Congestion Management Using Optimal Placement of TCSC in Deregulated Power System

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Abstract: This paper presents a congestion management methodology in deregulated power systems by making use of optimal placement of thyristor controlled series compensators (TCSCs) in transmission network. The problem formulation consists of maximization of social welfare function subject to real and reactive power balance, constant power factor of consumers, transmission congestion (line loading), generators' capability curve constraints, and bounds on variables. The social welfare function, which customarily comprises of demand benefits minus generation costs, has been modified to include the effect of usage cost of TCSCs. The proposed congestion management methodology takes into account number of potential scenarios of market conditions. The location of TCSCs in power system is decided by making use of integer variables; hence formulation of proposed problem takes the form of Mixed Integer Nonlinear Programming (MINLP) problem. The effectiveness of the proposed methodology is tested on a 5-bus and IEEE 14-bus systems and results obtained are compared with those obtained by existing approaches. It can be concluded that congestion management results obtained with proposed methodology are better than those obtained by existing approaches.

Keywords: Congestion Management, Power Market Deregulation, Social Welfare, Thyristor Controlled Series Compensator, Mixed Integer Nonlinear Programming (MINLP)

1. Introduction

The regulatory changes in electricity sector have caused the emergence of competition in generation and distribution of electric energy, all over the world. However, transmission system remains to be an inherent monopoly. This is necessary in order to avoid a number of related problems such as duplicity, right-of-the-way, environmental issues and requirement of huge investment for construction of new transmission lines, and to take the advantage of the interconnected network. The competitive environment has increased the electricity trade by many folds and caused the power to flow over the transmission corridors by unexpected amounts and directions. During certain periods, transmission system is unable to accommodate desired energy transactions, which leads to the congestion in the transmission system. Transmission system congestion is tackled by the independent system operator (ISO) of electricity markets by curtailments or adjustments in scheduled transactions. The occurrence of transmission congestion in deregulated power systems causes a huge revenue loss to market participants [1]. Fortunately, the advent of power electronics based flexible AC transmission system (FACTS) technology has achieved a sufficient maturity and FACTS devices can be incorporated to capture the unutilized potential of transmission systems. This paper makes use of thyristor controlled series compensator (TCSC), which is able to control the pattern of power flow over the designated transmission routes for the management of congestion [2-4].

A number of hindrances coming in the way of constructing new transmission lines have increased the importance of placement of FACTS devices in power system to increase its

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performance. A critical issue related to the placement of FACTS devices is to identify the optimal location of these devices in power system. Singh and David [5,6] have used the performance index sensitivity factors for placement of TCSC and thyristor controlled phase angle regulator for congestion management. Optimal location of FACTS devices based on reactive line loss sensitivity with respect to control parameter of the FACTS device to be incorporated, are determined in [7,8]. However, sensitivity based approaches can give only an approximate idea about the optimal location of FACTS devices [8], particularly when the objective of optimization problem is social welfare maximization. Acharya and Mithulananthan [9] have used the locational marginal price (LMP) differences and congestion rent contributions of different transmission lines for preparing a priority list, where TCSC can be placed. However, this direct search approach would become exhaustive and overwhelming, since LMP differences and congestion rent contributions of individual lines would be different under different market scenarios. An approach for combined active and reactive congestion management with FACTS devices is presented in [10]. However, the authors have assumed that the transmission system is owned by the ISO, so services of FACTS devices are available free of cost to ISO. A mixed integer linear programming based approach is presented in [11], for placement of phase-shifters to maximize the system loadability. However, it makes use of dc load flow equations and is suitable for approximate and preliminary planning studies only. A multiobjective mixed integer programming approach for allocation of TCSCs in transmission system is presented in [12]. The authors have linearized the nonlinear real and reactive power flow equations, which may give approximate results.

The present paper proposes a congestion management methodology in deregulated power system by making use of optimal placement of TCSCs in transmission network. The objective function of proposed problem formulation is maximization of social welfare function. The social welfare function is obtained by subtracting real power generation and reactive power procurement cost, and usage cost of TCSCs from demand benefits. The various constraints of proposed problem formulation are real and reactive power balance, constant power factor of consumers, transmission congestion (line loading) limits, bounds on variables (including the bound on maximum number of TCSCs to be placed), and generator capability curve. The proposed congestion management methodology takes into account number of potential scenarios of market conditions. The formulation of proposed problem takes the form of Mixed Integer Nonlinear Programming (MINLP) problem, in which location of TCSCs in power system is decided by making use of integer variables. The effectiveness of the proposed methodology is tested on a 5-bus and IEEE 14-bus systems and results obtained are compared with those obtained by existing approaches. It can be concluded that congestion management results obtained with proposed methodology are better than those obtained by existing approaches.

Rest of the paper is organized as follows. Section 2 presents the modeling of TCSCs in power system. Section 3 presents development of usage cost of TCSCs, problem formulation and solution methodology of the proposed optimization problem. Section 4 discusses and compares results obtained after solving a 5-bus and IEEE 14-bus systems. Concluding remarks are presented in Section 5.

2. Modeling of TCSC in Power System

Commonly, power injection model [5-9, 13] is used for the static modeling of TCSC in power system. However, a simpler way of modeling of TCSC can be obtained by modification of bus admittance matrix (Y_{BUS}). The Y_{BUS} can be used to represent the real and reactive power balance constraints (load flow equations) including the effect of TCSCs. Hence, the modeling of TCSCs in power system by modification of Y_{BUS}, is computationally simpler as compared to that by power injection model. Consider a pi-representation of transmission line connected between buses p and q, having series resistance r_{pq}, series reactance x_{pq} and line charging susceptance b_{pq}^{sh}. In any t^{th} market scenario, TCSC can be represented by a variable capacitive reactance xc_{pq}^{t} in series with the series impedance of line as shown in Figure 1.

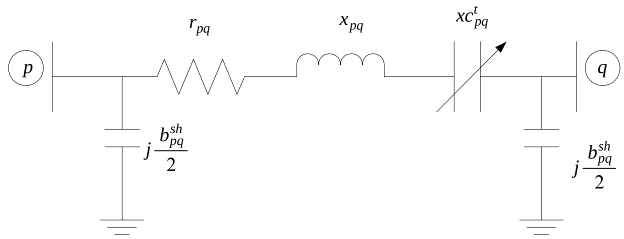

Figure 1. Pi-representation of transmission line with TCSC

The diagonal and off-diagonal elements of Y_{BUS} ($\overline{Y}_{pp}^{t}$ and $\overline{Y}_{pq}^{t}$), represented in complex form, by the inclusion of xc_{pq}^{t}, are represented as follows:

$$\overline{Y_{pp}^{t}} = \sum_{q=1}^{N}\left(j\frac{b_{pq}^{sh}}{2} + \frac{1}{r_{pq} + j(x_{pq} - v_{pq}xc_{pq}^{t})} \right); \forall p \in N, t \in T \tag{1}$$

$$\overline{Y_{pq}^{t}} = -\frac{1}{r_{pq} + j(x_{pq} - v_{pq}xc_{pq}^{t})}; \ \forall p, q \in N, p \neq q, t \in T \tag{2}$$

Where N is total number of buses; T is total number of market scenarios considered and v_{pq} is an integer decision variable (0/1). v_{pq} will be 1, if TCSC is to be placed in line $p-q$, as decided by the proposed optimization methodology.

3. Congestion Management using Optimal Placement of TCSCs in Deregulated Power System

The placement of TCSC in power system can control the pattern of power flow over the designated transmission routes. Controlling the power flows over overloaded lines would lead to the congestion management and increase in consumers and suppliers surpluses. In the deregulated environment, the commonly used criterion for placement of TCSCs (and FACTS devices, in general) is the maximization of social welfare [5-6, 8-9, 13] and minimization of the usage cost of TCSCs [6, 7]. The usage cost function of a TCSC can be developed from its investment cost [6], as presented in Section 3.1.

A. Usage Cost Function of TCSC

Consider that unit capital investment cost of TCSC is *UC* \$/KVAR, installed capacity of TCSC is *S* MVAR, discount rate is *r* and project evaluation period is *m* years, then total capital investment (*TC*) and annualized investment cost of TCSC (*AC*) can be determined from (3) and (4) [14]

$$TC = S \times UC \times 10^{-3} \left(M\$ \right) \tag{3}$$

$$AC = TC\frac{r\left(1+r\right)^{m}}{\left[\left(1+r\right)^{m}-1\right]}\left(M\$ \right) \tag{4}$$

Considering average utilization factor of TCSC over one annum is uf , the usage cost function of TCSC placed in line *p-q* $\left(\Psi^{t}_{pq}\right)$, during any t^{th} scenario can be developed by scaling down annualized investment cost on hourly basis as follows:

$$\Psi^{t}_{pq} = \frac{AC \times 10^{6}}{8760 \times uf \times S} \times \left(I^{t}_{pq}\right)^{2} xc^{t}_{pq} \times BaseMVA\left(\$/h\right) \tag{5}$$

Where I^{t}_{pq} is the current flowing through TCSC during t^{th} scenario, and is given by

$$I^{t}_{pq} = \sqrt{\left(V^{t}_{p} - V^{t}_{q}\right)^{2} \Big/ \left(r^{2}_{pq} + \left(x_{pq} - xc^{t}_{pq}\right)^{2}\right)} \tag{6}$$

where V^{t}_{p} and V^{t}_{q} are the bus voltages at buses *p* and *q* during t^{th} scenario.

B. Problem Formulation

In competitive electricity markets, Generator Companies (GenCos) and Distribution Companies/ Bulk Consumers (DistCos) submit their hourly supply and demand bids to ISO and ISO provides a market dispatch schedule based on maximization of social welfare subject to system operational and security constraints. The incremental price of supplying or consuming electric power at any bus during a particular interval, also called locational marginal price (LMP) is obtained from the solution of this optimization problem. In uniform price market design, payments charged from the DistCos and paid to the GenCos are based on the LMPs at their respective locations. In order to pay compensation to the generator companies for their reactive power supply and to provide an economic signal regarding the production and consumption of reactive power at various locations, the social welfare objective function should be modified to include the reactive power procurement cost. The reactive power procurement cost to be paid to the generators can be derived from their lost opportunity to trade maximum apparent power generation by making use of an approximate capability curve of the generators as given in [15, 16] as:

$$C^{n,t}_{i}\left(Q^{n,t}_{gi}\right) = k\left[C^{n,t}_{i}\left(\overline{S^{n}_{gi}}\right) - C^{n,t}_{i}\left(\sqrt{\left(\overline{S^{n}_{gi}}\right)^{2} - \left(Q^{n,t}_{gi}\right)^{2}}\right)\right] \tag{7}$$

where $Q^{n,t}_{gi}$ is reactive power generated during t^{th} scenario by i^{th} GenCo at n^{th} bus; $\overline{S^{n}_{gi}}$ is rated or maximum apparent power generation by i^{th} GenCo at n^{th} bus; $C^{n,t}_{i}\left(.\right)$ is cost function during t^{th} scenario by i^{th} GenCo at n^{th} bus and k is profit to be earned on lost opportunity (which varies between 5% -10%).

The social welfare function $\left(\text{SW}^{t}\right)$ of competitive electricity market during any t^{th} scenario can be written as:

$$\text{SW}^{t} = \sum_{n \in N}\left[\sum_{i \in D} B^{n,t}_{i}\left(P^{n,t}_{di}\right) - \sum_{i \in G}\left\{C^{n,t}_{i}\left(P^{n,t}_{gi}\right) + C^{n,t}_{i}\left(Q^{n,t}_{gi}\right)\right\}\right] \tag{8}$$

where $P^{n,t}_{gi}$ is real power generated during t^{th} scenario by i^{th} GenCo at n^{th} bus; $P^{n,t}_{di}$ is real power demand during t^{th} scenario by i^{th} DistCo at n^{th} bus; $B^{n,t}_{i}\left(P^{n,t}_{di}\right)$ is benefit function during t^{th} scenario of i^{th} DistCo at n^{th} bus; G is set of GenCos; D is set of DistCos and N is set of buses.

In the present paper, SW^t has been modified to include the effect of usage cost of TCSCs. The modified social welfare function $\left(SSW^t\right)$ of competitive electricity market during any t^{th} scenario can be written as:

$$SSW^t = SW^t - \sum_{(p-q)\in B}\left(\Psi^t_{pq}\, v_{pq}\right) \tag{9}$$

where B is set of lines in the power system.

The congestion management problem using optimal placement of TCSCs is formulated as to maximize social welfare, subject to transmission congestion and operational constraints. The problem has been extended to a set of potential scenarios by taking the overall social welfare function as weighted sum of individual SSW^t under different scenarios. The weight $\left(\omega^t\right)$ assigned to an individual SSW^t represents the influence level of that scenario in complete set of potential scenarios [17]. Mathematically, the problem can be formulated as:

$$Maximize \quad \sum_{t\in T}\omega^t * SSW^t \tag{10}$$

Subject to

- Power Flow Equations

The real and reactive power flow equations are given by (11) and (12) for all buses under all scenarios:

$$\sum_{i\in G_n} P_{gi}^{n,t} - \sum_{i\in D_n} P_{di}^{n,t} = \sum_{p\in N} V_n^t V_p^t Y_{np}^t \cos\left(\delta_n^t - \delta_p^t - \theta_{np}^t\right); \quad \forall n\in N, t\in T \tag{11}$$

$$\sum_{i\in G_n} Q_{gi}^{n,t} - \sum_{i\in D_n} Q_{di}^{n,t} = \sum_{p\in N} V_n^t V_p^t Y_{np}^t \sin\left(\delta_n^t - \delta_p^t - \theta_{np}^t\right); \quad \forall n\in N, t\in T \tag{12}$$

where G_n is set of GenCos at n^{th} bus; D_n is set of DistCos at n^{th} bus; δ_n^t is voltage angle at n^{th} bus; δ_p^t is voltage angle at p^{th} bus; and $Q_{di}^{n,t}$ is reactive power demand during t^{th} scenario by i^{th} DistCo at n^{th} bus. The elements of bus admittance matrix $\left(Y_{np}^t\angle\theta_{np}^t\right)$ used in (11) and (12) are obtained from (1) and (2).

- Constraint on constant power factor of consumers [13,18]

The real and reactive power consumptions of any i^{th} DistCo at n^{th} bus during t^{th} scenario are tied together by constant power factor:

$$Q_{di}^{n,t} = P_{di}^{n,t}\tan\alpha_i^{n,t}; \forall i\in D, n\in N, t\in T \tag{13}$$

- Transmission congestion (line flow limit) constraints

Transmission line flows are bounded by thermal limits for short lines and stability limits for long lines:

$$S_{pq}^{t}(V_p^t, V_q^t, \delta_p^t, \delta_q^t, v_{pq}) \le S_{pq}^{\max}; \forall (p-q) \in B, t \in T \tag{14}$$

where $S_{pq}^{t}(.)$ is apparent power flow through p-q^{th} line during t^{th} scenario and $S_{pq}^{\max}$ is line loading limit of p-q^{th} line.

- Bounds on variables

$$\begin{aligned}
&0 \le P_{gi}^{n,t} \le \overline{P_{gi}^{n}}; \forall i \in G, n \in N, t \in T \\
&\underline{Q_{gi}^{n}} \le Q_{gi}^{n,t} \le \overline{Q_{gi}^{n}}; \forall i \in G, n \in N, t \in T \\
&0 \le P_{di}^{n,t} \le \overline{P_{di}^{n,t}}; \forall i \in D, n \in N, t \in T \\
&\underline{V_n} \le V_n^t \le \overline{V}_n; \quad \forall n \in N, t \in T \\
&\sum_{(p-q)\in B} v_{pq} \le \overline{N}_{TCSC}
\end{aligned} \tag{15}$$

where $\overline{P_{gi}^{n}}$ is rated or maximum real power generation by i^{th} GenCo at n^{th} bus; $\underline{Q_{gi}^{n}}$ is minimum reactive power generation by i^{th} GenCo at n^{th} bus; $\overline{Q_{gi}^{n}}$ is maximum reactive power generation by i^{th} GenCo at n^{th} bus; $\overline{P_{di}^{n,t}}$ is maximum real power demand by i^{th} DistCo at n^{th} bus; $\underline{V_n}$ is minimum voltage limit at n^{th} bus; $\overline{V}_n$ is maximum voltage limit at n^{th} bus and $\overline{N}_{TCSC}$ is maximum number of TCSCs to be placed in power system.

- Additional constraints due to capability curve

The apparent power generated by the generators should lie within the boundaries of capability curve. This is achieved by following inequality [16, 19]:

$$\left(P_{gi}^{n,t}\right)^2 + \left(Q_{gi}^{n,t}\right)^2 \le \left(\overline{S_{gi}^{n}}\right)^2; \forall i \in G, n \in N, t \in T \tag{16}$$

In compact form, the optimization problem can be written as:

$$\begin{aligned}
\max_{(\mathbf{X},\mathbf{v})} \; & \boldsymbol{\omega}' * \mathbf{SSW} \\
\text{s.t.} \; & \mathbf{P_g} - \mathbf{P_d} - \mathbf{P}(\mathbf{X},\mathbf{v}) = 0 \\
& \mathbf{Q_g} - \mathbf{Q_d} - \mathbf{Q}(\mathbf{X},\mathbf{v}) = 0 \\
& \mathbf{Q_d} - \mathbf{P_d}\mathbf{tan\alpha} = 0 \\
& \mathbf{S}(\mathbf{X},\mathbf{v}) - \overline{\mathbf{S}} \le 0 \\
& \mathbf{G}(.) \le 0
\end{aligned} \tag{17}$$

And Lagrangian function for optimization problem (17) can be written as:

$$\begin{aligned}
L = \; & \boldsymbol{\omega}' * \mathbf{SSW} + \left[\mathbf{P_g} - \mathbf{P_d} - P(\mathbf{X},\mathbf{v})\right]^T \boldsymbol{\lambda}_\mathbf{p} \\
& + \left[\mathbf{Q_g} - \mathbf{Q_d} - Q(\mathbf{X},\mathbf{v})\right]^T \boldsymbol{\lambda}_\mathbf{q} \\
& + \left[\mathbf{Q_d} - \mathbf{P_d} tan\boldsymbol{\alpha}\right]^T \boldsymbol{\lambda}_\mathbf{d} - \left[\mathbf{S}(\mathbf{X},\mathbf{v}) - \overline{\mathbf{S}}\right]^T \boldsymbol{\mu} - \left[\mathbf{G}(.)\right]^T \boldsymbol{\gamma}
\end{aligned} \tag{18}$$

In (17) and (18), the various quantities are represented in vector form. The shadow prices $\left(\lambda_p^{n,t}, \lambda_q^{n,t}\right)$ associated with power flow equations at n^{th} bus of the optimization problem (18) represent the incremental costs of delivering real and reactive power at that bus during t^{th} scenario. These are termed as LMPs of real and reactive power at n^{th} bus during t^{th} scenario.

The lagrangian multiplier $\left(\mu^{pq,t}\right)$ associated with the p-q^{th} line limit constraint in (18) represents the severity of congestion in the line during t^{th} scenario.

C. Solution Methodology

The proposed problem of optimal allocation of TCSCs in the deregulated power systems takes the form of MINLP problem of convex nature. The proposed problem is solved by a combinatorial programming method [20], which takes care of integer variables within solution of continuous problems by Interior-Point/ Active-Set methods. In order to incorporate discrete variables, the method used for solving continuous problem is followed by solving a sequence of continuous relaxations, where the discrete variables are relaxed such that they can take on any continuous value. The global solution $f\left(x_R\right)$ of relaxed problem provides an upper bound on the optimal objective value of the maximization problems. If a feasible point is found that satisfies the discrete restrictions on the variables then this provides a lower bound on the optimal objective value, represented as $f\left(x_I\right)$. The optimality for a discrete problem has been declared when the gap between the best (i.e. smallest) upper bound $f^*\left(x_R\right)$ and best (i.e. largest) lower bound $f^*\left(x_I\right)$ is less than a threshold determined by the options mip_integral_gap_abs and mip_integral_gap_rel. Specifically when:

$$f^*\left(x_I\right)-f^*\left(x_R\right)\leq \text{mip\_integral\_gap\_abs} \tag{19}$$

or

$$f^*\left(x_I\right)-f^*\left(x_R\right)\leq \text{mip\_integral\_gap\_rel*max}\left(1,\left|f^*\left(x_I\right)\right|\right) \tag{20}$$

The default values of mip_integral_gap_abs and mip_integral_gap_rel are set as 10-6. Since the TCSCs placement problem comes under the category of discrete variables with “small steps”, it can be efficiently handled by combinatorial programming method of [20].

4. Results and Discussion

A. 5-Bus System

The proposed methodology is tested on a five bus system as shown in Figure 2, which consists of three GenCos G1, G2 and G3; two DistCos D1 and D2; and a bilateral contract S1-B1.

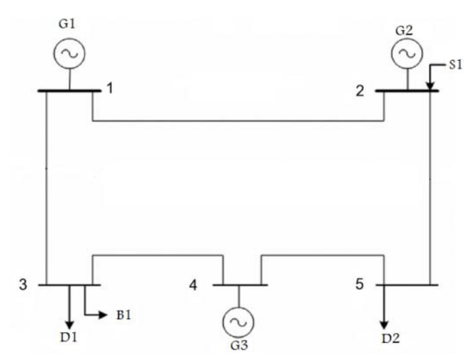

Figure 2. Five bus system

Two market scenarios, viz. peak and low loading scenarios are considered for the sake of comparison with an existing approach [13] under the three Cases:

- Case A: No TCSC is placed in the system
- Case B: One TCSC is to be placed in the system, but usage cost associated with the TCSC is not taken into account. This Case becomes similar to the one considered in [13], except the fact that selection of location of TCSC in [13] is decided by a methodology given in [9]; whereas the proposed methodology implicitly selects the location of TCSC so as to maximize the social welfare.
- Case C: One TCSC is placed in the system including its associated usage cost as given in the proposed formulation.

Considering the TCSC investment data as given in [14], the usage cost function of TCSC as determined using (5) and (6) is:

$$\Psi^t_{pq} = 11.30 \frac{\left(V^t_p - V^t_q\right)^2}{r^2_{pq} + \left(x_{pq} - xc^t_{pq}\right)^2} xc^t_{pq} \times BaseMVA(\$/h) \quad (21)$$

The reactance of TCSC is considered to be varying between 0 to 70% of series reactance of the line in which it would be placed. An equal weight of 0.5 is assigned to the two scenarios. For the moment, cost of reactive power procurement is not included, for the sake of comparison with the existing approach [13]. The line flows and congestion situations under the three Cases for peak and low loads are given in Tables I and II, respectively.

Table 1. Line flows and congestion situations for peak load under three Cases

			Power Flow (MVA)						Shadow price on line flow constraints (μ) ($/MVAh)					
			Case A		Case B		Case C		Case A		Case B		Case C	
Line	From	To	From	To	From	To	From	To	From	To	From	To	From	To
1	1	2	25.12	25.02	38.43	38.42	37.06	37.06	0.0	0.0	0.0	0.0	0.0	0.0
2	2	5	100.0	97.45	100.0	96.55	100.0	96.91	5.26	0.0	2.01	0.0	2.39	0.0
3	5	4	70.82	72.97	69.34	71.3	71.91	74.05	0.0	0.0	0.0	0.0	0.0	0.0
4	4	3	34.11	33.65	29.8	29.44	36.04	35.52	0.0	0.0	0.0	0.0	0.0	0.0
5	3	1	81.04	82.17	98.09	100.0	98.37	100.0	0.0	0.0	0.0	1.33	0.0	0.79

Table 2. Line flows and congestion situations for low load under three Cases

			Power Flow (MVA)						Shadow price on line flow constraints ($/MVAh)					
			Case A		Case B		Case C		Case A		Case B		Case C	
Line	From	To	From	To	From	To	From	To	From	To	From	To	From	To
1	1	2	23.70	23.70	31.39	31.39	28.87	28.87	0.0	0.0	0.0	0.0	0.0	0.0
2	2	5	100.0	97.05	100.0	96.58	100.0	96.87	1.19	0.0	0.20	0.0	0.46	0.0
3	5	4	46.25	47.19	43.08	43.91	45.79	46.72	0.0	0.0	0.0	0.0	0.0	0.0
4	4	3	17.67	17.55	18.39	18.30	19.58	19.46	0.0	0.0	0.0	0.0	0.0	0.0
5	3	1	80.76	82.12	89.05	90.90	86.46	88.04	0.0	0.0	0.0	0.0	0.0	0.0

Note that the results obtained under peak and low load scenarios of Case B exactly match with that of [13]. Originally, line 2-5 of the system was congested without any TCSC, with μ of line 2-5 as 5.26 $/MVAh under peak load and 1.19 $/MVAh under low load. The placement of TCSC in the system under Case B rearranges the line flow pattern, such that μ of line 2-5 has been reduced to 2.01 \$/MVAh and 0.20 \$/MVAh under peak and low load conditions respectively; and line 3-1 has become congested with corresponding μ of 1.33 \$/MVAh under high load conditions. On the other hand, when usage cost of TCSC is included (Case C), μ of line 2-5 become 2.39 \$/MVAh and 0.46 \$/MVAh under peak and low load conditions respectively; with congestion in line 3-1 as 0.79 \$/MVAh under high load conditions. It demonstrates that inclusion of TCSC in the system would certainly lead to reduction in overall system congestion or increase in system loadability, but originally uncongested line may become congested in high load condition. This drawback becomes less pronounced if usage cost of TCSC is included in the formulation, as in Case C. Figures 3 and 4 shows LMP profile of real power under peak and low load scenarios. This shows that LMP profile of the system tend to get flattened after placement of TCSC. Table 3 presents the results obtained by including the reactive power procurement cost (taking k=5%) in Case C during peak load scenario.

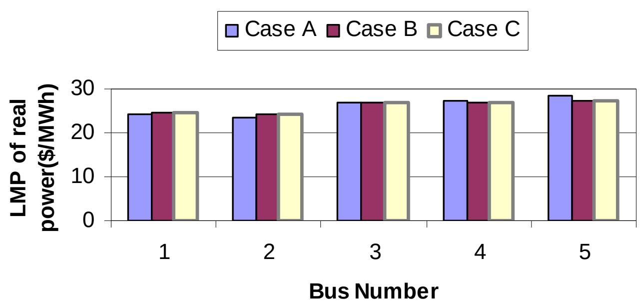

Figure 3. LMP of real power (\$/MWh) for peak load under three Cases

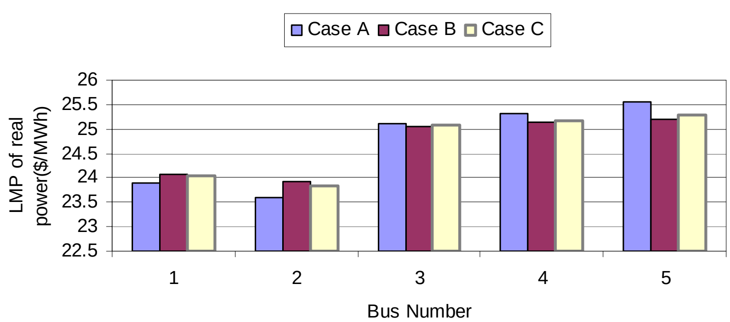

Figure 4. LMP of real power (\$/MWh) for low load under three Cases

After TCSC placement, a significant improvement in GenCo surplus, DistCo surplus and social welfare is obtained. Similarly, a significant reduction in merchandizing surplus occurs, which shows transmission congestion management. Cost of reactive power procurement has been reduced after TCSC placement in the system. This is due to the fact that inclusion of the capacitive reactance of TCSC in this system causes reduction in reactive power losses and more reactive power is procured from cheap generator for meeting the requirements of the system.

Table 3. Results obtained by including Reactive Power Procurement Cost during peak load

	Without TCSC	With TCSC
GenCo Surplus($/h)	447.52	503.54
DistCo Surplus($/h)	1481.20	1611.57
Merchandizing Surplus($/h)	468.19	330.66
Social Welfare($/h)	2365.63	2416.14
Reactive Power Procurement Cost ($/h)	31.29	29.63
TCSC Usage Cost ($/h)	---	11.88
Reactance of TCSC(p.u.)	---	0.04366
TCSC Placed in Line	---	5 (3-1)

B. IEEE 14-Bus System

The bus data, line parameters, and generators bid data of IEEE 14-bus system are taken with 50% increase in bus real and reactive power demands from base case values. In order to simulate congested system conditions, line limits have been taken into account. The demand bid data considered under this scenario is given in Table 4. The maximum number of TCSCs to be placed in the system is taken to be five. The reactance range of each TCSC is taken to be 0-70% of series reactance of associated line. The TCSC allocation problem on IEEE 14-bus system is solved taking into account the usage cost of TCSCs.

Table 4. Demand Bids for IEEE 14-Bus System

Bus Number	Demand Bids		
	($/MW^{2}h)	($/MWh)	($/h)
2	-0.03	55.0	0.0
3	-0.051	53.0	0.0
4	-0.082	50.0	0.0
5	-0.059	49.0	0.0
6	-0.025	58.0	0.0
9	-0.069	45.0	0.0
10	-0.051	38.0	0.0
11	-0.097	51.0	0.0
12	-0.054	40.0	0.0
13	-0.066	54.0	0.0
14	-0.045	49.0	0.0

Table 5. Optimal Location and TCSC Reactances (in p.u.) obtained for IEEE 14-Bus System

Number of TCSCs► Line▼	1	2	3	4	5
2(1-5)	0.1322	0.1304	0.1119	0.1118	0.123
4(2-4)	---	---	---	---	0.0518
6(3-4)	---	0.1197	0.1197	0.1197	0.1004
7(4-5)	---	---	0.0275	0.0266	0.0243
17(9-14)	---	---	---	0.1893	0.1893

Table 5 shows the optimal location and TCSC reactances (in p.u.) obtained for IEEE 14-bus system. For the sake of comparison, the locations of TCSCs to be placed in the present system have also been determined by applying the Performance Index (PI) sensitivity based approach [5], LMP difference and congestion rent contribution (CCC) based approaches [9]. The PI sensitivity based approach determines the location of TCSCs based on power flow in lines, maximum power flow limit in lines and sensitivity of line power flows with respect to TCSC reactances. The LMP difference and CCC based approaches determine locations of TCSCs based on LMP differences at end buses of lines and congestion rent contributed by lines, respectively. A comparison of results obtained for optimal placement of TCSCs with proposed and other approaches is given in Table 6.

Table 6. Priority Locations for Optimal Placement of TCSCs Suggested by Proposed and Other Approaches

Priority	Proposed Approach		PI Based Approach [5]	LMP Difference Based Approach [9]	CCC Based Approach [9]
	TCSC cost included	TCSC cost excluded			
1	2(1-5)	2(1-5)	7(4-5)	1(1-2)	1(1-2)
2	6(3-4)	6(3-4)	2(1-5)	2(1-5)	2(1-5)
3	7(4-5)	7(4-5)	5(2-5)	3(2-3)	3(2-3)
4	17(9-14)	17(9-14)	6(3-4)	13(6-13)	13(6-13)
5	4(2-4)	4(2-4)	17(9-14)	6(3-4)	4(2-4)

Table 7. Improvement in Social Welfare Values after Placement of TCSCs in Lines Suggested by Proposed and Existing Approaches

TCSCs Placed	Social Welfare ($/h)			
	Proposed Approach (TCSC cost excluded)	PI Based Approach [5]	LMP Difference Based Approach [9]	CCC Based Approach [9]
1	7158.10	6822.19	6756.73	6756.73
2	7214.39	7185.11	7158.32	7158.32
3	7235.49	7209.01	7158.32	7158.32
4	7249.16	7236.93	7158.32	7158.32
5	7258.73	7251.36	7214.39	7200.90

It can be observed from Table 6 that proposed, PI sensitivity and LMP difference and CCC based approaches assign different priorities to the different locations for placement of TCSCs. A comparison of improvement in social welfare obtained after placement of five TCSCs in the locations as per their priorities assigned by proposed and other approaches is shown in Table 7. Table 7 shows that improvement in social welfare comes out to be 7158.10 $/h when one TCSC is placed in line 2(1-5) as suggested by proposed approach and 6822.19$/h if one TCSC is placed in line 7(4-5), as suggested by PI sensitivity based approach. The placement of one TCSC at location 1(1-2), as suggested by LMP difference and CCC based approaches lead to no improvement in social welfare, as this line is already congested and placement of TCSC (having capacitive reactance) would further tend to increase the line flow in it. It can be observed from Table 7 that improvement in social welfare comes out to be highest by placing every new TCSC at a location suggested by proposed approach. The placement of TCSCs at locations 1(1-2), 3(2-3) and 13(6-13) as suggested by LMP difference and CCC based approaches lead to no improvement in social welfare due to the reason stated earlier. From the above discussion and comparisons, it can be concluded that the proposed approach is more suitable for placement of TCSCs in deregulated power systems.

5. Conclusion

A MINLP approach for congestion management using optimal placement of TCSCs in deregulated power systems has been presented in this paper. The optimization problem formulated decides the optimal location of TCSCs based on maximization of social welfare and minimization of usage cost of TCSCs, subject to operational and transmission congestion constraints. The optimization problem also performs the minimization of reactive power procurement cost to be paid to the generator companies for their supply of reactive power in deregulated environment. The proposed technique is able to handle a number of potential scenarios by assigning weights to objective functions of individual scenarios. The comparison of proposed approach with existing approaches reveal that highest improvement in social welfare is obtained by placing TCSCs in the locations as suggested by proposed approach, hence proposed approach is more suitable for congestion management using placement of TCSCs in deregulated power systems.

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