post-contingency violations, increase transfer capability and loadability, and increase the size of the secure operation region.

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