

# IMPROVING CONGESTION OF TRANSMISSION SYSTEM BY OPTIMAL PLACEMENT OF FACTS DEVICES

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*Abstract— In a deregulated electricity market, it may always not be possible to dispatch all of the contracted power transactions due to congestion of the transmission corridors. The ongoing power system restructuring requires an opening of unused potentials of transmission system due to environmental, right-of-way and cost problems which are major hurdles for power transmission network expansion. Flexible AC Transmission Systems (FACTS) devices can be an alternative to reduce the flow in heavily loaded lines, resulting in an increased loadability, low system loss, improved stability of the network, reduced cost of production and fulfilled contractual requirement by controlling the power flows in the network. A method to determine the optimal location of Thyristor Controlled Series Compensators (TCSC) is suggested in this present work. In case of TCSC, optimal location is determined based on real power performance index, based on reduction of total system VAR power losses and based on reduction of total system Active power losses.*

## I. INTRODUCTION

As restructuring and deregulation deepen in the electric power industry, open access is gaining greater attention. Open access implies that the opportunity to use the transmission system must be equally available to all buyers and sellers. This is an important step to promote the deregulation of the electricity supply system. Transmission networks are one of the main sources of difficulties on fair implementation of electricity restructuring.

The limitations of a power transmission network arising from environmental, right-of-way and cost problems are fundamental to both bundled and unbundled power systems. Power flow in lines and transformers should not be allowed to increase to a level where a random event could cause the network collapse because of angular instability, voltage

instability or cascaded outages. Transmission congestion may be defined as the condition where more power is scheduled or flows across transmission lines and transformers than the physical limits of those lines. Transmission congestion may prevent the existence of new contracts, leads to additional outages, increase the electricity prices in some regions of the electricity markets, and can threaten system security and reliability [1, 2, 3, 4]. The objective of congestion management is to take actions or control measures to relieve the congestion of transmission networks.

Reactive power plays an important role in supporting the real power transfer across a large-scale transmission system [5]. Reactive support is generally provided by the switching of shunt capacitors, the positioning of transformer taps and the reactive power outputs of generators. Thus, the Var support requirement from generators and capacitors to manage congestion along with real power rescheduling poses a great challenge to System Operator (SO) in an open-access electricity market.

Various congestion management schemes suitable for different electricity market structure have been reported in literature. In [6], congestion relief by the coordination between two different FACTS devices via implementation of intelligent real genetic algorithm technique to increase the capacity of power transfer. Alvarado [7] proposed power system application data dictionary to implement efficient codes in MATLAB used for congestion management. In [8], congestion management by optimal location of TCSC is determined based on real power performance index and reduction of total system reactive power. The multi-area congestion management is achieved through cross border coordinated redispatching by regional transmission system operators [9]. In [10], a simple and efficient model for optimal location of

FACTS devices is used for congestion management by controlling their parameters optimally. Huang and Yan examined the impact of FACTS devices in congestion management by reducing transaction curtailment and Total Transfer Capability (TTC) improvement issues [11]. A. Oudalove [12], proposed the coordinated emergency control system for overload limitations in a transmission system using load shedding combined with multiple FACTS devices. In [13], a sensitivity based approach for the optimal location of Unified Power Flow Controller (UPFC) was proposed for the congestion management.

The condition where overloads in a transmission lines or transformers occur is called congestion. When the producers and consumers of electric energy desire to produce and consume ill 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, that is, controlling the transmission system so that transfer limits are observed, it perhaps the fundamental transmission management problem. Congestion could prevent system operators from dispatching additional power from a specific generator. Congestion could be caused for various reasons, such as transmission line outages, generators outages, changes in energy demand and uncoordinated transactions.

Congestion may result in preventing new contracts, infeasibility in existing and new contracts, additional outages and monopoly of prices in some regions of power systems and damages to system components. Congestion may be prevented to some extent by means of reservations, rights and congestion pricing. Congestion is term that has come to power systems from economics in conjunction with deregulation, although congestion was present in power systems before deregulation. There it was discussed in terms of steady state security, and the basic objectives was to control generator output so that the system remained secure at the lowest cost. When dealing with the power flow within its operating area, one entity, the vertically integrated utility, controlled both generation and transmission, gained economically from lower generation costs and was responsible for the consequences and expected costs when less secure operation resulted in power outages. Conflicts between security and economics could be trade off within one decision making entity. There are two broad paradigms that may be employed for congestion management. These are cost free means and the non

cost free means. The former include actions like out aging of congested lines or operation of transformer taps, phase shifters, or FACTS devices. These means are termed as cost free only because the marginal costs (and not the capital costs) involved in their usage are nominal. The non cost free means rescheduled generation, prioritization and load curtailments.

Congestion in a transmission system, whether vertically organized or unbundled, cannot be permitted except for very short duration, for fear of cascade outages with uncontrolled loss of load. Some corrective measures such as outage of congested branch using FACTS devices, operation of transformer taps, redispatch of generation and curtailment of pool loads and/ or bilateral contracts can relieve congestion.

In the past three decades several optimization techniques have been proposed to solve OPF problems. The main existing techniques for solving OPF problems are the gradient method [14], Newton method [15], successive sparse Quadratic Programming (QP) method [16]. Each method has its own advantages and disadvantages. Since Karmarkar published his paper on an interior point method for linear programming in 1984[17], great interest on the subject has arisen. In [18] an interior point method was proposed for both linear and convex quadratic programming. It is used to solve power system optimization problems such as economic dispatch and reactive power planning. The papers[20-34] describes the publications which are related to operational issues, tools and technical analysis, for the series controlled device for relieving the transmission line congestion problems. In [35] methodologies to determine the location of TCSC for secure power flow in the grid system using novel sensitivity indices. In [36] a method of optimal reschedule of reactive power generation of both generator and capacitor along with the reschedule of active power is considered to relieve congestion.

In this paper, a sensitivity method for determining optimal location of TCSC has been explained. The approach is based on the reduction of total system real power loss. Interior point method which used for convex optimization has been proposed for minimizing generation rescheduling cost to alleviate congestion and device cost. The proposed method has been demonstrated on 5-bus system and Modified IEEE-30 bus system. The results show that above algorithm is suitable for relieving congestion and getting economical results.

## II. CONGESTION MANAGEMENT PROBLEM FORMULATION

In the congestion management problem formulation, first it is required to find the optimal location of TCSC for congestion alleviation process and then the application of one of available optimal power flow method to find minimum rescheduling cost to alleviate congestion. Certain criterion has been developed for finding out the Optimal location of TCSC. Thus the congestion management problem formulation consists of two parts which are as follows:

- 1) Sensitivity Analysis
- 2) Optimization Problem

The criteria for optimal placement of TCSC have been done through Sensitivity Analysis. The optimization problem has been solved using Interior Point Method.

### A. Sensitivity Analysis

The Sensitivity Analysis has been carried out by modeling of TCSC and then finding out the sensitivity coefficients for placement of TCSC.

#### 2.1 MODELLING OF TCSC

Fig.1 shows a simple transmission line represented by its lumped  $\pi$  equivalent parameters connected between bus-i and bus-j. Let complex voltages at bus-i and bus-j are  $V_i(\delta_i)$  and  $V_j(\delta_j)$ , respectively. The real and reactive power flow from bus-i to bus-j can be written as

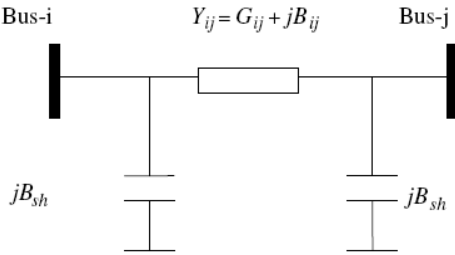


Figure 1 Model of Transmission line

$$P_{ij} = V_i^2 G_{ij} - V_i V_j [G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}] \quad (1)$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}] \quad (2)$$

where,  $\delta_{ij} = \delta_i - \delta_j$ .

Similarly, the real and reactive power flow from bus-j to bus-i is

$$P_{ji} = V_j^2 G_{ij} - V_i V_j [G_{ij} \cos \delta_{ij} - B_{ij} \sin \delta_{ij}] \quad (3)$$

$$Q_{ji} = -V_j^2 (B_{ij} + B_{sh}) + V_i V_j [G_{ij} \sin \delta_{ij} + B_{ij} \cos \delta_{ij}] \quad (4)$$

where,

$$G_{ij} = r_{ij} / (r_{ij}^2 + x_{ij}^2) \quad (5)$$

$$B_{ij} = -x_{ij} / (r_{ij}^2 + x_{ij}^2) \quad (6)$$

The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Fig.2. During the steady state operation, the TCSC can be considered as a static device with reactance  $-jx_c$ . The real and reactive power flow equations from bus-i to bus-j and from bus-j to bus-i of a line having series impedance and a series reactance are given by

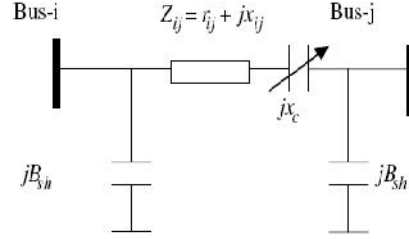


Figure 2 Model of Transmission line with TCSC

$$P_{ij}^c = V_i^2 G'_{ij} - V_i V_j [G'_{ij} \cos \delta_{ij} + B'_{ij} \sin \delta_{ij}] \quad (7)$$

$$Q_{ij}^c = -V_i^2 (B'_{ij} + B_{sh}) - V_i V_j [G'_{ij} \sin \delta_{ij} - B'_{ij} \cos \delta_{ij}] \quad (8)$$

$$P_{ji}^c = V_j^2 G'_{ij} - V_i V_j [G'_{ij} \cos \delta_{ij} - B'_{ij} \sin \delta_{ij}] \quad (9)$$

$$Q_{ji}^c = -V_j^2 (B'_{ij} + B_{sh}) + V_i V_j [G'_{ij} \sin \delta_{ij} + B'_{ij} \cos \delta_{ij}] \quad (10)$$

The active and reactive power loss equations in the line with TCSC can be written as

$$P_L = P_{ij} + P_{ji} = G'_{ij} (V_i^2 + V_j^2) - 2V_i V_j G'_{ij} \cos \delta_{ij} \quad (11)$$

$$Q_L = Q_{ij} + Q_{ji} = -(V_i^2 + V_j^2) (B'_{ij} + B_{sh}) + 2V_i V_j B'_{ij} \cos \delta_{ij} \quad (12)$$

where,

$$G'_{ij} = r_{ij} / (r_{ij}^2 + (x_{ij} - x_c)^2) \quad (13)$$

$$B'_{ij} = -(x_{ij} - x_c) / (r_{ij}^2 + (x_{ij} - x_c)^2) \quad (14)$$

### B. OPTIMAL LOCATION OF TCSC

The Sensitivity Analysis is carried out for finding the optimal location of TCSC.

#### 2.1.1 Reduction of total system VAR power loss:

Here, we look at a method [8] based on sensitivity of the total system reactive power loss with respect to the control variable of the TCSC. For TCSC placed between buses i and j, we consider net line series reactance as a control parameter. By differentiating the reactive power loss  $Q_L$  with respect to control parameter of TCSC we can obtain the sensitivity factor  $a_{ij}$ . Loss sensitivity with respect

to control parameter of TCSC placed between buses i and j can be written as

$$a_{ij} = \frac{\partial Q_L}{\partial x_{ij}} = [V_i^2 + V_j^2 - 2V_i V_j \cos \delta_{ij}]. \quad (15)$$

### 2.1.2 Real power flow performance index sensitivity indices:

The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index[13], which is given by,

$$Performance\ Index(PI) = \sum_{m=1}^{N_1} \frac{w_m}{2n} \left( \frac{P_{Lm}}{P_{Lm}^{max}} \right)^{2n} \quad (16)$$

where  $P_{Lm}$  is the real power flow and  $P_{Lm}^{max}$  is the rated capacity of the line-m, N is the exponent and  $w_m$  is a real non-negative weighting coefficient which may be used to reflect the importance of the lines.

PI will be small when all the lines are within their limits and reach a high value when there are overloads. Thus, it provides a good measure of severity of the line overloads for given state of the power system.

The real power flow PI sensitivity factors with respect to the parameters of TCSC can be defined as

$$b_k = \frac{\partial PI}{\partial x_{ck}} \text{ at } x_{ck} = 0 \quad (17)$$

The sensitivity of PI with respect to TCSC parameter connected between bus-i and bus-j can be written as

$$\frac{\partial PI}{\partial x_k} = \sum_{m=1}^{N_L} W_m P_{Lm}^3 \left( \frac{1}{P_{Lm}^{max}} \right)^4 \frac{\partial P_{Lm}}{\partial x_k} \quad (18)$$

where,

$$\frac{\partial P_{Lm}}{\partial x_{ck}} = \begin{cases} S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}}, & m \neq k \\ S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}} + \frac{\partial P_j}{\partial x_{ck}}, & m = k \end{cases} \quad (19)$$

where,

$$\frac{\partial P_i}{\partial x_{ck}} = -2(V_i^2 - V_i V_j \cos \delta_{ij}) \frac{r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} - V_i V_j \sin \delta_{ij} \frac{(x_{ij}^2 - r_{ij}^2)}{(r_{ij}^2 + x_{ij}^2)^2} \quad (20)$$

$$\frac{\partial P_j}{\partial x_{ck}} = -2(V_j^2 - V_i V_j \cos \delta_{ij}) \frac{r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} + V_i V_j \sin \delta_{ij} \frac{(x_{ij}^2 - r_{ij}^2)}{(r_{ij}^2 + x_{ij}^2)^2} \quad (21)$$

### 2.1.2 Reduction of total system Active power loss:

Here, we look at a method based on sensitivity of the total system active power loss with respect to the control variable of the TCSC. For TCSC placed between buses i and j we consider net line series

reactance as a control parameter. Loss sensitivity with respect to control parameter of TCSC placed between buses i and j can be written as,

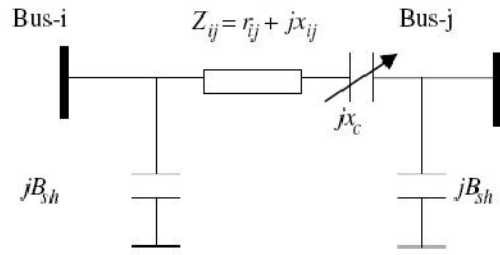


Figure 3 Model of Transmission line with TCSC

The active power loss in the line with TCSC can be written as

$$P_L = P_{ij} + P_{ji} = G'_{ij} (V_i^2 + V_j^2) - 2V_i V_j G'_{ij} \cos \delta_{ij} \quad (21)$$

Now by differentiating the equation (11) with respect to control parameter of TCSC, we will obtain the sensitivity factor  $c_{ij}$ , which is as follows:

$$c_{ij} = \frac{\partial P_L}{\partial x_{ij}} = [V_i^2 + V_j^2 - 2V_i V_j \cos \delta_{ij}] \cdot \frac{-2r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} \quad (22)$$

## 2.2 CRITERIA FOR OPTIMAL LOCATION OF TCSC

The location of FACTS devices can be based on static or dynamic performance of the system. The sensitivity factor methods are generally used to find the best location to enhance the static performance of the system. The sensitivity for determining optimal location of FACTS devices can at best give an idea about the optimal location for those devices in a deregulated environment. The FACTS devices should be placed on the most sensitive lines.

With the sensitivity indices computed for TCSC, following criteria can be used for optimal placement:

1. In Reactive power loss reduction method, TCSC should be placed in a line having the most positive loss sensitivity index.
2. In PI method, TCSC should be placed in a line having most negative sensitivity index.
3. In Active power loss reduction method, TCSC should be placed in a line having the most positive loss sensitivity index.

## 2.3 OBJECTIVE FUNCTION

Due to high cost of FACTS devices, it is necessary to use cost-benefit analysis to analyze whether new FACTS device is cost effective among

several candidate locations where they are actually installed. The TCSC cost in line-k is given by

$$C_{TCSC}(k) = c \cdot x_c(k) \cdot P_L^2 \cdot \text{Base Power} \quad (22)$$

The objective function for placement of TCSC will be

$$\min P_i \sum_i C_i(P_i) + C_{TCSC} \quad (23)$$

where  $c$  is the unit investment cost of FACTS device  $x_c(k)$  is the series capacitive reactance and  $P_L$  is the power flow in line-k.

### III. CONGESTION MANAGEMENT PROBLEM FORMULATION

#### 3.1 Optimization Problem

The costs of rescheduled active and reactive powers are  $f_1$  and  $f_2$ , the objective function is formulated as optimization problem which has to be minimized is as follows:

$$\text{Minimize } Z = f_1 + f_2$$

Mathematically, an OPF for minimization of the total operating cost can be formulated as follows:

Objective:

$$\text{Min } f(x) = \sum_i^{Ng} (\alpha_i * P g_i^2 + \beta_i * P g_i + \gamma_i) + C_{TCSC} \quad (1.1)$$

Subject to the following constraints:

1. Non linear equality constraints (load flow equations)

$$g(x)=0 \quad (23)$$

where  $g(x)$  represents equality constraints including bus power flow equations. i.e.,

$$P g_i - P d_i - P_i(V, \theta, T) = 0$$

$$Q g_i - Q d_i - Q_i(V, \theta, T) = 0$$

$$i = 1, 2, \dots, N$$

2. Non linear inequality constraints such as line flow constraints, interface flow constraints and simple inequality constraints of variables such as voltage magnitudes, generator active powers, generator reactive powers, transformer tap ratios

$$h_j^{min} \leq h_j(P_g, Q_g, V, \theta, T) \leq h_j^{max} \quad (24)$$

$$j = 1, 2, \dots, N_h$$

where  $x = [V, \theta, T, P g, Q g]^T$ ,  $\alpha_i, \beta_i, \gamma_i$  are the coefficients of quadratic production cost functions at bus  $i$ ,  $P g$  is the bus active generation,  $Q g$  is the bus reactive generation,  $P d$  is the bus active load,  $Q d$  is bus reactive load,  $V$  is the bus voltage magnitude,  $\theta$  is the bus angle vector,  $T$  is the transformer Tap ratio vector,  $h^{min}, h^{max}$  are lower bound and upper bound vectors, respectively, for inequality constraints,  $Ng$  is the total number of generators,  $N$  is total number of

buses, and  $N_h$  is the total number of double-side inequality constraints.

For satisfactory system operation the region of feasible solutions may not be able to converge whilst satisfying all constraints simultaneously. A robust non linear OPF formulation which introduces reactive slack variables and load-shedding variable in the problem shown in equations 1-4 is proposed to handle the infeasibility of a solution.

The Newton equation for the nonlinear interior point OPF algorithm derived may be expressed in the following compact form,

$$\begin{bmatrix} -nl^{-1}Sl & 0 & -\nabla h & 0 \\ 0 & -nl^{-1}Sl & -\nabla h & 0 \\ -\nabla h^T & -\nabla h^T & H & -J^T \\ 0 & 0 & -J & 0 \end{bmatrix} \begin{bmatrix} \Delta nl \\ \Delta mu \\ \Delta x \\ \Delta \lambda \end{bmatrix} = \begin{bmatrix} -\nabla_{nl}L_\mu + nl^{-1}\nabla_{sl}L_\mu \\ -\nabla_{nu}L_\mu + nu^{-1}\nabla_{su}L_\mu \\ -\nabla_x L_\mu \\ g(x) \end{bmatrix} \quad (25.1)$$

$$\Delta sl = nl^{-1}(-\nabla_{sl}L_\mu - Sl\Delta\pi l) \quad (25.2)$$

$$\Delta su = nu^{-1}(-\nabla_{su}L_\mu - Su\Delta\pi u) \quad (25.3)$$

where,

$$H(x, \lambda, \pi l, \pi u) = \nabla^2 f(x) - \lambda \nabla^2 g(x) - (\pi l + \pi u) \nabla^2 h(x),$$

$$J(x) = \frac{\partial g(x)}{\partial x}.$$

By solving the Newton equation (7),  $\Delta nl, \Delta mu, \Delta x, \Delta \lambda, \Delta sl, \Delta su$  can be obtained. Then the Newton solution can be updated as follows,

$$sl = sl + \sigma \alpha_p \Delta sl \quad (26.1)$$

$$su = su + \sigma \alpha_p \Delta su \quad (26.2)$$

$$x = x + \sigma \alpha_p \Delta x \quad (26.3)$$

$$\pi l = \pi l + \sigma \alpha_d \Delta \pi l \quad (26.4)$$

$$\pi u = \pi u + \sigma \alpha_d \Delta \pi u \quad (26.5)$$

$$\lambda = \lambda + \sigma \alpha_d \Delta \lambda \quad (26.6)$$

Where  $\sigma = 0.995 \sim 0.99995$ .  $\alpha_p, \alpha_d$  are primal and dual step length respectively. They can be determined by

$$\alpha_p = \min \left\{ \min \left( \frac{sl}{-\Delta sl}, \min \left( \frac{su}{-\Delta su}, 1.0 \right) \right), 1.0 \right\} \quad (27.1)$$

$$\alpha_d = \min \left\{ \min \left( \frac{-nl}{-\Delta nl}, \min \left( \frac{-nu}{-\Delta nu}, 1.0 \right) \right), 1.0 \right\} \quad (27.2)$$

The complementary gap of the nonlinear interior point OPF is,

$$C_{gap} = su^T nu - sl^T nl \quad (28)$$

The barrier parameter can be determined by,

$$\mu = \frac{\beta * C_{gap}}{2 * m} \quad (29)$$

where  $\beta=0.01\sim 0.2$ ,  $m$  is the number of inequality constraints in (21.3)

### 3.2 Algorithm:

The solution procedure for the nonlinear interior point OPF is summarized as follows:

Step 0) Set iteration count  $k=0, \mu = \mu_0$ , and initialize the OPF solution

Step1) If KKT conditions are satisfied and complementary gap is less than a tolerance, output results. Otherwise go to step 2.

Step 2) Form and solve Newton equation in (25.1), then (25.2) and (25.3).

Step 3) Update Newton solution by equation (26).

Step 4) Compute complementary gap by equation (28).

Step 5)  $k=k+1$  go to step 1.

## IV. RESULTS AND DISCUSSIONS

MATLAB software is used for implementing the three sensitivity methods. Programming is written for all the three sensitivity methods. Separate programming is written for the interior point method in MATLAB. The reactive power reduction method [8] has been named as method 1, the PI reduction method [13] is named as method 2 and the active power loss reduction method is named as method 3. All these three methods are discussed for the 5-bus & IEEE 30 bus system.

### A. 5 bus system

The 5-bus system consists of 3 generator buses and 2 load buses. The slack bus is numbered as 1 followed by the generator buses and load buses.

The load flow of 5-bus system is shown in Table I. From the load flow, it is found that real power flow in line 2-5 was 1.034 p.u which is more than the line loading limit.

The sensitivities of reactive power loss reduction, real power flow performance index and active power loss reduction with respect to TCSC control parameter has been computed and shown in Table-II. The sensitive line in each case is presented in bold type. It can be observed from Table-II (column 3) that placement of TCSC in line-3 is suitable for reducing the total reactive power loss. The value of power flow in the congested line-2 after placing TCSC is 0.9956 p.u which can be observed from Table-III. It is clear

that congestion has been relieved in the system after placing the TCSC.

The value of Control parameter of TCSC for computing power flow is taken as 0.2885p.u. It can be observed from Table III that congestion has been relieved

It can be observed from Table-II (column 4) that placing a TCSC in line-5 is optimal for reducing the PI and congestion relief. Power flow Value of the congested line-2 after placing TCSC in line-5 is 0.9954 p.u which is shown in Table-III. The value of Control parameter of TCSC for computing power flow is taken as 0.0326p.u. It can be observed that congestion has been relieved.

From the Table-II (column 5) it can be observed that placing a TCSC in line-5 is optimal for reducing the Active power loss and for congestion relief. System power flow result after placing TCSC in line-1 is shown in Table-III. The value of Control parameter of TCSC for computing power flow is taken as 0.3106p.u. It can be observed from Table III that congestion has been relieved.

Placement of TCSC in line-5 will reduce the PI value and placement of TCSC in line-3 may reduce the reactive power loss but it will be less effective than placing a TCSC in line-1 as can be seen from its sensitivity factors. Total cost of three methods is shown in Table IV. It can be observed from Table IV that reduction of total system active power loss method is more economical than VAR power loss method and PI method for placing the TCSC and congestion management. The Voltage Profile of the 5-bus system obtained for the three sensitivity analysis is shown in Table V.

**TABLE I**

POWER FLOW RESULT FOR 5-BUS SYSTEM

Line	i-j	Method reported in [8]
		Power flow(pu)
1	2-1	0.07798
2	<b>2-5</b>	<b>1.034</b>
3	3-5	0.08441
4	5-4	0.40379
5	1-4	0.4145
6	3-2	0.51559

**TABLE II**  
SENSITIVITY INDICES FOR 5-BUS SYSTEM

Line	i-j	Method 1	Method 2	Proposed Method
		a <sub>ij</sub>	b <sub>ij</sub>	c <sub>ij</sub>
1	2-1	-0.008057	-0.0789	<b>-0.0004</b>
2	2-5	-0.970852	1.95327	-0.5107
3	3-5	<b>-0.00784</b>	-0.10536	-0.0018
4	5-4	-0.261704	0.34953	-0.0837
5	1-4	-0.967394	<b>-0.41433</b>	-0.0897
6	3-2	-0.240349	0.45582	-0.1235

**TABLE III**  
POWER FLOW RESULT FOR 5-BUS SYSTEM AFTER PLACING TCSC BASED ON SENSITIVITY METHODS

Line	i-j	Method 1	Method 2	Proposed Method
		Power flow(pu)	Power flow(pu)	Power flow(pu)
1	2-1	0.07614	0.10893	0.08791
2	2-5	0.99956	0.99954	0.99936
3	3-5	0.08441	0.08798	0.08798
4	5-4	0.40379	0.37453	0.40379
5	1-4	0.41123	0.46051	0.42237
6	3-2	0.47879	0.51202	0.49789

**TABLE IV**  
TOTAL COST FOR OPTIMAL LOCATION OF TCSC IN 5-BUS SYSTEM

Method	Total cost(\$/day)
VAR reduction[8]	2126.30
PI[13]	2346.34
Active power reduction	2031.30

**TABLE V**  
VOLTAGE MAGNITUDE VALUES OBTAINED FROM VARIOUS METHODS

BUS	METHOD 1	METHOD 2	METHOD 3
1	1.020	1.020	1.020
2	1.040	1.040	1.040
3	1.050	1.050	1.050
4	1.090	1.120	1.060
5	1.019	1.102	1.017

### B.Modified IEEE- 30 bus system

The 30 bus system consists of 6 generator buses and 24 load buses. The slack bus is numbered as 1 followed by the generating buses and load buses. The load flow of 30-bus system is shown in Table VI. In case of 30-bus system there are two congested lines. Those are line 1(between 1-2) and line 6 (between 2-9). From the load flow, it was found that real power flow in line 1(between 1-2) was 1.1248 p.u. and the real power flow in line 6 (between 2-9) was 1.046 p.u. which are more than the line loading limits.

The sensitivities of reactive power loss reduction, real power flow performance index and active power loss reduction with respect to TCSC control parameter has been computed and shown in Table-VII. The sensitive line in each case is presented in bold type. It can be observed from Table-VIII (column 3) that placement of TCSC in line-20 is suitable for reducing the total reactive power loss. The value of power flow in the congested line-1 after placing TCSC is 0.9987p.u and the value of line flow in line-6 is 0.9568p.u as shown in Table VIII. It can be observed that congestion has been relieved in the system after placing the TCSC.

The value of Control parameter of TCSC for computing power flow is taken as 0.17885p.u.

It can be observed from Table-VII (column 4) that placing a TCSC in line-4 is optimal for reducing the PI and congestion relief. Power flow Value of the congested line-1 after placing TCSC in line-4 is 0.9984 p.u and the value of line flow in line-6 is 0.9476 p.u as shown in Table VIII. The value of Control parameter of TCSC for computing power flow is taken as 0.0326p.u. It can be observed that congestion has been relieved.

From the Table-VII (column 5) it can be observed that placing a TCSC in line-36 is optimal for reducing the Active power loss and for congestion relief. Power flow Value of the congested line-1 after placing TCSC in line-36 is 0.9876 p.u and the value of line flow in line-6 is 0.9321 p.u. as shown in Table VIII. The value of Control parameter of TCSC for computing power flow is taken as 0.2356p.u. It can be observed that congestion has been relieved.

Placement of TCSC in line-4 will reduce the PI value and placement of TCSC in line-20 may reduce the reactive power loss but it will be less effective than placing a TCSC in line-36 as can be seen from its sensitivity factors. The Voltage Profile for the 30-bus system obtained from the three sensitivity analysis is shown in the form of voltage variations in the form

bar chart representation for methods one, two and three respectively . Total costs of three methods are shown in Table IX. It can be observed from Table IX that reduction of total system active power loss method is more economical than VAR power loss method and PI method for placing the TCSC and congestion management.

**TABLE-VI**  
CONGESTED LINE DETAILS FOR 30-BUS SYSTEM

Congested Line	Power flow (MW)	Line Limit (MW)
1-2	1.2748	1.00
2-9	1.046	1.00

**TABLE VII**  
SENSITIVITY INDICES FOR 30-BUS SYSTEM

Line	i-j	a <sub>ij</sub>	b <sub>ij</sub>	c <sub>ij</sub>
1	1-2	-0.0012	1.1352	-0.0023
2	1-7	-0.5181	-0.6546	-0.3065
3	2-8	-0.1755	-0.8522	-0.1291
4	7-8	-0.3965	<b>-0.8696</b>	-0.3143
5	2-3	-0.3331	-0.0650	-0.1681
6	2-9	-0.3028	0.0099	-0.2239
7	8-9	-0.4864	0.0001	-0.3048
8	3-10	-0.0151	-0.1674	-0.0142
9	9-10	-0.0282	-0.1678	-0.0205
10	9-4	-0.0924	-0.2237	-0.0575
11	9-11	-0.2399	0	-0.0026
12	9-12	-0.0423	-0.3252	-0.0037
13	11-5	-0.0468	0	-0.0043
14	11-12	-0.0341	-0.3270	-0.0024
15	8-13	-0.1850	1.0923	-0.0012
16	13-6	-0.1319	0.0169	-0.0032
17	13-14	-0.0052	-0.1687	-0.0065
18	13-15	-0.0319	-0.2155	-0.0437
19	13-16	-0.0112	-0.0872	-0.0138
20	14-15	<b>0.0001</b>	-0.2378	-0.0008
21	16-17	-0.0064	-0.2607	-0.0066
22	15-18	-0.0056	-0.0933	-0.0072
23	18-19	-0.0024	-0.2607	-0.0031
24	19-20	-0.0011	-0.0636	-0.0015
25	12-20	-0.0030	-0.0654	-0.0033
26	12-17	-0.0013	-0.2618	-0.0012
27	12-21	-0.0200	-0.5054	-0.0237
28	12-22	-0.0042	0.6215	-0.0054
29	21-22	-0.0010	0.6329	-0.0013
30	15-23	-0.0042	0.4660	-0.0056

31	22-24	-0.0016	-0.2532	-0.0035
32	23-24	-0.0014	-0.2505	-0.0018
33	24-25	-0.0006	0.0004	-0.0010
34	25-26	-0.0007	-0.1014	-0.0018
35	25-27	-0.0026	0.7824	-0.0038
36	28-27	-0.0425	0.7821	<b>0.0015</b>
37	27-29	-0.0024	-0.0678	-0.0035
38	27-30	-0.0030	-0.3048	-0.0045
39	29-30	-0.0008	-0.3071	-0.0012
40	4-28	-0.0051	-0.0003	-0.0036
41	9-28	-0.0184	0	-0.0113

**TABLE VIII**

POWER FLOW RESULT FOR 30-BUS SYSTEM AFTER PLACEMENT OF TCSC BASED ON THE SENSITIVITY METHODS

Line	i-j	Power flow based on Method1	Power flow based on Method2	Power flow based on Method3
1	1-2	0.9987	0.9984	0.9876
2	1-7	0.7670	0.7742	0.7637
3	2-8	0.4590	0.4630	0.4571
4	7-8	0.5851	0.6045	0.5763
5	2-3	0.5978	0.6023	0.5957
6	2-9	0.9568	0.9476	0.9321
7	8-9	0.5603	0.5764	0.5530
8	3-10	0.0741	0.0756	0.0735
9	9-10	0.1374	0.1393	0.1366
10	9-4	-0.0166	-0.0194	-0.0154
11	9-11	0.4752	0.4790	0.4735
12	9-12	0.2038	0.2044	0.2035
13	11-5	0.0667	0.0672	0.0664
14	11-12	0.1159	0.1176	0.1151
15	8-13	0.4073	0.4100	0.4061
16	13-6	-0.2256	-0.2282	-0.2244
17	13-14	0.0881	0.0886	0.0878
18	13-15	0.2116	0.2141	0.2104
19	13-16	0.1270	0.1280	0.1265
20	14-15	0.0273	0.0274	0.0272
21	16-17	0.0919	0.0926	0.0915
22	15-18	0.0919	0.0925	0.0916



23	18-19	0.0583	0.0589	0.0580
24	19-20	-0.0276	-0.0284	-0.0273
25	12-20	0.0534	0.0539	0.0532
26	12-17	-0.0060	-0.0059	-0.0061
27	12-21	0.1167	0.1196	0.1154
28	12-22	0.0565	0.0572	0.0562
29	21-22	-0.0308	-0.0323	-0.0301
30	15-23	0.0701	0.0707	0.0698
31	22-24	0.0153	0.0157	0.0152
32	23-24	0.0388	0.0391	0.0387
33	24-25	-0.0298	-0.0299	-0.0297
34	25-26	0.0348	0.0349	0.0347
35	25-27	-0.0635	-0.0639	-0.0633
36	28-27	0.1952	0.1960	0.1948
37	27-29	0.0608	0.0611	0.0607
38	27-30	0.0701	0.0703	0.0700
39	29-30	0.0364	0.0365	0.0364
40	4-28	0.0507	0.0513	0.0505
41	9-28	0.1296	0.1326	0.1282

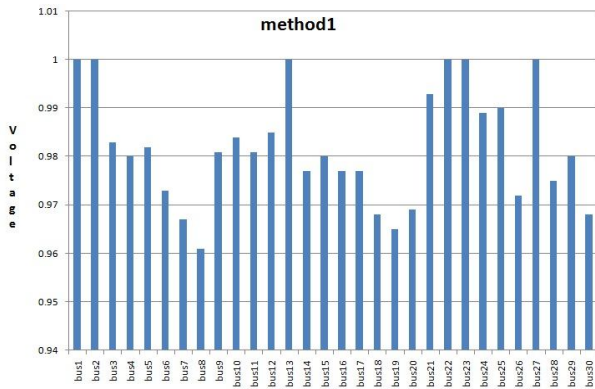


Figure4: Voltage Profile for IEEE 30-bus system obtained from Method 1

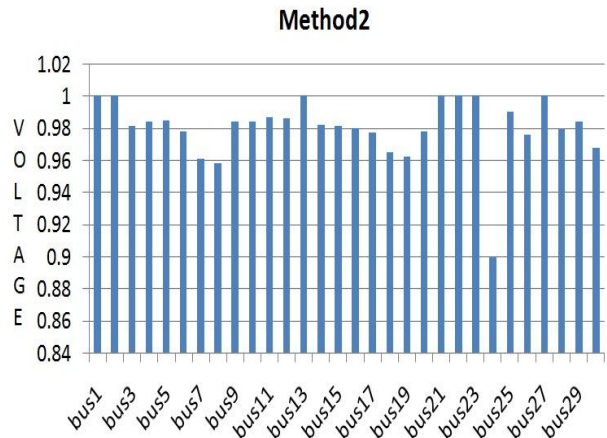


Figure5: Voltage Profile for IEEE 30-bus system obtained from Method 2

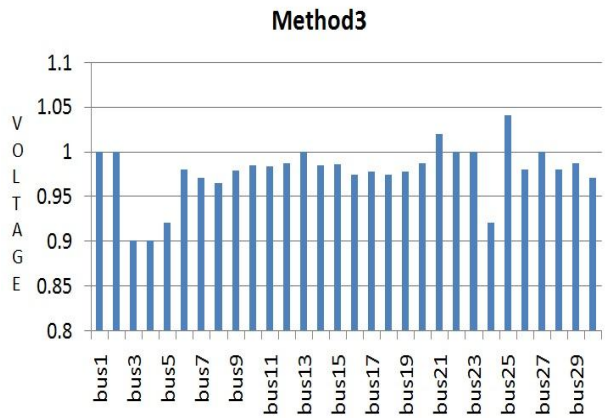


Figure6: Voltage Profile for IEEE 30-bus system obtained from Method 3

Figure 4 represents the voltage profile for IEEE 30 bus system obtained from method1. Figure 5 represents the voltage profile for IEEE30 us system obtained from method2. Figure 6 represents the voltage profile for IEEE 30 –bus system obtained from method 3. From figures it clearly observed that method 3 voltage profile is smooth as compared to method 1 and 2. Figures were obtained from voltage magnitude values obtained from various methods.

**TABLE IX**  
TOTAL COST FOR OPTIMAL LOCATION OF TCSC

Method	Total cost(\$/day)
VAR reduction	1186.48
PI	1222.91
Active power reduction	<b>1067.98</b>

## V. CONCLUSION

Congestion Management is an important issue in deregulated power systems. FACTS devices such as TCSC is used to control the power flows in the network, can help to reduce the flows in heavily loaded lines. Because of the considerable costs of FACTS devices, it is important to obtain optimal location for placement of these devices. Here, three sensitivity-based methods have been developed for determining the optimal location of TCSC in an electricity market. In a system, first three optimal location of TCSC can be decided based on the sensitivity factors  $a_{ij}$ ,  $b_{ij}$  and  $c_{ij}$  and then optimal location is selected based on minimizing production cost using the Interior point method. Test results obtained for 5-bus system and IEEE 30-bus system shows that sensitivity factors could be effectively used for determining the optimal location of TCSC. Results obtained on the above said systems are compared with the results reported. The cost values for the three sensitivity methods were compared and clearly depicted in tabular form. Proposed sensitivity methods have been derived by the extension of basic load flow program, hence it is free from complex mathematical formulations and easy understanding. Test results divulge that the proposed methodology is effective in managing congestion compared to other reported techniques.

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