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Regular paper

Power Market Analysis Tool for Congestion Management

In this paper a Power Market Analysis Tool (PMAT) is designed for congestion management. The tool creates an interface between PowerWorld©, a professional software tool that computes power flows, and MATLAB®. The tool helps analyze power flow results, batch-process large case studies, and provide the user with options to manage congestions. A graphical user interface has been designed to help the user learn and interact with the tool. Based on generator and load bid data, the tool performs (N-1) security analysis. In case of congestion, the user can choose one of three congestion relief methods: (1) Transmission Line Relief Sensitivity (sensitivities of line flows to load curtailment), (2) Economic Load Management (a product of three indices that measure (i) the sensitivity of the line flow to load curtailment, (ii) the level of customer incentive to cut down consumption, and (iii) the customer's acceptable range of curtailment), and (3) VAR Support (installment of additional VAR devices). The congestion alleviation methods are explained and tested on the IEEE 24 bus Reliability Test System.

Keywords: electricity markets, load curtailment, congestion management, LMP, (N-1) contingency analysis, PowerWorld

1. INTRODUCTION

The privatization and deregulation of electricity markets has a very large impact on almost all the power systems around the world. Competitive electricity markets are complex systems with many participants who buy and sell electricity. In any competitive market, system security plays a vital role from the market/system operator's point of view. When the producers and consumers of electric energy desire to produce and consume in amounts that would cause the transmission system to operate at or beyond one or more transfer limits, the system is said to be congested. Congestion management is about controlling the transmission system so that transfer limits are observed and is perhaps the most fundamental transmission management problem. Congestion before deregulation was treated in terms of steady-state security and the basic objective was to control the generators' output so that system remained secure (no limits were violated) at the lowest cost as seen by the mutually agreeing vertically integrated utilities. But with deregulation, congestion has become a term in conjunction with power systems and competition. When there is a congestion in a transmission system, locational prices can be significantly different from those of unconstrained optimal solutions. Hence, congestion alleviation is very important issue and is an active area of research [1]-[6].

For years, power systems have been expected to remain operational following a single contingency, the widely known (N-1) criterion. A contingency, as defined by North American Electric Reliability Council (NERC), is the unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, or switch. Systems are designed to withstand one contingency, i.e., (N-1) criterion. Unfortunately, some events trigger others and cascading failures might occur. Therefore, not all contingencies are equal, and the number of components in a given system makes it prohibitive to evaluate all (single) contingencies. The system is considered (N-1) secure when a single (the next) contingency will not cause any system limits to be violated. In this paper, (N-1) criterion refers to the outage of any line or any generator in the network and the congestion management process includes studies of sequential outages of these elements.

Using an Optimal Power Flow (OPF), a spot price market can be simulated with all engineering constraints enforced. In this way, the impact of transmission constraints on the spot prices in the market can be directly assessed. In this paper, PowerWorld [7] is used as a tool that simulates electricity market behavior through AC or DC power flow computations and linear programming to minimize costs. Simulation Automation Server (SimAuto) allows to extend the functionality of PowerWorld simulator to any external program. The SimAuto acts as a Component Object Model (COM) object, which can be accessed by various Windows-based programming languages that support the COM interface. In this paper, a power market analysis tool designed for congestion management (PMAT) is discussed.

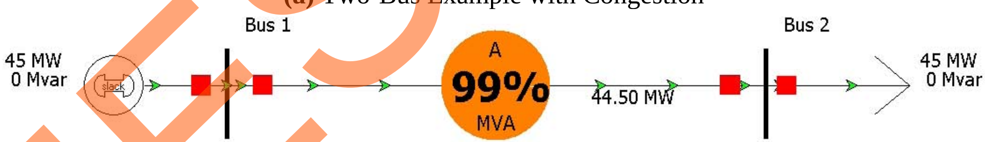
This paper is organized as follows: In section 2, the concepts of congestion and negative LMPs with examples and the methods used for congestion relief in PMAT are explained. Section 3 discusses the overview, and the workflow of PMAT. The LMP statistics with and without congestion management for (N-1) security analysis of IEEE 24 bus RTS using PMAT is demonstrated in section 4.

2. CONGESTION MANAGEMENT

2.1 Definition

In deregulated power systems, congestion in the transmission system is a major problem and may lead to price spikes. In heavily congested conditions, transmission congestion can be relieved by curtailing a portion of non-firm transactions.

(a) Two-Bus Example with Congestion



(b) Two-Bus Example with Congestion Alleviated

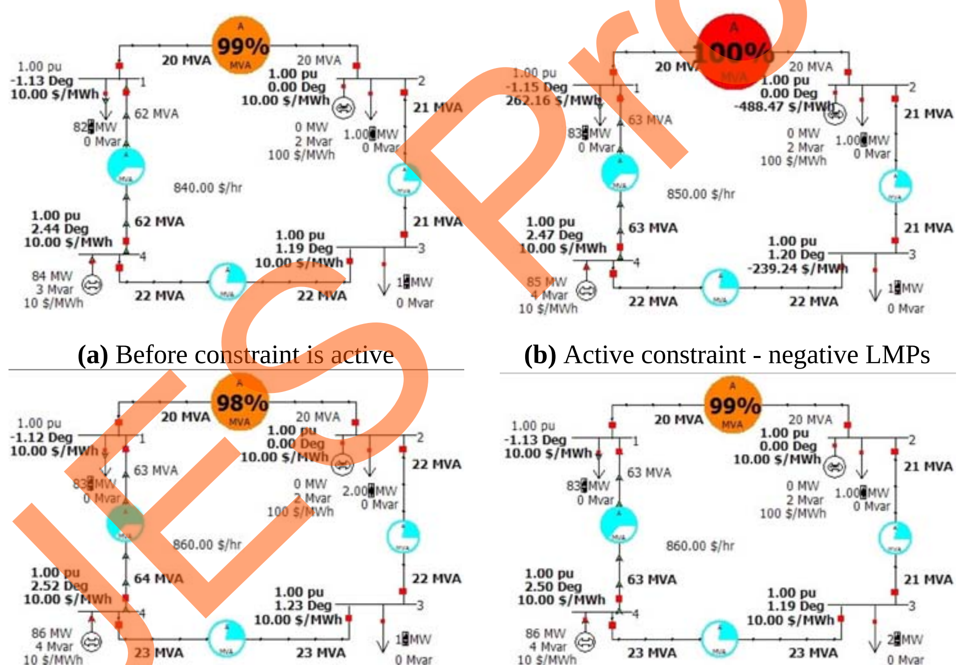
Fig 1: Power System Two Bus Example

An example of a two-bus system shown in Figure 1 explains transmission congestion. In subfigure (a), the maximum real power output of the generator is 50 MW, the transmission line flow limit is 45 MVA and the load is 48 MW. There is a transmission overload in the transmission line to serve the load. Congestion can be alleviated by curtailing some portion of the load. In subfigure (b), the load is curtailed from 48 MW to 45 MW and the congestion is alleviated.

2.2 Negative LMPs

An example of a two-bus system shown in Figure 2 explains transmission congestion. In subfigure (a), the maximum real power output of the generator is 50 MW, the transmission line flow limit is 45 MVA and the load is 48 MW. There is a transmission overload in the transmission line to serve the load. Congestion can be alleviated by curtailing some portion of the load. In subfigure (b), the load is curtailed from 48 MW to 45 MW and the congestion is alleviated.

Negative LMPs can occur in highly congested systems at one or more buses. This is usually always coupled with high LMPs at other buses. Serving an additional MW of load at the negative LMP bus will reduce the operating costs. More flow to the loads at these buses create counterflows that tends to mitigate congestion in an element. This allows for dispatch of cheaper generation, thereby decreasing the overall operating costs. The results are typically neglected and load needs to be reduced to alleviate the congestion in the system. Examples and explanation can be found at PowerWorld's [8] and New England ISO's web sites [9]. An example of a 4 bus power system shown in Figure 2 demonstrates negative LMPs. In subfigure (a), the load at bus 1 is 82 MW and the transmission line from bus 2 to bus 1 is not constrained. The LMPs at all the buses are 10 \$/MWh. In subfigure (b), the load at bus 1 is increased to 83 MW and the line 1-2 is congested and hence the LMP at bus 1 is very high and the LMPs at buses 2 and 3 are negative. From subfigures (c) and (d), the congestion in the line 1-2 can be removed either by increasing the load at bus 2 from 1 MW to 2 MW or by increasing the load at bus 3 by 1 MW respectively. By increasing loads at these buses creates counterflows that avoid congestion costs and for dispatch of cheaper generation.



(a) Before constraint is active

(b) Active constraint - negative LMPs

(c) Increasing load at bus 2 removes constraint

(d) Increasing load at bus 3 removes constraint

Fig. 2: Power System 4 Bus Example

2.3 Methods of Congestion Management

The power flow P_{ij} through the transmission line $i-j$ is a function of the line reactance X_{ij}, the voltage magnitude V_i, V_j and the phase angle between the sending and receiving end voltages $\delta_i - \delta_j$ as shown in equation (1).

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \quad (1)$$

From the Equation (1), one can see that the power flow can be affected by changing the voltage magnitudes, the reactance of the transmission lines or the power angle $(\delta_i - \delta_j)$ Voltage magnitudes can be controlled through VAR support. The reactance of the line can be reduced through series compensation and the power angle can be varied via power injection changes at either bus, e.g. generation or load changes.

In this paper, voltage magnitudes and power angle are considered for congestion management. The three methods of congestion management provided in the tool are:

1. TLR Sensitivities Based Load Curtailment
2. Economic Load Management for Congestion Relief
3. VAR Support

1) TLR Sensitivities Based Load Curtailment

Transmission Line Relief (TLR) sensitivities can be considered as the inverse of the Power Transfer Distribution Factors (PTDFs) [10]. Both TLR sensitivities and PTDFs measure the sensitivity of the flow on a line to load curtailment. PTDFs determine the sensitivity of the flow on an element such as transmission line to a single power transfer. TLR Sensitivities determine the sensitivity of the flow on the single monitored element such as a transmission line to many different transactions in the system. In other words, TLR sensitivities gauge the sensitivity of a single monitored element to many different power transfers.

The TLR sensitivity values at all the load buses for the most overloaded line are considered and used for calculating the necessary load curtailment for the alleviation of the transmission congestion. The TLR sensitivity at a bus k for a congested line $i-j$ is S_{ij}^k and is calculated by

$$S_{ij}^k = \frac{\overline{\Delta P_{ij}}}{\Delta P_k} \quad (2)$$

The excess power flow on transmission line $i-j$ is given by:

$$\overline{\Delta P_{ij}} = P_{ij} - \overline{P_{ij}} \quad (3)$$

where

P_{ij} : Actual power flow through transmission line $i-j$

$\overline{P_{ij}}$: Flow limit of transmission line $i-j$

The new load P_k^{new} at bus k can be calculated by

$$P_k^{new} = P_k - \frac{S_{ij}^k}{\sum_{l=1}^{N} S_{ij}^l} \overline{\Delta P_{ij}} \quad (4)$$

where

P_k^{new} = Load after curtailment at bus k

P_k = Load before curtailment at bus k

S_{ij}^l = Sensitivity of power flow on line $i-j$ due to load change at bus k

N = Total number of load buses

The higher the TLR sensitivity the more the effect of a single MW power transfer at any bus. So, based on the TLR sensitivity values the loads are curtailed in required amounts at the load buses in order to eliminate the transmission congestion on the congested line $i-j$. This method can be implemented for systems where load curtailment is a necessary option for obtaining (N-1) secure configurations.

2) Economic Load Management for Congestion Relief

Another possible solution for congestion management is to find customers who will volunteer to lower their consumption when transmission congestion occurs. By lowering the consumption, the congestion will "disappear" resulting in a significant reduction in bus marginal costs. A strategy to decide how much load should be curtailed for what customer is discussed here. The anticipated effect of this congestion relief solution is to encourage consumers to be elastic against high prices of electricity. Hence, this congestion relief procedure could eventually protect all customers from high electricity prices in a deregulated environment. In [11], a set of indices are introduced to represent the level of effective and agreeable load curtailment in congested conditions. A very brief discussion on these indices is given below. This method has three indices that are computed to calculate the overall index for the load management.

1. Sensitivity Index

The coefficient of the linear relationship between the amount of a transaction and the flow on a line is called the *sensitivity*. Using the sensitivity factor S_{ij}^{k}, the expected change of power flow on the target branch $i-j$, due to a change in load power at bus k is given by

$$\Delta P_{ij} = S_{ij}^{k} \Delta P_{k} \tag{5}$$

The sensitivity factors of different locations of the system are ranked by the following index:

$$\mu_{S_k} = \frac{S_{ij}^{k} - S^{\min}}{S^{\max} - S^{\min}} \tag{6}$$

The $S^{\max}$ is the maximum sensitivity and $S^{\min}$ the minimum. The index μ_{S_k} is highest at 1 for the bus with highest sensitivity and 0 for the bus with the smallest sensitivity.

2. LMP Index

High electricity price is an incentive to reduce load. The following index measures the level of customer incentive to cut down on electricity consumption.

$$\mu_{C_k} = \frac{LMP_k - LMP^{\min}}{LMP^{\max} - LMP^{\min}} \tag{7}$$

LMP_k is the LMP value at bus k, $LMP^{\max}$ and $LMP^{\min}$ are the highest and lowest locational prices, respectively. If μ_{C_k} is 1, the incentive is highest and if μ_{C_k} is 0, there is no such incentive.

3. Customer load curtailment Index

If the required reduction of the power flow on the congested branch is given by ΔP_d, the required amount of adjustment ΔP^k at bus k will be given by

$$\Delta P^k = \frac{\Delta P_d}{S_{ij}^k} \tag{8}$$

Generally, the higher the sensitivity, the smaller the amount of curtailment needed. The customer is supposed to express the acceptable range of curtailment by $P^{\max}$ and $P^{\min}$ at bus k, and the curtailment acceptance level is measured by

$$\mu_{L_k} = \frac{P^{\max} - \Delta P^k}{P^{\max} - P^{\min}} \tag{9}$$

If the index μ_{L_k} is 1 then the required amount of load reduction is in the acceptable range of the customer and if μ_{L_k} is 0 then the required amount of load curtailment is more than the acceptable range.

Overall, the index for a possible load management can then be given by

$$\mu_k = \mu_{S_k} \mu_{L_k} \mu_{C_k} \tag{10}$$

A high μ_k represents a condition where the sensitivity is high, the amount of load curtailed is agreeable, and price incentive is attractive. The load curtailment should be as small as possible and the price after load curtailment should be reduced as much as possible. The load is curtailed at the bus with the highest μ_k value and the amount of load curtailment is ΔP^k.

3) VAR Support for Congestion Relief

In the present day scenario, unplanned power transactions are rapidly increasing due to the competition among utilities to meet increasing demand and if transactions are not properly controlled, transmission lines are often operated and stressed to the limit. The increased use of existing transmission is made possible, in part, by reactive power compensation. The role of VAR support in the open power market is to help manage congestion. Better utilization of the existing power system to increase power transfer capability by installing VAR support such as capacitor banks and FACTS (Flexible AC Transmission Systems) devices becomes imperative. Capacitors, Static VAR Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), Unified Power Flow Controller (UPFC) are some of the examples of FACTS devices used for VAR support.

The main advantage of FACTS devices is the possibility of their installation for a short period compared to the planning and construction of new transmission lines. FACTS not only improve the transmission capacity but also reduce the losses. However, FACTS devices are expensive. The investment cost of FACTS devices as described in [12] can be categorized as 1) device equipment cost, 2) necessary infrastructure cost, and 3) operation maintenance.

3. POWER MARKET ANALYSIS TOOL (PMAT)

3.1 Outline of PMAT

PMAT is a MATLAB interface tool that provides access to the PowerWorld simulator functionality via SimAuto. MATLAB's object-oriented programming capabilities are used for implementing an API and a GUI. A one line diagram of the test system has to be designed in PowerWorld before PMAT can be used. The tool helps in adding, modifying, and retrieving data from the simulator at run time and to change settings and run case studies. The outline of the Power Market Analysis Tool and its main features is shown in

Figure 3. PMAT takes the bid curves and system conditions from the MATLAB user's application. It loads the PowerWorld binary (*.pwb) data file for solving the power flow computations using PowerWorld simulator. PMAT implements the congestion relief methods to obtain (N-1) secure configurations.

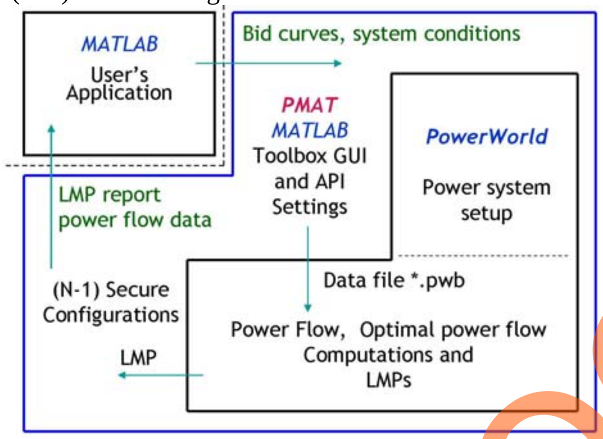


Fig. 3: Outline of PMAT

3.2 Workflow of PMAT

The flow chart showing the steps and workflow of a case study using PMAT is given in Figure 4.

3.3 Output Data

The results of the power flows can be saved as a *.txt file after every power flow. The results provided in the report for different power flows are:

- Power Flow: Provides the parameters for buses, transmission lines, generators, loads, and switched shunts.
- OPF and SCOPF: Provides all the data of the power flow and also generator bids and limits, load bids and limits, LMPs at the buses, operating cost and losses in the system.

PMAT also provides a graphical view of the power flow results. The following are various plots available in PMAT:

1. The LMPs at all the buses for the test system in case of OPF and SCOPF with and without contingencies
2. LMP statistics which include the Average, Maximum, Minimum, Average±Standard Deviation
3. Voltage magnitudes
4. Voltage phase angles
5. Transmission line flows and limits
6. Generator cost function
7. Load cost function

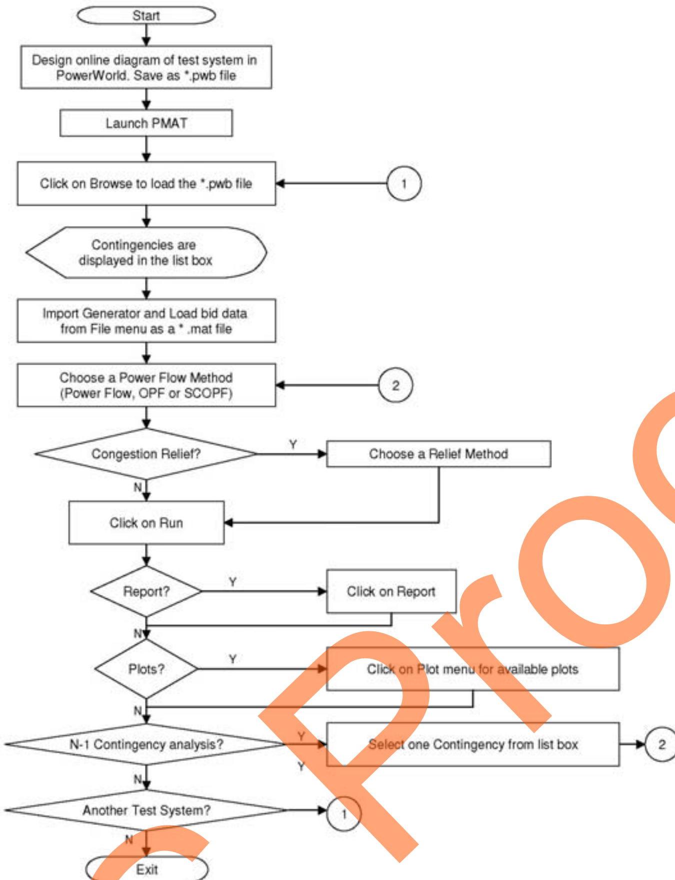


Fig. 4: Flow Chart of PMAT

4. TEST SYSTEM

The IEEE 24-bus Single Area Reliability Test System is a relatively large system with 24 buses including 33 generators, 17 loads, and 37 lines. Some of the transmission line MVA limits are modified in the test system in order to increase the transmission congestion in case of contingencies and demonstrate the effect of various congestion relief techniques provided in PMAT. The transmission line from bus 6 to bus 10 is out of service (disconnected) because of its high susceptance value when the power flow is run the line 6-10 is heavily congested. The one line diagram of IEEE 24-bus Single Area RTS is shown in Figure 5.

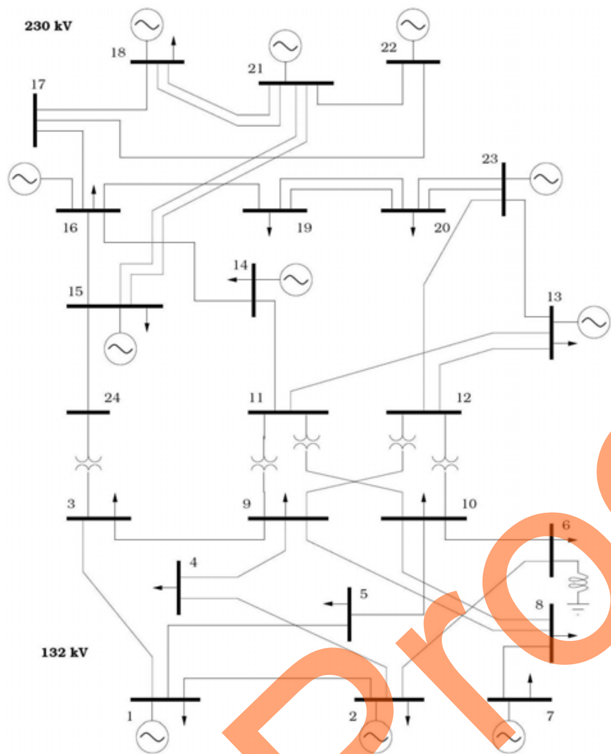


Fig. 5: Single line diagram of IEEE 24 Bus Single Area Reliability Test System [13]

4.1 LMP Statistics

There are 70 contingencies altogether (33 generators + 37 transmission lines) for the IEEE 24 bus RTS. The LMP statistics before and after congestion relief for the IEEE 24 bus RTS are discussed in this section.

The LMP statistics for 70 (N-1) contingencies are shown in Figure 6. The maximum LMP value is as high as 2200 \$/MWh. The average LMPs at almost all the buses are around 30 \$/MWh but at bus 6 the average LMP is as high as 200 \$/MWh as the transmission line from bus 2 to bus 6 is the most congested line for many contingencies.

LMP Statistics for TLR Sensitivity Relief Method: The LMP statistics after the TLR sensitivity congestion relief method for 70 (N-1) contingencies are shown in Figure 7. The average LMPs at almost all the buses are 29 \$/MWh which explains that by appropriate amount of load curtailment, the LMPs are not very high even under contingencies.

LMP Statistics for Economic Load Management: The maximum and minimum load curtailment parameters P^{max} and P^{min} are assumed to be 35% and 5% of the load at each load bus, respectively. The index for load reduction is the product of the three indices and the maximum value of the overall index is considered to curtail the load at the corresponding load bus. The LMP Statistics after the Economic Load Management congestion relief method for 70 (N-1) contingencies are shown in Figure 8. It can be observed that the maximum LMP at bus 6 has again reduced from 2200 to 29 \$/MWh.

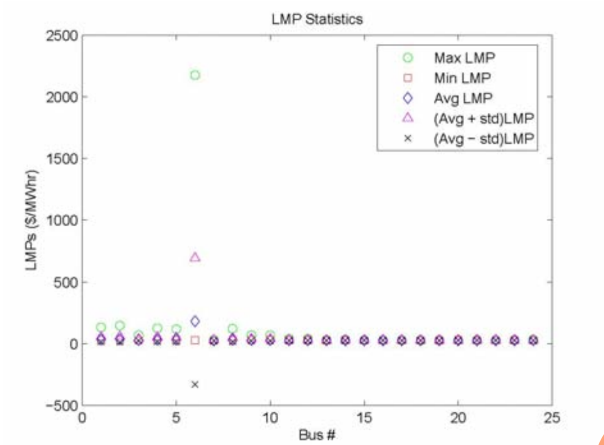


Fig. 6: LMP Statistics of IEEE RTS for 70 (N-1) contingencies without Congestion Relief

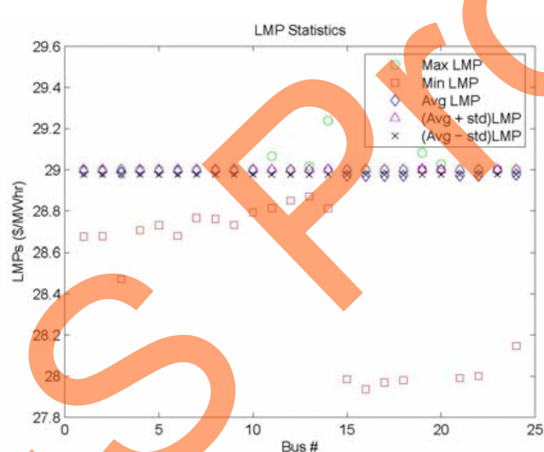


Fig. 7: LMP Statistics of IEEE RTS for 70 (N-1) contingencies with TLR Sensitivity Method

<u>LMP Statistics for VAR Support:</u> It is assumed that VAR support (Switched Shunts) is installed at the buses initially but is disconnected from the system. The IEEE 24 bus RTS has already two VAR support devices provided with the system data. A capacitor with 100 MVAR capacity is connected at bus 6 and a synchronous condenser with 200 and -50 as the maximum and minimum MVAR limits is connected at bus 14. Apart from the most congested line between the buses 2 and 6, second line that is congested most often is line from bus 7 to bus 8. Therefore a switched shunt with 30 MVAR capacity is connected at bus 8. This additional VAR support is supplied to the system when the congestion relief with VAR support is chosen.

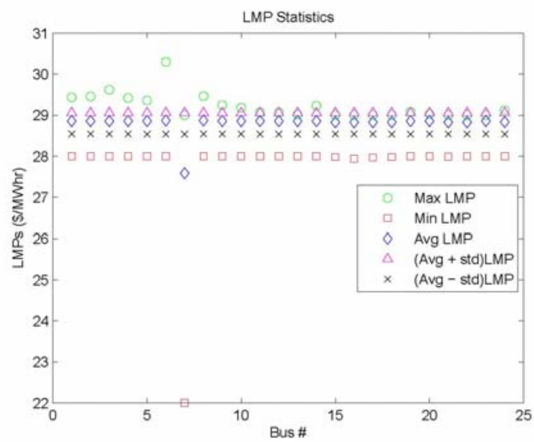


Fig. 8: LMP Statistics of IEEE RTS for 70 (N-1) contingencies with Economic Load Management Method

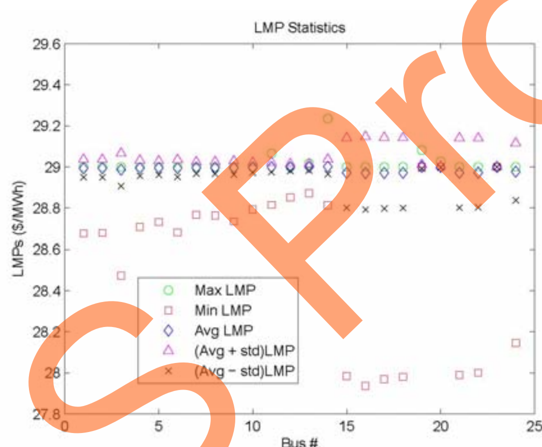


Fig. 9: LMP Statistics of IEEE RTS for 70 (N-1) contingencies with VAR Support

Comparison of load curtailment for different VAR support

The data given in Table 1 compares the maximum amount of load served through different MVAR capacities of VAR support to obtain (N-1) secure LMPs. A switched shunt with maximum value of 30 MVAR capacity is used as additional VAR support at bus 8. Load curtailment is minimal for highest MVAR capacity.

Table 1: Max load served for 70 (N-1) contingencies - IEEE 24 Bus RTS

MVAR Capacity	Total Load (MW)	Curtailment (MW)
30	2831.98	18.02
25	2826.78	23.22
20	2818.04	31.96
15	2810.55	39.45
10	2800.00	50.00
5	2785.98	64.02
1	2766.00	84.00

Comparison of three Congestion Relieving Methods

The load curtailment requirements to obtain (N-1) secure LMPs are different for the three congestion relieving methods. From Table 2 it can be observed that by installing VAR support at the load buses, the requirement for load curtailment is the least. The Economic Load Management curtails the most load to obtain (N-1) secure LMPs. Of course though the VAR support serves most load is the most expensive method of congestion relief methods presented as it requires additional components. Sensitivity Analysis method is the simple and fair method to alleviate transmission congestion for obtaining secure LMPs for the IEEE 24 bus RTS. The effect of the relieving methods may vary from one power system to another power system. PMAT helps in analyzing the power system to choose the best method for congestion relief.

Table 2: Comparison of all the Congestion Relief Methods - IEEE 24 RTS

Congestion Relief Method	Total Load (MW)	Curtailment (MW)	Average LMP	Min LMP	Max LMP	STD
None	2850	--	200	29	2200	550
TLR Sensitivity	2764.95	85.05	29	27.9	29.2	0.1
Economic Load Management	2673	177	29	22	30.2	1.5
VAR Support	2831.98	18.02	29	27.9	9.22	0.2

5. CONCLUSIONS

Load curtailment is sometimes a necessary option to reduce congestion. The LMPs can be very high and even negative in congested power systems. This paper provides the user a tool to analyze the different congestion managements options. Specifically, a Power Market Analysis Tool (PMAT) developed in this paper creates an interface between PowerWorld, a professional power flow software, and MATLAB. The tool helps analyze power flow results, batch-process large case studies, and provide the user with options to manage congestions. A graphical user interface has also been designed. Among the three congestion relief options, VAR support serves the maximum load but is not cost effective. In alternative relief methods, the TLR sensitivity method serves more load than the Economic load management method. TLR sensitivity is simpler than Economic load management as it does not include customer choices. The tool is demonstrated using the IEEE 24 bus Reliability Test System.

Acknowledgment

This research is sponsored in part by grants from the US DoE and the US DEPSCoR/ONR (DOD/ONR N000 14-031-0660).

References

[1] Goncalves, M. J. D., Z. A. Vale, Evaluation of transmission congestion impact in market power, *IEEE Bologna Power Tech Conference*, Vol.4, pp. 6, June 2003.

[2] Huang, G. M., Ping Yan, The impacts of TCSC and SVC on power system load curtailments, *IEEE Power Engineering Society Summer Meeting*, Vol. 1, pp. 33-37, July 2001.

[3] Song, Y. H., Phichaisawat, S., Taylor, G. A., Congestion management considering voltage security constraints, *International Conference on Power System Technology*, Vol. 3, pp. 13-17, October 2002.

[4] Srivastava, S. C., Perveen Kumar, Optimal power dispatch in deregulated market considering congestion management, *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, pp. 53-59, April 2000.

[5] Xiaoming Feng, Jiuping Pan, Le Tang, Henry Chao, Jian Yang, Economic evaluation of transmission congestion relief based on power market simulations, *IEEE Power Engineering Society General Meeting*, Vol. 2, pp. 13-17, July 2003.

[6] Yuen, Y. S., Lo, K. L., Snider, L. A., Congestion management in deregulated electricity markets, *IEEE International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, pp. 47-52, April 2000.

[7] PowerWorld, Online: *http://www.powerworld.com*, last accessed January 2008.

[8] PowerWorld, Negative LMPs, Online: *http://powerworld.com/support/faq.asp*, last accessed January 2008.

[9] New England ISO, Online: *http://www.iso-ne.com/support/training/5bus/index.html*, last accessed January 2008.

[10] Yan, H. H., PTDF and TLR From A Power Marketer's Perspective, *Proceedings: IEEE Power Engineering Society Summer Meeting*, Vol. 1, pp. 156-161, July 1999.

[11] Niimura, T., Niu, Y., Transmission congestion relief by economic load management, *Proceedings: IEEE Power Engineering Society Summer Meeting*, Vol. 3, pp. 1645-1649, July 2002.

[12] Habur, K., Oleary, D., A FACTS - flexible AC transmission systems for cost effective and reliable transmission of electrical energy, Online: *http://www.siemenstd.com/TransSys/pdf/CostEffectiveReliabTrans.pdf*, last accessed January 2008.

[13] Reliability Test System Task Force of the Application of Probability Methods Subcommittee, The IEEE Reliability Test System - 1996, *IEEE Transactions on Power Systems*, Vol. 14, No.3, August 1999.