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Science Publications

American Journal of Applied Sciences 5 (3): 242-247, 2008
ISSN 1546-9239
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Transmission Congestion Management by Determining Optimal Location of FACTS Devices in Deregulated Power Systems

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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 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 flows in the network. A method to determine the optimal location of thyristor controlled series compensators has been suggested in this paper based on real power performance index and reduction of total system reactive power loss.

Keywords: Congestion, Optimal Location, Deregulated Power System

INTRODUCTION

In a competitive electricity market, congestion occurs when the transmission network is unable to accommodate all of the desired transactions due to a violation of system operating limits. Congestion does occur in both electrically bundled and unbundled systems but the management in the bundled system is relatively simple as generation, transmission, and in some cases, distribution systems are managed by one utility. The management of congestion is somewhat more complex in competitive power markets and leads to several disputes.

In the present day competitive power market, each utility manages the congestion in the system using its own rules and guidelines utilizing a certain physical or financial mechanism[1].

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. Patterns of generation that result in heavy flows tend to incur greater losses, and to threaten stability and security, ultimately make certain generation patterns economically undesirable[2, 3]. Hence, there is an interest in better utilization of available power system capacities by installing new devices such as Flexible AC Transmission Systems (FACTS).

FACTS devices by controlling the power flows in the network without generation rescheduling or topological changes can improve the performance considerably[4-6]. The insertion of such devices in electrical systems seems to be a promising strategy to decrease the transmission congestion and to increase available transfer capability. Using controllable components such as controllable series capacitors line flows can be changed in such a way that thermal limits are not violated, losses minimized, stability margins increased, contractual requirement fulfilled etc, without violating specific power dispatch. The increased interest in these devices is essentially due to two reasons. Firstly, the recent development in high power electronics has made these devices cost effective[7] and secondly, increased loading of power systems, combined with deregulation of power industry, motivates the use of power flow control as a very cost-effective means of dispatching specified power transactions. It is important to ascertain the location for placement of these devices because of their considerable costs.

There are several methods for finding optimal locations of FACTS devices in both vertically integrated and unbundled power systems[8-12]. In[8], a sensitivity approach based on line loss has been proposed for placement of series capacitors, phase shifters and static VAR (Volt Ampere Reactive) compensators. Other works in optimal power flow with FACTS devices[9,10] have used optimization with different objective functions. In [13,14], the optimal locations of FACTS devices are obtained by solving the economic dispatch problem plus the cost of these devices making the assumption that all lines, initially, have these devices. In the presence of bilateral and

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multilateral contracts it would be difficult to use this objective.

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, re-dispatch of generation and curtailment of pool loads and/or bilateral contracts can relieve congestion.

A method to determine the optimal location of TCSC has been suggested in this paper. The approach is based on the sensitivity of the reduction of total system reactive power loss and real power performance index. In section 2 static modeling of TCSC is obtained. In section 3 the objective function for using in OPF (Optimal Power Flow) is presented. The optimal location is based on the minimizing the production and device cost. The proposed method has been demonstrated on two 5-bus power systems. The results show that above algorithm is suitable for relieving congestion and getting economical results.

MATERIALS AND METHODS

The Figure1.a shows a simple transmission line represented by its lumped π equivalent parameters connected between bus-i and bus-j. Let complex voltage at bus-i and bus-j are $V_i\angle\delta_i$ and $V_j\angle\delta_j$ respectively. The real and reactive power flow from bus-i to bus-j can be written as

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

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

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

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

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

The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Fig.1.b. 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, and from bus-j to bus-i of a line having series impedance and a series reactance are[15]

$$P_{ij}^c = V_i^2 G_{ij}' - V_i V_j (G_{ij}'\cos\delta_{ij} + B_{ij}'\sin\delta_{ij}) \tag{5}$$

$$Q_{ij}^c = -V_i^2 (B_{ij}' + B_{sh}) - V_i V_j (G_{ij}'\sin\delta_{ij} - B_{ij}'\cos\delta_{ij}) \tag{6}$$

$$P_{ji}^c = V_j^2 G_{ij}' - V_i V_j (G_{ij}'\cos\delta_{ij} - B_{ij}'\sin\delta_{ij}) \tag{7}$$

$$Q_{ji}^c = -V_j^2 (B_{ij}' + B_{sh}) + V_i V_j (G_{ij}'\sin\delta_{ij} + B_{ij}'\cos\delta_{ij}) \tag{8}$$

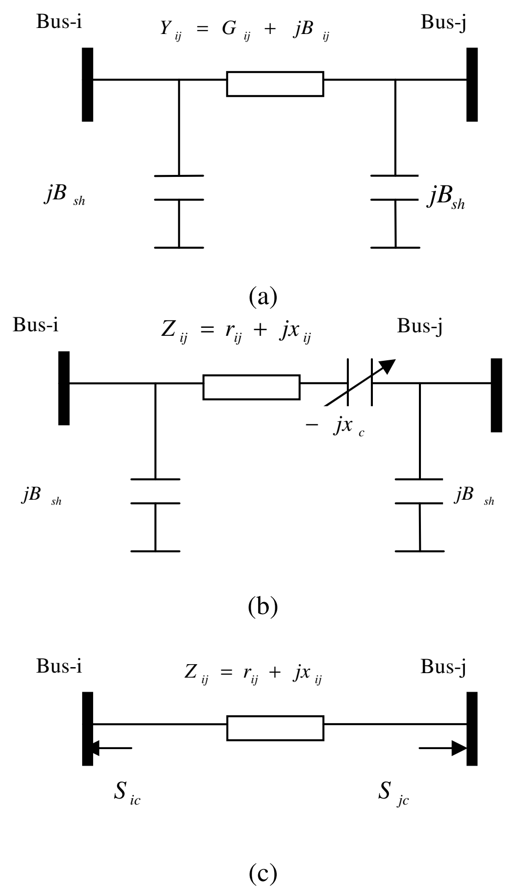

Fig.1: (a) Model of Transmission line (b) Model of TCSC (c) Injection Model of TCSC

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

$$P_L = P_{ij} + P_{ji} = G_{ij}'(V_i^2 + V_j^2) - 2V_i V_j G_{ij}'\cos\delta_{ij} \tag{9}$$

$$Q_L = Q_{ij} + Q_{ji} = -(V_i^2 + V_j^2)(B_{ij}' + B_{sh}) + 2V_i V_j B_{ij}'\cos\delta_{ij} \tag{10}$$

where $G_{ij}' = \dfrac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2}$ and $B_{ij}' = \dfrac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2}$.

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.1.c. The real and reactive power injections at bus-i and bus-j can be expressed as

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij}\cos\delta_{ij} + \Delta B_{ij}\sin\delta_{ij}] \tag{11}$$

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

$$Q_{ic} = -V_i^2 \Delta B_{ij} - V_i V_j [\Delta G_{ij} \sin\delta_{ij} - \Delta B_{ij} \cos\delta_{ij}] \quad (13)$$

$$Q_{jc} = -V_j^2 \Delta B_{ij} + V_i V_j [\Delta G_{ij} \sin\delta_{ij} + \Delta B_{ij} \cos\delta_{ij}] \quad (14)$$

where $\Delta G_{ij} = \frac{x_c r_{ij}(x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$ and $\Delta B_{ij} = \frac{-x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})}{(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)}$.

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 actually installed. The TCSC cost in line-k is given by [16],

$$C_{TCSC}(k) = c.x_c(k).P_L^2.Base\_power \quad (15)$$

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

The objective function for placement of TCSC will be

$$\min_{P_i} \sum_i C_i(P_i) + C_{TCSC} \quad (16)$$

OPTIMAL LOCATION OF TCSC

Reduction of total system reactive power loss: 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

$$a_{ij} = \frac{\partial Q_L}{\partial x_{ij}} = [V_i^2 + V_j^2 - 2V_i V_j \cos\delta_{ij}].\frac{r_{ij}^2 - x_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2} \quad (17)$$

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 [17], as given below.

$$PI = \sum_{m=1}^{N_L} \frac{w_m}{2n} \left(\frac{P_{Lm}}{P_{Lm}^{\max}} \right)^{2n} \quad (18)$$

where P_{Lm} is the real power flow and $P_{Lm}^{\max}$ is the rated capacity of line-m, n is the exponent and w_m a real non-negative weighting coefficient which may be used to reflect the importance of 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. Most of the works on contingency selection algorithms utilize the second order performance indices which, in general, suffer from masking effects. The lack of discrimination, in which the performance index for a case with many small violations may be comparable in value to the index for a case with one huge violation, is known as masking effect. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. Masking effect to some extent can be avoided using higher order performance indices, that is n > 1. However, in this study, the value of exponent has been taken as 2 and $w_i = 1$.

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

$$b_k = \left. \frac{\partial PI}{\partial x_{ck}} \right|_{x_{ck}=0} \quad (19)$$

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

$$\frac{\partial PI}{\partial x_{ck}} = \sum_{m=1}^{N_L} w_m P_{Lm}^3 \left(\frac{1}{P_{Lm}^{\max}} \right)^4 \frac{\partial P_{Lm}}{\partial x_{ck}} \quad (20)$$

The real power flow in a line-m can be represented in terms of real power injections using DC power flow equations [17] where s is slack bus, as

$$P_{Lm} = \begin{cases} \sum_{\substack{n=1 \\ n \neq s}}^{N} S_{mn} P_n & for \quad m \neq k \\ \sum_{\substack{n=1 \\ n \neq s}}^{N} S_{mn} P_n + P_j & for \quad m = k \end{cases} \quad (21)$$

Using equation (21), the following relationship can be derived,

$$\frac{\partial P_{Lm}}{\partial x_{ck}} = \begin{cases} \left(S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}} \right) & for \quad m \neq k \\ \left(S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}} \right) + \frac{\partial P_j}{\partial x_{ck}} & for \quad m = k \end{cases} \quad (22)$$

The terms $\left. \frac{\partial P_i}{\partial x_{ck}} \right|_{x_{ck}=0}$, $\left. \frac{\partial P_j}{\partial x_{ck}} \right|_{x_{ck}=0}$ can be derived as below

$$\left. \frac{\partial P_i}{\partial x_{ck}} \right|_{x_{ck}=0} = \left. \frac{\partial P_{ic}}{\partial x_{ck}} \right|_{x_{ck}=0} = -2(V_i^2 - V_i V_j \cos\delta_{ij}) \frac{r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} - V_i V_j \sin\delta_{ij} \frac{(x_{ij}^2 - r_{ij}^2)}{(r_{ij}^2 + x_{ij}^2)^2} \quad (23)$$

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$$\left.\frac{\partial P_j}{\partial x_{ck}}\right|_{x_{ck}=0} = \left.\frac{\partial P_{jc}}{\partial x_{ck}}\right|_{x_{ck}=0}$$
$$= -2(V_j^2 - V_i V_j \cos\delta_{ij})\frac{r_{ij}x_{ij}}{(r_{ij}^2+x_{ij}^2)^2} + V_i V_j \sin\delta_{ij}\frac{(x_{ij}^2-r_{ij}^2)}{(r_{ij}^2+x_{ij}^2)^2} \quad (24)$$

Criteria for optimal location: The FACTS device should be placed on the most sensitive line. With the sensitivity indices computed for TCSC, following criteria can be used for its optimal placement.

a) In reactive power loss reduction method TCSC should be placed in a line having the most positive loss sensitivity index.

b) In PI method TCSC should be placed in a line having most negative sensitivity index.

RESULTS AND DISCUSSION

The approach has been examined on two 5-bus power systems. MATPOWER, a toolbox of MATLAB, has been used for simulations[18]. The prices bid by generators for each 5-bus system are given in Table 1 where P is in MW and $ is a momentary unit which may be scaled by any arbitrary constant without affecting the results and $P_{i\min}$, $P_{i\max}$ are generation power limits of each generator.

Table 1: Bid prices of generators

Generator	Bid Prices ($/h)	$P_{i\min}$	$P_{i\max}$
1	$0.11P_1^2+5P_1+150$	10	250
2	$0.085P_2^2+1.2P_2+60$	10	200
3	$0.1225P_3^2+P_3+335$	10	200

The first 5-bus system is shown in Fig.2.a. Bus-1 has been taken as a reference bus.

From the load flow, it was found that real power flow in line 2-5 was 1.034 pu which is more than its line loading limit.

The sensitivities of reactive power loss reduction and real power flow performance index with respect to TCSC control parameter has been computed and are shown in Table 2. The sensitive line in each case is presented in bold type. It can be observed from Table 2 (column 3) that placement of TCSC in line-3 is suitable for reducing the total reactive power loss. System power flow result after placing TCSC in line-3 is shown in Table 3 (column 4). The value of control parameter of TCSC for computing power flow is taken as 0.2885 pu. It can be observed from Table 3 (column 4) that congestion has been relieved. Placement of TCSC in line-1 also will reduce the total system reactive power loss but it will be less effective than placing a TCSC in line-3 as can be seen from its sensitivity factors.

It can be observed from Table 2 (column 4) that placing a TCSC in line-5 is optimal for reducing the PI and congestion relief. System power flow result after placing TCSC in line-5 is shown in Table 3 (column 5). The value of control parameter of TCSC for computing power flow is taken as 0.0423 pu. It can be observed from Table 3 (column 5) that congestion has been relieved.

Placement of TCSC in line-3 will reduce the PI value but it will be less effective than placing a TCSC in line-5 as can be seen from its sensitivity factors. Total costs of two methods are shown in Table 6. It can be observed from Table 6 that reduction of total system reactive power loss method is more economical than PI method for placing the TCSC and congestion management.

Table 2: Calculated sensitivity indices of first 5-bus system

Line	i-j	a_{ij}	b_{ij}
1	2-1	-0.008057	-0.0789
2	2-5	-0.970852	1.95327
3	3-5	-0.00784	-0.10536
4	5-4	-0.261704	0.34953
5	1-4	-0.967394	-0.41433
6	3-2	-0.240349	0.45582

Table 3: Power flow result of first 5-bus system

Line	i-j	Power flow without TCSC (pu)	Power flow with TCSC in Line-3 (pu)	Power flow with TCSC in Line-5 (pu)
1	2-1	0.07798	0.07614	0.10893
2	2-5	1.034	0.99956	0.99956
3	3-5	0.08441	0.08441	0.08798
4	5-4	0.40379	0.40379	0.37453
5	1-4	0.4145	0.41123	0.46051
6	3-2	0.51559	0.47879	0.51202

The second 5-bus system is shown in Fig.2.b. Bus-1 has been taken as a reference bus.

From the load flow, it was found that real power flow in line 1-2 was 1.0181 pu which is more than its line loading limit.

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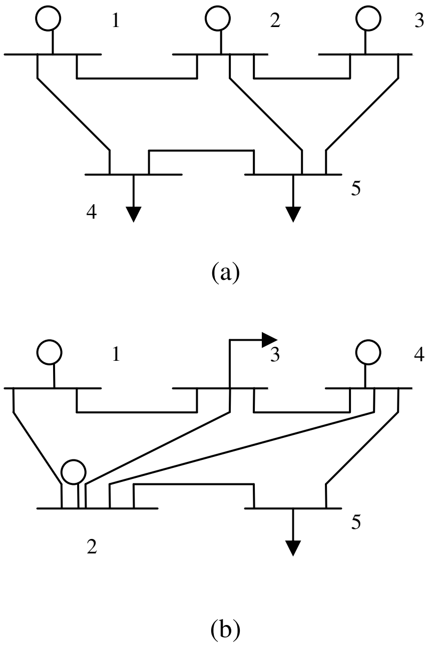

Fig.2 (a): First 5-bus system (b) Second 5-bus system

The sensitivities of reactive power loss reduction and real power flow performance index with respect to TCSC control parameter has been computed and are shown in Table 4. The sensitive line in each case is presented in bold type. It can be observed from Table 4 (column 3) that placement of TCSC in line-6 will reduce the total system reactive power loss but it will be less effective than placing a TCSC in line-7 as can be seen from its sensitivity factors. System power flow result after placing TCSC in line-7 is shown in Table 5 (column 4). The value of control parameter of TCSC for computing power flow is taken as 0.17815 pu. It can be observed from Table 5 (column 4) that congestion has been relieved. From the calculated sensitivity factors b_{ij} of Table 4 (column 4) it can be observed that placement of TCSC in line-7 will reduce the PI but it will be less effective than placing a TCSC in line-2. System power flow result after placing TCSC in line-2 is shown in Table 5 (column 5). The value of control parameter of TCSC for computing power flow is taken as 0.014315 pu. It can be observed from Table 5 (column 5) that congestion has been relieved. Total costs of two methods are shown in Table 6. It can be observed from Table 6 that PI method in this case is more economical than reduction of total system reactive power loss method for installing the TCSC and congestion relief.

Table 4: Calculated sensitivity indices of second 5-bus system

Line	i-j	a_{ij}	b_{ij}
1	1-2	-1.20822	3.45
2	1-3	-0.19303	**-1.11**
3	2-3	-0.18757	0.609
4	2-4	-0.10456	0.124
5	2-5	-0.60931	1.39
6	3-4	-0.05629	0.15
7	4-5	-0.0368	-0.18

Table 5: Power flow result of second 5-bus system

Line	i-j	Power flow without TCSC (pu)	Power flow with TCSC in line-7 (pu)	Power flow with TCSC in line-2 (pu)
1	1-2	1.0181	0.99956	0.99956
2	1-3	0.48796	0.50718	0.50751
3	2-3	0.43934	0.48785	0.42892
4	2-4	0.33076	0.37522	0.32527
5	2-5	0.76539	0.65385	0.76276
6	3-4	0.1133	0.17992	0.12135
7	4-5	0.14286	0.25336	0.14546

Table 6: Total cost

Power system	Method	Total Cost
First 5-bus system	Reactive loss reduction	2250.11
	PI	2276.78
Second 5-bus system	Reactive loss reduction	5040.51
	PI	4929.44

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 two sensitivity-based methods have been developed for determining the optimal location of TCSC in an electricity market. In a system, first two optimal locations of TCSC can be achieved based on the sensitivity factors a_{ij} and b_{ij} and then optimal location is selected based on minimizing production cost plus device cost. Test results obtained on two 5-bus power systems show that sensitivity factors along with

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TCSC cost could be effectively used for determining optimal location of TCSC.

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