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Transmission Congestion Management Comparative Studies In Restructured Power System

J.Srinivasa Rao,
Faculty,
EEE Department,
QIS College of Engineering &Technology,Ongole.
jsreee123@yahoo.co.in

Dr.J.Amarnath,
Professor,
Department of EEE,
JNTU College of Engineering,Hyderabad.
Amarnathjinka@yahoo.com

Abstract— The deregulated power system offers more benefits to the customers so that it is quite popular in now a days. Due to the enormous rise of power demand, the existing power system is operated very closer to its stability limits. So we get two major problems like transmission congestion and voltage instability problems in power system. These are very serious problems which causes severe damage to the total power system. Due to the congestion in the network, there is not always possible to transmit the entire contracted power at all situations. The above mentioned problems are managed by using series FACTS devices. But for getting more benefits from these FACTS devices, we place those devices in optimal location. In this paper two different methodologies such as sensitivity approach and pricing approaches were going to be discussed to place the series FACTS devices in optimal location to manage the transmission congestion and voltage instability problems. These methods are tested on modified IEEE 14 bus system.

Index Terms— Deregulated power system, congestion, Total VAR power losses, Thyristor Controlled Series capacitor (TCSC), Transmission Load Relief (TLR) factors, Locational Marginal Pricing (LMP), Total Congestion Cost (TCC), Congestion Cost/Rent Contribution (CCC).

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1 Introduction

The transmission network is a vital mechanism in competitive electricity markets. In present days all our basic needs are relates with electricity. Like the growth of population, the demand for electricity is also tremendously increases day to day. So there may be a need to enhance either the existing power system or establish the new system to supply the power to meet the particular load demands. The establishment of new power system is very costliest choice. So we mostly concentrate on the first choice that is enhancing the existing power system. The main objective of the deregulation of a power industry is creating a competitive environment in between the power producers and prevents monopolies and also provides many choices to consumers to pick up a good utility. Due to the lack of coordination in between generation and transmission utilities, transmission congestion is occurs. So due to this transmission congestion, there may not be possible to dispatch all contracted power transactions. The series FACTS device TCSC is placed in series with the line for congestion management. In [1], sensitivity approach is used to find the optimal location for placement of TCSC[6].The reduction of total system reactive power losses method is one used to find optimal location of FACTS devices [4-5]. In this method, an over loaded sensitivity factor (power flow index) is used for optimal location of series FACTS device (i.e. TCSC) for static congestion management[7-8]. But for large systems, this enumerative approach is not practical given to the large number of combinations that have to be exam. In [2], here congestion is managed by Transmission line relief (TLR) method used in deregulated power industry [3]. Moreover, as power flows influence transmission charges, transmission pricing may not only determine the right of entry but also encourage efficiencies in power markets. During the last few years, different transmission pricing schemes have been proposed and implemented in various markets. In the new environment, it is essential to involve transmission tariffs in transmission pricing according to flow-based pricing and congestion-based pricing. A proper pricing scheme should allocate congestion charges to participants who cause congestion and should reward participants whose schedules tend to relieve congestion. In a competitive market, such an occurrence would cause different locational marginal prices (LMPs) between the two locations [9]. If transmission losses are ignored, a difference in LMPs would appear when lines are congested. Congestion rent method and congestion rent contribution methods are also used to find the optimal location of placement of FACTS devices to alleviate congestion and as well as used to reduce congestion rents [10].

2 Modeling [Static] Of TCSC

For static application like congestion management FACTS devices can be modelled as power injection model. The TCSC model shown as follows

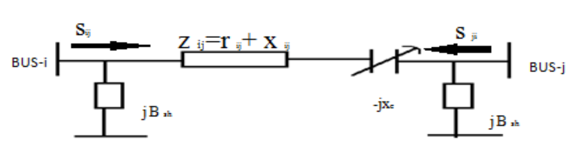

Fig1. Modelling of TCSC

Let the complex voltage at bus i and bus j be denoted as $V_i \angle \delta_i$ and $V_j \angle \delta_j$ respectively. The expression for real and reactive power flows from bus i and j can be written as follows

$$P^c_{ij} = V_i^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} \cos\delta_{ij} + \Delta B_{ij} \sin\delta_{ij}) \quad (1)$$

$$Q^c_{ij} = -V_i^2 (B_{ij} + B_c) - V_i V_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) \quad (2)$$

Similarly, the real and reactive power flows from bus i to bus j can be expressed as,

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} \cos \delta_{ij} + \Delta B_{ij} \sin \delta_{ij}) \quad (3)$$

$$P_{jc} = V_j^2 \Delta G_{ij} - V_i V_j (\Delta G_{ij} \cos \delta_{ij} + \Delta B_{ij} \sin \delta_{ij}) \quad (4)$$

$$Q_{ic} = -V_i^2 \Delta B_{ij} - V_i V_j (\Delta G_{ij} \sin\delta_{ij} - \Delta B_{ij} \cos\delta_{ij}) \quad (5)$$

$$Q_{jc} = -V_j^2 \Delta B_{ij} + V_i V_j (\Delta G_{ij} \sin\delta_{ij} + \Delta B_{ij} \cos\delta_{ij}) \quad (6)$$

Where $\Delta G_{ij} = \frac{x_c\, r_{ij}\, (x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)\,(r_{ij}^2 + (x_{ij} - x_c)^2)}$

& $\Delta B_{ij} = \frac{-x_c\,(r_{ij}^2 - x_{ij}^2 + x_c\, x_{ij})}{(r_{ij}^2 + x_{ij}^2)\,(r_{ij}^2 + (x_{ij} - x_c)^2)}$

3 Selection Of Best Location For TCSC Placement

The optimal location of FACTS devices is one of the important concepts. The main goal of the congestion management is to perform a best utilization of the existing transmission lines.

3.1 Optimal placement of TCSC based on sensitivity approach

Based on sensitivity approach, we find the optimal location of TCSC for congestion management. The static conditions are considering here for the placement of FACTS devices in the power system. The objectives for device placement may be one of the following:

1.Total system real power losses are reduced
2.The real power loss of a particular line is reduced
3.The total system reactive power losses are reduced
4.Maximum relief of congestion in the system

For the first three objectives, methods based on the sensitivity approach may be used. If the objective of FACTS device placement is to provide maximum relief of congestion, the devices may be placed in the most congested line or, alternatively, in locations determined by trail-and-error.

3.1.1 Total system VAR power loss

A method based on the sensitivity of the total system reactive power loss with respect to the control variable of the TCSC.Net line series reactance (X_{ij}) for a TCSC placed between buses i and j,The reactive power loss sensitivity factors with respect to these control variables may be given as follows:
Loss sensitivity with respect to control parameter X_{ij} of TCSC placed between buses i and j,

$$a_{ij} = \frac{\partial Q_L}{\partial X_{ij}} \quad (7)$$

These factors can be computed for a base case power flow solution. Consider a line connected between buses i and j and having a net series impedance of X_{ij}, that includes the reactance of a TCSC, if present. The loss sensitivities with respect to X_{ij} can be computed as:

$$a_{ij} = \frac{\partial Q_L}{\partial X_{ij}} = [V_i + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \frac{R_{ij}^2 - X_{ij}^2}{(R_{ij}^2 + X_{ij}^2)^2} \quad (8)$$

With the sensitivity indices computed for TCSC following criteria can be used for its optimal placement.In reactive power loss reduction method TCSC should be placed in a line having most positive loss sensitivity index

3.2. Load curtailment method based on TLR sensitivities:

Transmission load relief sensitivities can be used for the purpose of congestion alleviation by load curtailment. In the method of congestion alleviation using load curtailment, TLR sensitivities at all load buses for the most overloaded line is considered**.** The TLR sensitivity at a bus k for a congested line i-j is S_{ij}^k and is calculated by

$$S_{ij}^k = \frac{\Delta P_{ij}}{\Delta P_k} \quad (9)$$

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

$$\Delta P_{ij} = P_{ij} - \Delta P_{ij}^* \quad (10)$$

Where P_{ij} = actual power flow through transmission line i-j
P_{ij}^* = flow limit of transmission line i-j
ΔP_k = change in load after curtailment at bus k

3.3. Pricing methods

3.3.1.locational marginal pricing (LMP) method:

LMP is the marginal cost of supplying the increment of electric energy at a specific bus considering that generation marginal cost and the physical aspects of the transmission system. LMP is given as

LMP = Generation marginal cost + Congestion cost + Cost of marginal losses.

Mathematically, LMP at any node in the system is the dual variable for the equality constraint at that node. Or, LMP is the additional cost for providing one additional MW at a certain node.
Using LMP, buyers and sellers experience the actual price of delivering energy to locations on the transmission systems. The difference in LMPs appears when lines are constrained. If the line flow constraints are not included in the optimization problem or if the line flow limits are assumed to be very large, LMPs will be the same for all buses, and this is the marginal cost of the most expensive dispatched generation unit (marginal unit). In this case, no congestion charges apply. However, if any line is constrained, LMPs will vary from bus or zone to bus or zone, which may cause possible congestion charges.
For finding the optimal location FACT device to manage congestion, the LMP difference method is one which makes the use of economic signal given by LMP. It is motivated from the fact that LMP contains significant information regarding level of congestion in the system. For a meshed system, generally loss component is neglected because it is small. Hence, the difference in LMP between two buses gives direct hint regarding the level of congestion in that line.
The congested or over headed lines (i.e. line operating at a limit) have the highest LMP difference. The overloaded lines are not always the best location for the placement of series FACTS devices, a neighbourhood search method is required which will be taken care by formation of priority list.
Hence, in this method, a priority list is formed based on the magnitude of the difference in LMPs. Priority list will essentially capture the congested lines as well as the neighbourhood lines that are linked to the congested lines through which the power can be diverted when FACTS is placed. There are no specific rules for taking the number of priorities. The number of lines to be considered for priority list depends on the size of the system. But however, it should be greater than the number of congested lines in the net-

work.

This LMP difference method had the benefit that is it avoids the excessive computation and it directly founds the optimal location for placement of FACTS device from OPF result using priority list. Only few lines in the priority list need to examined in detail to access the best location. Since, these methods make use of economic signal given as LMP; it is easily applicable in the deregulated electricity environments. This method presents the additional advantage, where historical LMP values can be used to analyze the best location and avoid risk associated with improper installation.

3.3.2. Congestion rent method:

The LMP or spot price at each bus is location specific and differs by the congestion and loss components. If the transferring or retrieving of power at a particular bus increases the total system losses. Then cost of power at that particular location increases. Similarly, if any transmission line limit is binding, then corresponding μ_{Lij} will be non- zero and will have effect on prices at all buses. If the transferring or extracting at a particular bus increase the flows across the congested interface, then LMP at that bus increases. For a case of real power spot price at bus i

$$P_i = \lambda + \lambda_{L,i} + \lambda_{C,i} \quad (11a)$$

Similarly, for bus j, the LMP can be denoted as follows

$$\rho_j = \lambda + \lambda_{L,j} + \lambda_{C,j} \quad (11b)$$

Taking the LMP difference between two buses I and j.

Therefore $\Delta \rho_{ij} = (\lambda_{L,i} - \lambda_{L,j}) + (\lambda_{C,i} - \lambda_{C,j})$
(12)

From the above equation says that the LMP or spot price difference between any two buses depend on the marginal losses and the congestion throughout the network. The price differential, by definition gives the congestion rent. The surplus arises because generators are compensated by LMP at the respective generator buses (which are generally low) and loads are charged by LMP at the respective load buses (which are generally high).

The calculation of total congestion rent is represented as follows

$$TCC = \sum_{ij=1}^{N_L} \Delta \rho_{ij} P_{ij} \quad (13)$$

Congestion rent contribution method is one of advanced method for managing congestion . In this method the percentage congestion contributed value is taken for priority list. The locational marginal price difference method is very simple and its implementation is also is easy. However, there can be a situation where a line of low rating is congested, that might lead to a large difference in LMP across that line. However, the effect in terms of congestion rent to the market participant due to such congested line may not be significant. The priority list formed by LMP difference alone may not capture the best possible location in such cases. So to make the method more reliable, a proposed method is modified with the smaller computations.

In this new method, the LMP difference is multiplied by the power flow through the line, which is nothing but the congestion rent in the base case. This value can be divided by the total congestion rent. So this will be the congestion rent contribution value. Therefore, if the LMP difference is high but power flow is small, this line is not represented in the priority list and makes the analysis more accurate.

The priority ranking is purely based on the congestion rent contribution of individual lines in the base case. If historical LMP values are used to find the best location for the placement of FACT devices, then additional calculation is needed for this refined method is just the load flow calculation to determine the power flow through each line section. It can be performed relatively quickly and efficiently.

The formula for calculation of congestion rent of individual line section is as follows

$$CC_{ij} = \Delta \rho_{ij} P_{ij} \quad (14)$$

The congestion rent contribution of individual line is written as follows

$$CCC_{ij} = \frac{CC_{ij}}{TCC} \quad (15)$$

3.4. PROCEDURE

The procedure for calculation of LMP difference method and congestion rent contribution method is as follows:

- **Step 1**: Firstly run the base case OPF to calculate the power flow in all line sections and LMP values at all buses.
- **Step 2**: Calculate the total congestion rent and the value of the objective function (i.e. total generation cost or total social welfare) with the run OPF by placing TCSC in lines and with LMP values.
- **Step3: C**alculate the absolute LMP difference value and arrange in descending order of magnitude to form priority list (for LMP difference method).
- **Step4:** Calculate congestion rent contribution of individual lines (using equations) using LMP values and power flows calculated in step 1 and total congestion rent calculated in step 2. Then arrange the values in descending order of magnitude to form priority list (for congestion rent contribution method).
- **Step5:** The best location of TCSC is the one where by placing TCSC gives the minimum congestion cost or minimum value of the objective function (i.e. minimum generation cost or maximum social welfare). If the founded best location is in between two generator buses, then the next best location is selected.

4. Results and discussions

4.1. Sensitivity approach:

In this study the modified IEEE 14 bus system has been analysed for congestion management by the optimal location of FACTS device such as TCSC using the power world simulator software based on sensitivity indices approach. Fig 2 indicates the single line diagram of modified IEEE 14 bus system. Fig 2 shows the transmission line flows without TCSC. It is observed that the line 1-2 is congested/overloaded compared to other lines. The percentage loadability values of modified IEEE 14 bus system is tabulated(Table.1) below. From the table 1, the highest loadable line is 1-2. Due to the increased loading this line is congested. So by using TCSC, congestion is alleviated. For placing TCSC at optimal location we will use sensitivity analysis. The sensitivity indices table of modified IEEE 14 bus system is shown in below

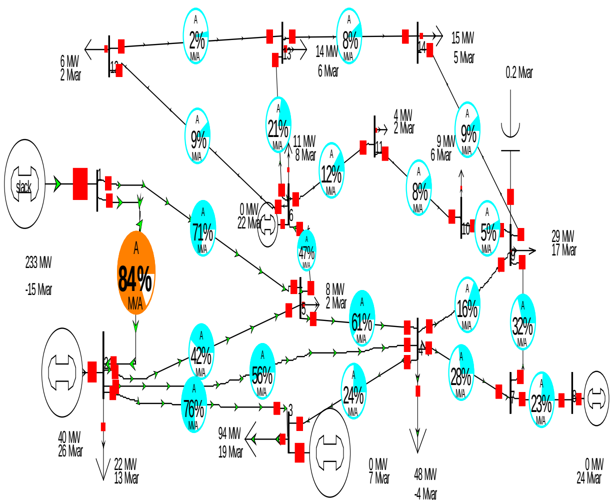

Fig 2: Modified IEEE 14 bus system without TCSC

Lines	From bus	To bus	Lodability (%)
1	1	2	84.2
2	1	5	70.7
3	2	3	75.5
4	2	4	56
5	2	5	41.8
6	3	4	24.1
7	4	9	15.8
8	4	5	61.1
9	5	6	47.1
10	6	11	11.6
11	6	12	8.6
12	6	13	20.6
13	4	7	27.8
14	7	9	31.5
15	7	8	23.1
16	9	10	4.5
17	9	14	8.8
18	10	11	7.6
19	12	13	2.3

Table1: OPF results without TCSC

Lines	From bus	To bus	Sensitivity index
1	1	2	-3.345153
2	1	5	**0.650905**
3	2	3	-0.408476
4	2	4	-0.241770
5	2	5	0.238214
6	3	4	-0.799789
7	4	5	-7.943644
8	4	7	-0.969198
9	4	9	-0.076715
10	5	6	-0.064863
11	6	11	-0.026468
12	6	12	-0.059494
13	6	13	-0.229679
14	7	8	-0.000486
15	7	9	-1.809541
16	9	10	-0.043225
17	9	14	-1.000418
18	10	11	-0.06203
19	12	13	0.000309
20	13	14	-0.0000028

Table 2: Sensitivity index values

From the above table 2, the line 1-5 has the most positive sensitivity factor. So this is the best location for placement of TCSC to relieve congestion in the network. By placing the TCSC in line 1-5, the congestion in the network is relieved.

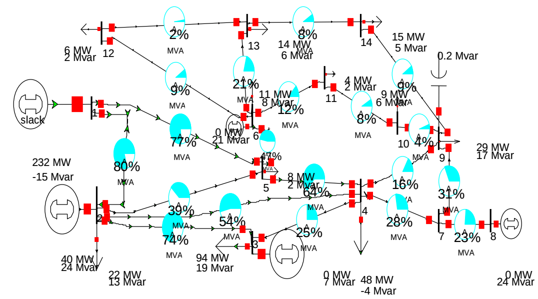

Fig 3: Modified IEEE 14 bus system with TCSC in line 1-5

The fig 3 shows the transmission line flows with TCSC. It is observed that after placing TCSC the congestion in the network is relieved.The comparison of power flows of modified IEEE 14 bus system with and without TCSC is shown in fig-4. The comparison of voltage profiles of modified IEEE 14 bus system with and without TCSC is shown in fig-5.

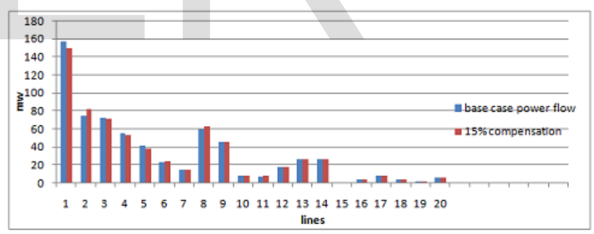

Fig 4: Comparison of power flows of modified IEEE 14 bus system with and without TCSC

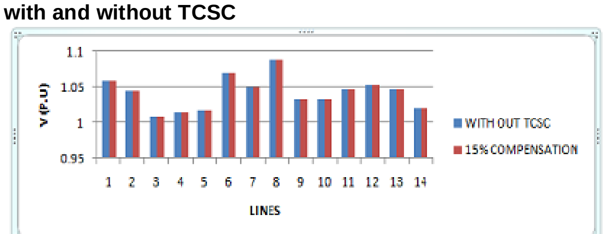

Fig 5: Comparison of voltage profiles of modified IEEE 14 bus system with and without TCSC

4.2.Transmission Load Relief (TLR) sensitivity method:

This transmission load relief method is based on the load curtailment. In this method of congestion management, TLR sensitivities at all the load buses for the most overloaded line are considered.

The TLR sensitivity values of modified IEEE 14 bus system is shown in table3.

Buses	Congested Line 1-2	Buses	Congested Line 1-2
1	-0.838	8	-0.181
2	0	9	-0.186
3	**-0.091**	10	-0.190
4	-0.171	11	-0.199
5	-0.227	12	-0.206
6	-0.208	13	-0.205
7	-0.181	14	-0.194

Table3: TLR sensitivities

From the above table 3, the most positive sensitivity factor having the bus is bus3. So by doing the load curtailment on bus3 i.e. from 94.2 M.W to 83 M.W. Then the congestion of the line 1-2 is relieved from 84% to 79%. So by doing load curtailment based on TLR sensitivity method at bus3 the congestion is relieved ,shown in fig 6.

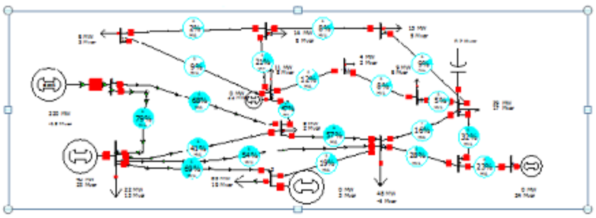

Fig 6: Congestion relief by load curtailment at bus 3

4.3. Pricing approach:

The proposed methodologies are tested on modified IEEE 14 bus system. The generator cost coefficients for modified IEEE 14 bus system is shown as follows

Generator number	Bus number	a (Rs/MW^{2}h)	b (Rs/MWh)	C (Rs/h)
1	1	1.3719	871.04	0
2	2	7.6216	762.16	0
3	3	27.22	435.52	0
4	6	3.6311	1415.44	0
5	8	10.8880	1306.56	0

Table 4: Generator cost coefficients for modified IEEE 14 bus System

These cost data is given to the generators and by using cubic cost model method, the system is analysed. The list of priority table based on OPF result with TCSC for modified IEEE 14 bus system is shown as follows

Priority number	Congestion rent with TCSC Total congestion rent (Rs/h)	TCSC location
1	136689.573	LINE1:1-2
2	57752.52	LINE2:1-5
3	8294.4	LINE5:2-5
4	7532.06	LINE4:2-4
5	4783.0068	LINE7:4-5
6	2662.7496	LINE 6:3-4
7	2322.03	LINE3:2-3
8	358.547	LINE13:6-13
9	11.8864	LINE 19:12-13
10	11.74362	LINE16:9-10

Table 5: Priority table based on OPF with TCSC for modified IEEE 14 bus systems

From the above table 5, the congestion rent values with placing of TCSC at particular line are showed. Here we choosen10 best locations for placing of TCSC. From the table the line 1[1-2] has higher congestion rent. That means the line 1 is over loaded/ congested. So by placing the FACTS device, at that line congestion is going to be relieved. But over loaded lines are not always the best locations for placement of series FACTS devices. So by placing the FACTS device in line1 [1-2] is not so advantageous. So from the priority list we picked up the next location for placement of TCSC. Now by placing the TCSC in line 2[1-5], the congestion of the network is relieved and also the total congestion cost is decreases from 136689.573(Rs/h) to 57752.52(Rs/h). So by placing TCSC in optimal location, we got two benefits. One is congestion is relieved and another is congestion rent is reduced.

The priority list based on LMP difference table for modified IEEE 14 bus system is shown as follows

Priority number	LMP difference (Rs/MWH)	Priority location
1	913.09	LINE1:1-2
2	698	LINE2:1-5
3	140.76	LINE4:2-4
4	107.76	LINE6:3-4
5	75.24	LINE7:4-5

Table 6: Priority table based on LMP difference for modified IEEE 14 bus system

From the above table 6, shows the priority list based on LMP differences for placement TCSC in optimal location. The line 2[1-5] is best location for placement of TCSC for relieving congestion. It is the second priority in the LMP difference table. This proves the effectiveness of the LMP difference method. The LMP differences were reduced by placing the TCSC at optimal location using LMP difference method.

The priority list based on the congestion rent contribution method for modified IEEE 14 bus system is shown as follows

Priority number	Congestion rent contribution (%)	Priority location
1	58.25	LINE1:1-2
2	24.61	LINE 2:1-5
3	3.53	LINE5:2-5
4	3.209	LINE4:2-4
5	2.038	LINE7:4-5

Table 7: Priority table based on congestion rent contribution for modified IEEE 14 bus system.

Table 7 shows that the result of congestion rent contribution method, where priority list is formed according to the contribution of each line to total congestion rent. The congestion rent contribution table also reveals that the best location for placing TCSC is line 2[1-5]. This line 2[1-5] is the second priority in the congestion rent contribution table.

So these efficient proposed pricing methodologies give the best optimal location for placement of TCSC to relieves the congestion of the network and as well as reduces the congestion rents, locational marginal prices.

5 CONCLUSION:

In the environment of deregulated power system, congestion management is the quite critical task. In this paper there are two different approaches were proposed to predict the optimal location for placement of series FACTS devices such as TCSC to alleviate the congestion in the power system. Based on the total system VAR power loss and TLR sensitivity methods we found optimal location for placing of TCSC to manage the congestion. In pricing methods, we discussed about LMP difference, congestion rent and congestion rent contribution methods. These methods gave the priority list, so based on priority list we place the FACT device in proper location to manage the congestion in the power system. These proposed methods were successfully tested on modified IEEE 14 bus system and these pricing methods were correctly capture the best locations than sensitivity methods, for placing series FACTS devices to alleviate the congestion and also where the non-linearity associated with the systems too.

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