Congestion Management by Selecting Best Location of TCSC in Multimachine Power System

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***Abstract*—Congestion management is one of the most challenging aspects in the recently deregulated electricity markets. Flexible Alternative Current Transmission System (FACTS) devices can be an alternative to reduce the flows 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 flow in the network. The paper investigates selection of the best location of Thyristor Controlled Series Compensator (TCSC) in a transmission system from many candidate locations in order to have minimum total congestion rent and minimum total generation cost. The effect of TCSC on the network can be modeled as a controllable reactance inserted in the related transmission line. Seeking the best place of TCSC is performed using sensitivity indices based on reduction of total system reactive power loss, real power flow performance index, reduction of total system active power loss and the Available Transfer Capability (ATC) calculation. The effectiveness of the analyzed methods is demonstrated on IEEE 14 Bus power system in MATLAB/PSAT (Power System Analysis & Simulation Toolbox).**

***Index Terms*—congestion management, best location, sensitivity indices, FACTS, OPF, TCSC, ATC**

I. Introduction

In today's competitive electricity markets, generators compete to sell more power and consumers try to buy the most economical energy for more profit. However, the transmission network, as a medium between power generation and consumption centers, has a limited capacity as well as its own security concerns. Congestion in electricity markets occurs when the transmission network is unable to accommodate all of market desired transactions due to some violations in its operating limits [1]. Congestion may also cause by generation or power grid outages, increase in demand or loop flow problems. Congestion management, that is, controlling the transmission system so that transfer limits are observed, is perhaps the fundamental transmission management problem [2].

Recently, there has been growing interest in solving congestion management using FACTS devices. Impacts of these devices utilization in enhancing loadabililty and removing congestion have been conducted in [3] and [4], respectively. Thyristor Controlled Series Compensator (TCSC) is one of the most effective FACTS devices which offer smooth and flexible control of the line impedance with much faster response compared to the traditional control devices. TCSC can also enhance the stability, ameliorate the dynamic characteristics of power system, and increase the transfer capability of the transmission system by reducing the transfer reactance between the buses at which the line is connected. Controlling the power flows over overloaded lines would lead to the congestion management.

However, to achieve the above mentioned benefits, the TCSC should be properly installed in the transmission network. There are several methods for finding optimal locations of FACTS devices in power systems. Genetic Algorithm was proposed for solving the optimal location of FACTS in [5], [6]. Differential Evolution Optimization technique for optimal location of FACTS devices was also proposed in [7], [8]. The sensitivity based method has been used to find optimal placement of TCSC to reduce congestion in [9], [10]. In [11] a novel method has been introduced in which differences between local marginal prices (LMP) are used to make a priority list to find suitable placement to install TCSC. A multiobjective mixed integer programming approach for allocation of TCSCs in transmission system is presented in [12]. In [13] a genetic algorithm based technique has been proposed to identify the best location for fixing FACTS devices for improving the Available Transfer Capability (ATC) of power transactions between source and sink areas in the deregulated power system.

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To determine the optimal location of TCSC, two methods are implemented in this paper. The first is based on the sensitivity of three objectives: reduction of total system reactive power loss, real power flow performance index and reduction of total system active power loss. The second method based on the calculation of Available Transfer Capability (ATC). An economic evaluation based optimal power flow (OPF) has been proposed to select the best location of TCSC among other candidate locations for congestion management. The results have been obtained on IEEE 14 Bus system.

II. Static Model of Thyristor Controlled Series Compensator (TCSC)

The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Fig. 1. Where Z_{ij} and jB_{sh} represent the series and shunt impedance of the transmission line, respectively. Complex voltages at bus-i and bus-j are $V_i\angle\delta_i$ and $V_j\angle\delta_j$ respectively. During the steady state the TCSC can be considered as a static reactance $-jx_c$. The real and reactive power flow from bus-i to bus-j can be written as [9]-[14]

$$P_{ij}^{c} = V_i^2 G'_{ij} - V_i V_j (G'_{ij}\cos\delta_{ij} + B'_{ij}\sin\delta_{ij}) \quad (1)$$

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

where $\delta_{ij} = \delta_i - \delta_j$. Similarly, the real and reactive power flow from bus-j to bus-i is

$$P_{ji}^{c} = V_j^2 G'_{ij} - V_i V_j (G'_{ij}\cos\delta_{ij} - B'_{ij}\sin\delta_{ij}) \quad (3)$$

$$Q_{ji}^{c} = -V_j^2 (B'_{ij} + B_{sh}) + V_i V_j (G'_{ij}\sin\delta_{ij} + B'_{ij}\cos\delta_{ij}) \quad (4)$$

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

$$P_L = G'_{ij}(V_i^2 + V_j^2) - 2V_i V_j G'_{ij}\cos\delta_{ij} \quad (5)$$

$$Q_L = -(V_i^2 + V_j^2)(B'_{ij} + B_{sh}) + 2V_i V_j B'_{ij}\cos\delta_{ij} \quad (6)$$

where

$$G'_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2} \quad (7)$$

$$B'_{ij} = \frac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2} \quad (8)$$

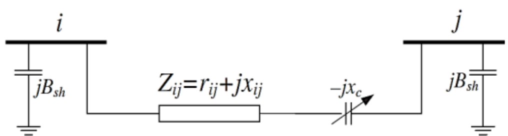

Figure 1. Model of transmission line with TCSC.

The change in the line flow due to series capacitance can be represented as a line without series capacitance with power injected at the receiving and sending ends of the line as shown in Fig. 2. The real and reactive power injections at bus-i and bus-j can be expressed as

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j \left[\Delta G_{ij}\cos\delta_{ij} + \Delta B_{ij}\sin\delta_{ij}\right] \quad (9)$$

$$P_{jc} = V_j^2 \Delta G_{ij} - V_i V_j \left[\Delta G_{ij}\cos\delta_{ij} - \Delta B_{ij}\sin\delta_{ij}\right] \quad (10)$$

$$Q_{ic} = -V_i^2 \Delta B_{ij} - V_i V_j \left[\Delta G_{ij}\sin\delta_{ij} - \Delta B_{ij}\cos\delta_{ij}\right] \quad (11)$$

$$Q_{jc} = -V_j^2 \Delta B_{ij} + V_i V_j \left[\Delta G_{ij}\sin\delta_{ij} + \Delta B_{ij}\cos\delta_{ij}\right] \quad (12)$$

where

$$\Delta G_{ij} = \frac{x_c r_{ij}(x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)} \quad (13)$$

$$\Delta B_{ij} = \frac{-x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)} \quad (14)$$

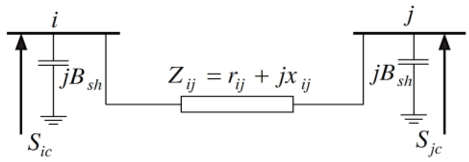

Figure 2. Injection model of TCSC

III. Selection of Best Location for TCSC Placement

A. Sensitivity Indices

Many sensitivity performance indices have been proposed for the analysis of power systems. There are some sensitivity indices which have the most attraction for optimal placement of series compensators.

Reduction of total system reactive power loss (Method 1): Here, we look at a method based on the 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. Loss sensitivity with respect to control parameter of TCSC placed between buses i and j can be written as [9]

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

In this method TCSC must be installed in a line having the most positive loss sensitivity index

Real power flow performance index (Method 2): The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index [9], [15], [16], as given below

$$PI = \sum_{m=1}^{N_l} \frac{w_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{\max}} \right)^{2n} \quad (16)$$

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

$$b_k = \left. \frac{\partial PI}{\partial x_{ck}} \right|_{x_{ck}=0} \quad (17)$$

where x_{ck} is the value of the reactance, as provided by the TCSC installed on line k.

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

$$\frac{\partial PI}{\partial x_{ck}} = \sum_{m=1}^{N_l} w_m P_{lm}^3 \left(\frac{1}{P_{lm}^{\max}} \right)^4 \frac{\partial P_{lm}}{\partial x_{ck}} \quad (18)$$

The real power flow in a line-m can be represented in terms of real power injections using DC power flow equations where s is slack bus, as

$$P_{lm} = \begin{cases} \sum_{\substack{n=1 \\ n \neq s}}^{N} S_{mn} P_n & \text{for } m \neq k \\ \sum_{\substack{n=1 \\ n \neq s}}^{N} S_{mn} P_n + P_j & \text{for } m = k \end{cases} \quad (19)$$

Using (19), the following relationship can be derived

$$\frac{\partial P_{lm}}{\partial x_{ck}} = \begin{cases} \left(S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}} \right) & \text{for } m \neq k \\ \left(S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}} \right) + \frac{\partial P_j}{\partial x_{ck}} & \text{for } m = k \end{cases} \quad (20)$$

The term

$$\left. \frac{\partial P_i}{\partial x_{ck}} \right|_{x_{ck}=0} , \quad \left. \frac{\partial P_j}{\partial x_{ck}} \right|_{x_{ck}=0} \quad (21)$$

Can be derived as

$$\left. \frac{\partial P_i}{\partial x_{ck}} \right|_{x_{ck}=0} = \left. \frac{\partial P_{ic}}{\partial x_{ck}} \right|_{x_{ck}=0} \quad (22)$$

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

$$\left. \frac{\partial P_j}{\partial x_{ck}} \right|_{x_{ck}=0} = \left. \frac{\partial P_{jc}}{\partial x_{ck}} \right|_{x_{ck}=0} \quad (23)$$

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

In this method TCSC should be placed in a line having most negative sensitivity index.

Reduction of total system active power loss (Method 3): A method based on sensitivity of the total system active power loss with respect to the control variable of the TCSC. If TCSC placed between buses i and j we consider net line series reactance as a control parameter. By differentiating the active power loss P_L with respect to control parameter of TCSC we can obtain the sensitivity factor c_{ij}, which is as follows [17]

$$c_{ij} = \frac{\partial P_L}{\partial x_{ij}} = [V_i^2 + V_j^2 - 2V_i V_j \cos \delta_{ij}] \frac{-2 r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} \quad (24)$$

In this method TCSC must be installed in a line having the most positive loss sensitivity index.

B. Available Transfer Capability (ATC) Calculation (Method 4)

Available Transfer Capability (ATC) is an important term in restructured power system that affects the planning and controlling of transmission infrastructure. ATC of transmission network is the measure of unutilized capacity of the transmission network, which can be made available for further transactions to the market participants without losing its security. According to NERC report [18], Available Transfer Capability (ATC) is the amount of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. As stated by NERC, ATC has to be calculated for the transaction between two buses or areas for specified time duration. Since the system conditions continuously change, ATC must be continuously updated.

Mathematically ATC can be given as

$$ATC = TTC - TRM - CBM - ETC \quad (25)$$

where

TTC: Total Transfer Capability

TRM: Transmission Reliability Margin

CBM: Capacity Benefit Margin

ETC: Existing Transmission Commitments

For Available Transfer Capability calculation, the increases in power (Real and Reactive) both at source and sink buses are functions of loading parameter (λ). Where λ=0 corresponds to the base case and $\lambda = \lambda_{max}$ corresponds to the maximal transfer.

The TTC level in normal or contingency state is given by

$$TTC = \sum_{i \in \sin k} P_{Di}(\lambda_{\max}) \quad (26)$$

And ATC neglecting TRM, ETC is given by

$$ATC = \sum_{i \in \sin k} P_{Di}(\lambda_{\max}) - \sum_{i \in \sin k} P_{Di}^{0} \quad (27)$$

where

$\sum_{i \in \sin k} P_{Di}(\lambda_{\max})$ is the sum of load in sink area when $\lambda=\lambda_{max}$

$\sum_{i \in \sin k} P_{Di}^{0}$ is the sum of load in sink area when $\lambda=0$

IV. Optimal Power Flow (OPF)

A. Objective Function

Since the fuel cost minimization is primarily concerned in system operation, the objective function selected is the sum of fuel cost of all generating units.

$$C_T = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} \alpha_i + \beta_i P_i + \gamma_i P_i^2 \quad (28)$$

where C_T is the total production cost; C_i is the i-th generating unit's fuel cost; P_i is the active power generation output in MW of the i-th generator α_i, β_i and γ_i are the cost coefficients of i-th generator and n is the number of generators committed to the operating system.

B. The Equality Constraints

In the power balance criterion, the equality constraint should be satisfied as the real power balance equations, expressed as follows

$$\sum_{i=1}^{n} P_i - P_D - P_L = 0 \quad (29)$$

where P_D is the total active power demand; P_L is the transmission losses generally approximated by the Kron's loss formula, which represents the losses as a function of the output level of the system generating units

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} B_{oi} P_i + B_{00} \quad (30)$$

The coefficients B_{ij}, B_{0i}, B_{00} are called loss coefficients or B-coefficients.

C. The Inequality Constraints

For stable operation, the real output of each generator is restricted by lower and upper limits as follows

$$P_i^{\min} \le P_i \le P_i^{\max} \quad i = 1, \ldots\ldots, n \quad (31)$$

where P_i^{min} and P_i^{max}, are minimum and maximum output of the generator *i* respectively.

V. Simulation Results

The Proposed methods for optimal placement of TCSC for congestion management are tested on IEEE 14 Bus system. The programs are developed using MATLAB/PSAT software. The IEEE 14 Bus system consists of 14 buses, 5 existing generators and 11 loads. Line, generator, and demand data can be found in [19]. The Generators limits data with cost coefficients are taken from [20].

For ATC problem analysis, the network is divided into two areas where each area contains seven buses as shown in Fig. 3. The base load in area 2 is 76.5MW. The TCSC is inserted in transmission line as a variable reactance. Here, it represents 60% of series compensation and reduces the total reactance of transmission line.

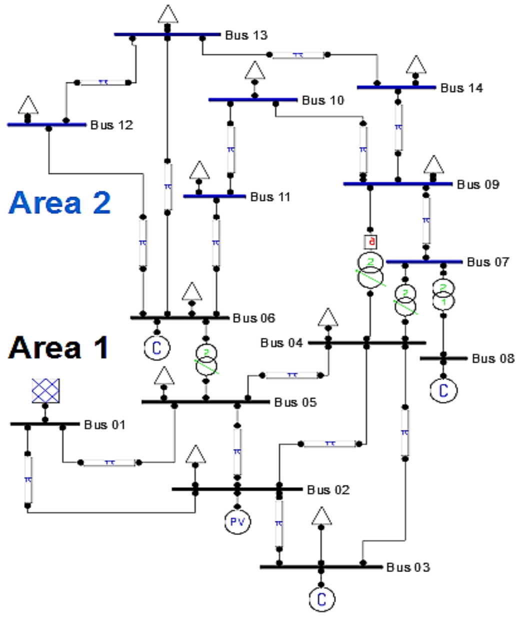

Figure 3. IEEE 14 bus system

The ATC (MW) and sensitivities of reduction of total system real power and total system reactive power losses and real power flow performance index with respect to TCSC control parameter have been computed. The most sensitive line in each method is shown in Table I.

TABLE I. Sensitivity Indices and ATC for IEEE 14 Bus System

Line	Method1	Method2	Method3	Method4
1-2	-1.7885	**-19.0393**	-1.3132	234.5413
2-5	-0.1300	-1.0026	-0.0955	**245.8786**
7-9	-0.0894	-0.9740	**0**	232.3458
12-13	**0.0001**	-0.0409	-0.0006	227.5951

From the table it can be observed that the placement of TCSC in line 1-2 is optimal for reducing the PI. After placing TCSC in this line, the power flow increases from 135.69MW to 148.55MW. Line 2-5 is chosen as the optimal location of TCSC for ATC improvement. After TCSC installation, the power transfer increases from 34.93MW to 52.86MW. The placement of TCSC in line 7-9 is suitable for reducing the total active power loss. An increase in power flow after TCSC installation in this line from 28.97MW to 32.70MW. The placement of TCSC in line 12-13 is optimal for reducing the total reactive power loss. After placing TCSC in this line, the power transfer increases from 1.92MW to 2.39MW.

Table II presents an economic evaluation based OPF of selected lines to choose the best location of TCSC for congestion management.

TABLE II. OPF SOLUTION FOR IEEE 14 BUS SYSTEM

Line With TCSC	OPF	
	Total Cost ($/h)	P_L (MW)
1-2	831.34	10.3891
2-5	831.55	10.4567
7-9	**829.78**	**9.8933**
12-13	829.94	9.9444

The total costs and losses of four lines with TCSC are shown in Fig. 4. The line 7-9 is more economical than other lines. It represents minimum total generation cost and minimum total transmission losses.

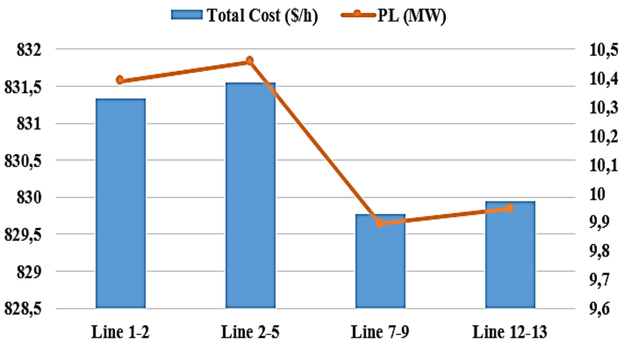

Figure 4. Comparison of costs and losses for IEEE 14 bus system

Table III shows the congested line 5-6 with the amount of power 36.60MW which is more than its line loading limit (35MW).

TABLE III. CONGESTED LINE DETAILS FOR IEEE 14 BUS SYSTEM

Congested line	Power flow (MW)	Line limit (MW)	Loading (%)
5-6	36.60	35.00	104.58

The power flow in congested line 5-6 after placing TCSC in the selected lines with different values of series compensation is shown in Table IV.

TABLE IV. CONGESTED LINE DETAILS OF IEEE 14 BUS SYSTEM AFTER PLACEMENT OF TCSC

TCSC Series Compensation		Congested line 5-6	
		Power flow (MW)	Loading (%)
In line 1-2	40%	36,025	102,93%
	60%	35,892	102,55%
	80%	36,055	103,01%
In line 2-5	40%	36,985	105,67%
	60%	37,282	106,52%
	80%	37,696	107,70%
In line 7-9	40%	35,247	100,71%
	60%	34,483	**98,52%**
	80%	33,652	**96,15%**
In line 12-13	40%	36,624	104,64%
	60%	36,637	104,68%
	80%	36,652	104,72%

Fig. 5 shows the congested line loading with different degrees of series compensation of TCSC installed in the selected lines. It can be observed that the congestion is relieved in line 5-6 after placing TCSC in line 7-9 with 60% and 80% series compensation. It removes the congestion from 104.58% to 96.15%. Hence the system is operated within the limit.

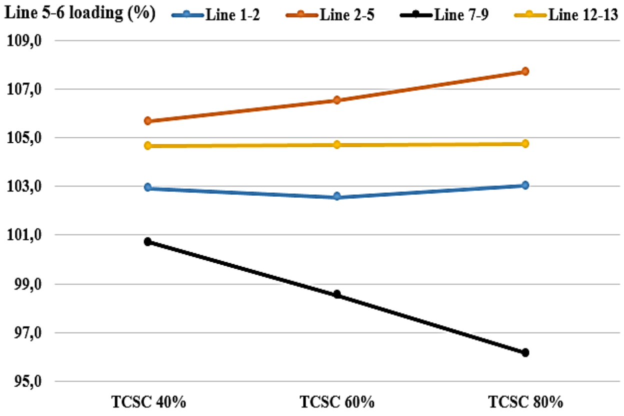

Figure 5. Line 5-6 loading for IEEE 14 bus system

Based on the obtained results, the line 7-9 is the best location for placing the TCSC.

VI. CONCLUSION

Congestion management is an important issue in deregulated power systems. FACTS devices such as TCSC by controlling 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.

In this paper, four methods based on sensitivity indices and ATC calculation have been developed for determining the optimal location of TCSC in an electricity market. In IEEE 14 Bus system, four lines are selected for TCSC placement.

OPF is carried out when TCSC is placed on each line and best location for minimum production cost, minimum losses and minimum congestion rent is selected.

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