OPTIMAL LOCATION OF TCSC AND ITS USE IN CONGESTION MANAGEMENT

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Abstract

Over the last two decades, electricity demand has increased substantially while the expansion of generation and transmission network has been limited due to environmental and/or economic constraints of building new generating plants and transmission lines. As a consequence, transmission lines are driven close to their transfer limits, and congestion often results. This paper proposes a method of locating series FACTS devices in a power system, with aim of alleviating congestion. Congestion rent is used to pinpoint lines suitable for TCSC placement. The proposed method is tested on the Western System Coordinating Council (WSCC) 9-bus test system, and results obtained show that locating FACTS devices optimally reduces the level of congestion in a power system.

Keywords: Locational marginal price, Congestion rent, FACTS devices, TCSC.

1. INTRODUCTION

Power transfer limits in transmission systems are constrained by thermal capacities of transmission lines, voltage magnitude and voltage angle deviation across the line. The thermal limit of a line is the most difficult to alleviate as this would require changing the material of the line. However, voltage and stability limits can be increased by modifying the transmission line impedance. FACTS devices offer the possibility to modify series and shunt impedances across a line, and such would influence power transfer over existing lines without endangering system security (Milanovic, 2010) (J. S.Sarda, 2012). The potential benefits of FACTS devices are widely recognized by power systems engineering community. These include improving system stability, increasing line loadability and reducing system losses. The greatest challenge however lies in locating FACTS devices optimally, to obtain maximum benefits from them, at minimum cost (J.Sridevi, 2012) (L.Rajalakshmi, 2011). A number of studies devoted to the application of FACTS devices are ongoing, with the aim of obtaining optimal location and size of the appropriate device for utilization. In (J.Sridevi, 2012), Sridevi et al. proposes the application of TCSC and SVC for congestion relief and improving voltage stability under contingencies. Authors determine the optimal location of TCSC and SVC using line and bus performance indices, which are derived from loss sensitivity factors. Optimal placement of FACTS devices based on voltage stability index (VSI) is discussed in (P.P.Bedekar, 2012), with aim of improving voltage profile in a power system. Debnath et al. in (A. Debnath, 2013) investigate the effect of UPFC on voltage profile of modified IEEE 30-bus system, whereas eigen value analysis was employed in (Dube, 2012) to show the performance of UPFC for stability enhancement.

Evolutionary techniques have also been proposed, such as in (Kamaraj, 2012). Authors use particle swarm optimization (PSO) and genetic algorithm (GA) to find the optimal location and value of static VAr compensator (SVC) which results in minimum voltage stability index and real power loss in power systems. Other approaches have been reported in literature, and results depend on the overall objective. In this paper, optimal location of thyristor controlled series capacitor (TCSC) is done by use of a cost of generation minimization algorithm. Congestion rent is used to pinpoint transmission lines suitable for TCSC placement. Evaluation of system performance is done with TCSC incorporation and finally a cost benefit analysis undertaken to determine if investing in TCSC would be financially viable. Simulations were carried out on the WSCC 9-bus test system, and results obtained show that installing FACTS devices in the proper location reduces congestion. It was observed that the capital cost of FACTS devices can be recovered in a relatively short period of time. This paper is organized as follows: section 2 presents power system congestion, use of FACTS devices in congestion management and their optimal placement. Case study is given in section 3, whereas simulation results and discussion are found in section 4. Section 5 concludes the paper.

2. POWER SYSTEM CONGESTION

Generators, transmission, as well as distribution lines and transformers are designed to operate within certain specified limits. When any system limit is reached or exceeded, the resulting situation is defined as congestion (Shi, 2006). Power transfer in a transmission network is constrained by three factors:

1. Thermal limits - the limit for short lines, governed by line resistance. If exceeded, conductors risk overheating.
2. Voltage limits - the limiting factor for medium lines, which ensure that voltage magnitude at the receiving end does not go below a certain level. Their violation might lead to wide spread black-outs and disconnection of end-user devices.
3. Stability limits - the limiting factor for long lines, enforced to ensure that the system will survive transient and dynamic time periods following a disturbance (Johansson, 2011).

2.1 Congestion management

Congestion management refers to the activities of the system operator that relieve constraints in power systems (Anitha, 2013). There are various ways of alleviating congestion, the most common being:

1. Generation re-dispatch - the system operator re-dispatches generation to ensure that congestion is gotten rid of.
2. Load shedding - the load is reduced until system constraints are satisfied.
3. Expansion of transmission lines - this is the long term solution to transmission network congestion. It involves upgrading the existing transmission lines or building new ones.
4. Using VAr support - VAr support is done using static devices (capacitor banks and reactors) or dynamic devices (generators, synchronous condensers and FACTS devices) (D. Murali, 2010) (Nwohu, 2009).

The use of series FACTS devices in congestion management will be explored in this work.

2.2 FACTS devices

Flexible AC transmission system (FACTS) devices use power electronics and other static controllers to enhance controllability and increase power transfer capability of a power system (R. S. Lubis, 2012). Generally, the value of a transmission line resistance is small compared to its reactance and is often neglected. The active power transfer from bus i to bus j can be approximated by:

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin \delta \tag{1}$$

where

1. V_i and V_j - voltage magnitude at bus i and j respectively.
2. X_{ij} - line reactance
3. δ - load angle

From (1) the active power flow between two buses can be controlled by adjusting the bus voltage magnitude, load angle and/or reactance of the connecting transmission line. FACTS devices act by modifying either of the three parameters in a transmission network. The most common FACTS devices in use today are:

1. Thyristor controlled series capacitor (TCSC) - permits decrease or increase the reactance of a line.
2. Static VAr compensator (SVC): absorbs or injects reactive power to the system.
3. Unified power flow controller (UPFC): controls the voltage magnitude and phase angle of the sending end bus (J. S.Sarda, 2012).

This paper investigates the application of TCSC in congestion management.

2.2.1 Thyristor controlled series compensator (TCSC)

The TCSC is a series compensation device used to decrease or increase the effective series line impedance, by adding a capacitive or inductive reactance to the transmission line. This helps to increase or decrease the maximum power transfer limit of a transmission line (J. S.Sarda, 2012) (J.Sridevi, 2012). In this paper, TCSC is modelled as a variable reactance shown in figure 1.

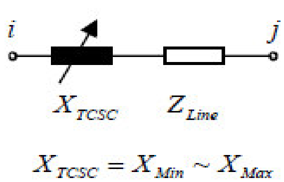

Figure 1: TCSC model

The variable line reactance (X_{TCSC}) is given by:

$$X_{TCSC} = r_{TCSC} X_{line} \tag{2}$$

where:

1. X_{line} - initial transmission line reactance.
2. r_{TCSC} - line compensation coefficient.

High line compensation increases the complexity of switching circuit needed, and also increases the risk of sub-synchronous resonance. A practical range of line compensation is usually between

-70% to 20% (Johansson, 2011) (Kundur, 1994). The new line reactance X_{ij} is obtained as:

$$X_{ij} = X_{line} + X_{TCSC} \tag{3}$$

A typical range of line reactance with TCSC is:

$$0.3X_{line} \leq X_{line} \leq 1.2X_{line} \tag{4}$$

2.2.2 Optimal location of TCSC

Due to the high cost of FACTS devices, it is necessary to locate them optimally, to maximize their benefits. Congestion rent is used in this work to short list lines suitable for TCSC location. Congestion rent is simply the product of locational marginal price (LMP) difference and the power flowing through a given line. The use of LMPs in distribution networks was proposed by Sotkiewicz and Vignolo (Vignolo, 2007) to obtain price signals for locating distributed generation (DG) resources, whereas Warkad et al. (S. B. Warkad, 2009) assess the impact of incorporating HVDC link on LMPs. LMP is the price of supplying an additional MWh of electricity at each bus in the system. It is obtained from the solution of optimal power flow (OPF), subject to transmission network constraints. The OPF problem of a power system for the given loads (P,Q) is stated as:

$$F = \min f(X, P, Q) \tag{5}$$

subject to:

$$g(X, P, Q) = 0 \tag{6}$$

$$h(X, P, Q) \leq 0 \tag{7}$$

where:

1. $f(X, P, Q)$ - the operating cost function.
2. $g(X, P, Q)$ - equality constraints.
3. $h(X, P, Q)$ - inequality constraints.
4. X - variables in power system (voltage magnitude, angle and line loading).

To solve the optimization problem, a Lagrangian function is formed as:

$$\mathcal{L}(X, \lambda, \beta, P, Q) = f(X, P, Q) + \lambda g(X, P, Q) + \beta h(X, P, Q) \tag{8}$$

Neglecting the cost of losses and congestion, the necessary condition for a minimum operating cost is that the incremental cost rate of generation should be the same for all generating units:

$$\frac{\partial F_i}{\partial P_i} = \lambda \tag{9}$$

If system congestion is neglected but transmission losses considered, the incremental cost of generation at bus i can be approximated as:

$$\rho_i = \lambda \left(1 + \frac{\partial P_{loss}}{\partial P_i}\right) \tag{11}$$

Congestion occurs if transmission component limits are violated. These include bus voltage limits and transmission line limits. The congestion cost is obtained by taking partial derivatives of the objective function with respect to the control variables (Song, 2008). The total incremental cost of generating one MWh of electricity can now be expressed as:

$$\rho_i = \lambda\left(1 + \frac{\partial P_{loss}}{\partial P_i}\right) + \frac{\partial F}{\partial u_i} \quad (12)$$

where u is the upper or lower limit on control variables . If u_i violates a limit, it can either be upper or lower limit and not both simultaneously, since:

$$u - u_{max} \leq 0 \quad (13)$$

$$u_{min} - u \leq 0 \quad (14)$$

The procedure for obtaining the optimal location for TCSC begins by running a base case OPF to obtain LMPs at all buses and power flow across all branches. Next, the LMP difference is calculated and congestion rent of individual lines evaluated. The congestion rent is determined using:

$$CC_{ij} = \Delta\rho_{ij} P_{ij} \quad (15)$$

where:

1. P_{ij} - power flow in the line connected between buses i and j.
2. $\Delta\rho_{ij}$ - LMP difference between bus i and bus j.

A suitable list of lines is then formed in descending order of congestion rent, and OPF evaluated again, with TCSC in those lines. The best location of TCSC is the one which results in minimum cost of generation (Hosseini, 2009).

3. CASE STUDY

The problem is formulated as outlined in subsection 2.2.2, where we minimize the total cost of generation simply represented as:

$$F = \min f(P_G) \quad (16)$$

subject to:

1. Power balance (equality) constraints

$$P_G = P_D + P_L \quad (17)$$

$$Q_G = Q_D + Q_L \quad (18)$$

where:

a) P_G and Q_G - total active and reactive power generated in the system respectively.
b) P_D and Q_D - total active and reactive power demand of the system respectively.
c) P_L and Q_L - total active and reactive power loss in the system respectively.

2. Inequality constraints
   a) Power generating limits - each generator in operation has a minimum and maximum permissible output, according to its capability curve.

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max} \quad (19)$$

$$Q_{Gi,min} \leq Q_{Gi} \leq Q_{Gi,max} \quad (20)$$

   b) Transmission line limits: this is the maximum power a given transmission line, between bus i and j, is capable of transmitting.

$$S_{ij} \leq S_{ij,max} \quad i \neq j \quad (21)$$

   c) Voltage limits: imposed for bus voltage magnitudes in order to maintain desired voltage profile.

$$V_{i,min} \leq V_i \leq V_{i,max} \quad (22)$$

Simulations were carried out on the Western System Coordinating Council (WSCC) 9-bus system. This system was obtained from (P.P.Bedekar, 2012) and has 3 generators as shown in figure 2.

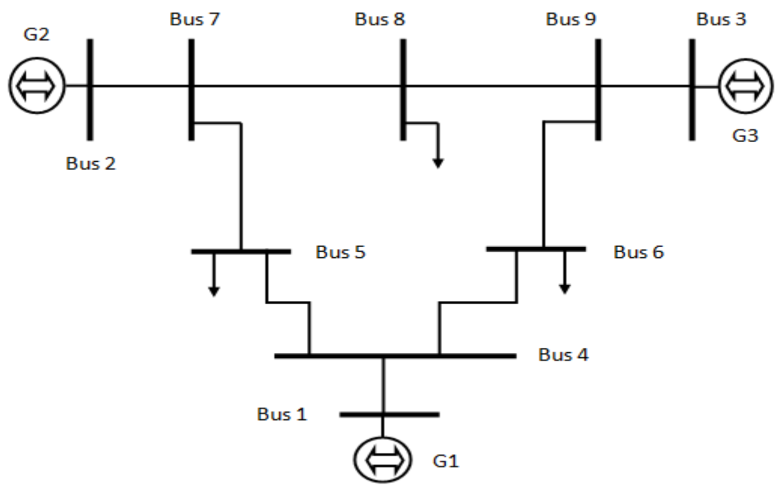

Figure 2: One-line diagram of WSCC 9-bus system

3.1 Generator data

Bus no.	Pmin (MW)	Pmax (MW)	Qmin (MVAr)	Qmax (MVAr)	a	b	c
1	10	250	-300	300	0.110	5.000	150
2	10	300	-300	300	0.085	1.200	600
3	10	270	-300	300	0.123	1.000	335

Table 1: Generator limits

3.2 Load data

Bus number	P(MW)	Q(MVAr)
5	125	50
6	90	30
8	100	35

Table 2: Load data

Table 2 gives the base load which was linearly increased to maximum load. Only results at twice the base load (630MW) are presented.

3.3 Line data

From bus	To bus	R (p.u.)	X (p.u.)	B (p.u.)
1	4	0.000	0.058	0.000
2	7	0.000	0.063	0.000
3	9	0.000	0.059	0.000
4	5	0.010	0.085	0.176
4	6	0.017	0.092	0.158
5	7	0.032	0.161	0.308
6	9	0.039	0.170	0.358
7	8	0.009	0.072	0.149
8	9	0.012	0.101	0.209

Table 3: Line data

Simulations were done in MATPOWER (version 2), a toolbox of MATLAB with the objective of minimizing the total cost of generation.

4 RESULTS AND DISCUSSION

4.1 TCSC placement

Bus no.	LMP ($/MWh)	Line no.	From bus	To bus	LMP diff
1	49.484	1	1	4	0.016
2	45.716	2	2	7	0.080
3	46.127	3	3	9	0.044
4	49.562	4	4	5	1.158
5	51.515	5	4	6	1.457
6	51.239	6	5	7	4.299
7	45.822	7	6	9	4.446
8	47.122	8	7	8	1.125
9	46.170	9	8	9	0.973

Table 4: LMPs

Lines 6 and 7 have the highest LMP difference, which is modified by the power flowing through the branch, to obtain the congestion rent, given in table 5.

Line no.	LMP diff	P(MW)	Congestion rent	Normalized	Rank
1	0.016	199.840	3.197	0.002	9
2	0.080	262.120	20.970	0.014	7
3	0.044	183.460	8.072	0.005	8
4	1.158	119.470	138.346	0.091	4
5	1.457	80.370	117.099	0.077	5
6	4.299	131.910	567.081	0.373	1
7	4.446	101.090	449.446	0.296	2
8	1.125	124.160	139.680	0.092	3
9	0.973	77.270	75.184	0.049	6

Table 5: Congestion rent

From table 5, the top five candidate lines selected for TCSC placement by use of congestion rent method were lines 6, 7, 4, 8 and 5. Short listed lines were then tested for TCSC placement to identify the best location. Results are given in table 6.

Line no.	Compensation	Loss (MW)	Cost of generation ($/hr)
4	-70%	17.54	17041.78
5	-30%	18.21	17074.30
6	-30%	18.08	17066.21
7	-50%	18.02	17064.18
8	-70%	18.09	17068.09
9	-10%	18.25	17076.26

Table 6: Optimal location of TCSC

Line 4 gives the minimum cost of generation, hence the best location for TCSC.

4.2 Voltage magnitude

Voltage magnitude of the system is plotted for both scenarios

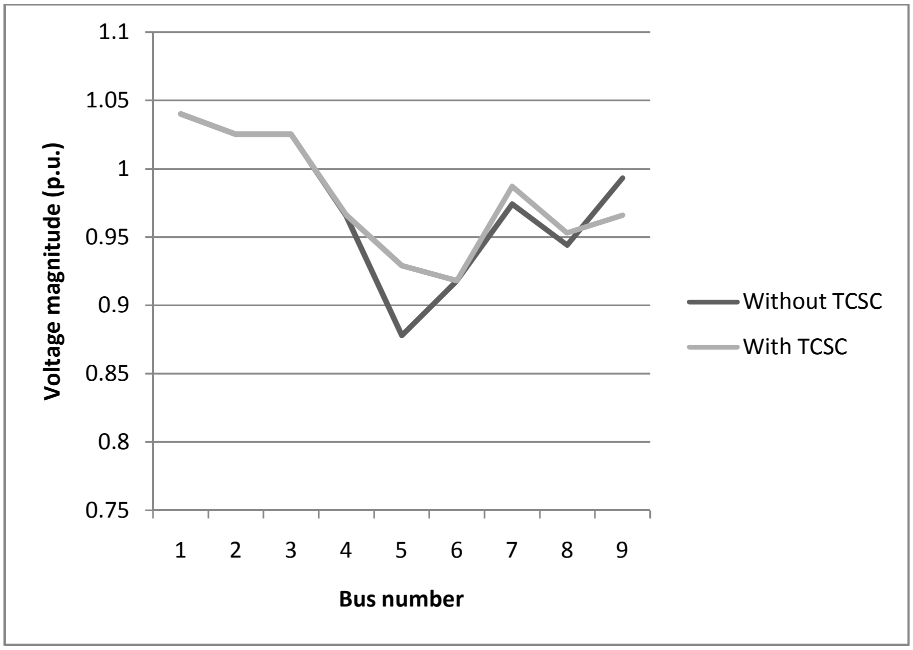

Figure 3: Voltage magnitude

The voltage magnitude at bus 5 slightly improves from 0.878p.u. to 0.929p.u., while that of bus 6 remains at 0.918p.u. with TCSC.

4.3 Transmission line loading

Transmission line loading is shown in figure 4

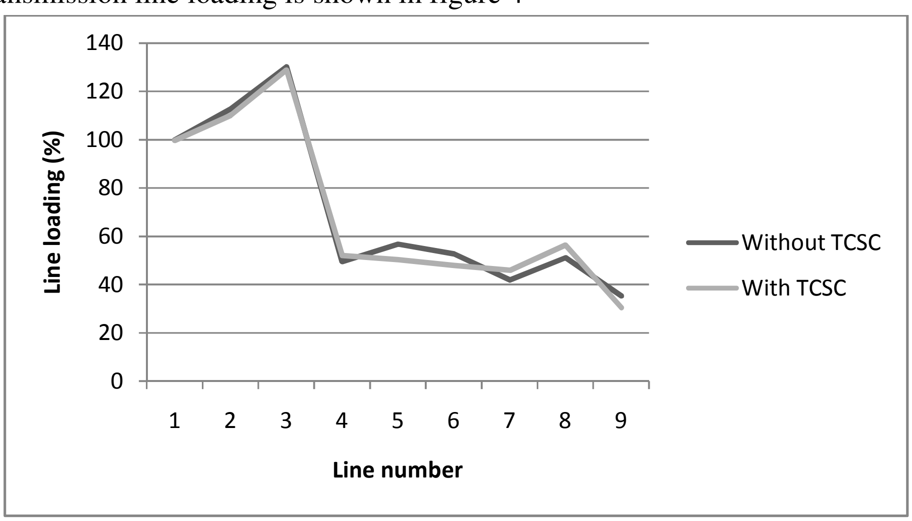

Figure 4: Transmission line loading

From figure 4, with or without TCSC, lines are 1, 2 and 3 are overloaded. When TCSC is installed, loading in line 1 does not change. Line 2 drops from 113% to 110% whereas line 3 slightly moves from 130% to 129% with TCSC.

4.4 Cost analysis

This paper only considers the capital cost of TCSC, as their operations and maintenance costs are very low, since they do not have moving parts. The capital cost of TCSC is obtained from Siemens AG database (Kamaraj, 2012) (N. Tabatabaei, 2011) as:

$$C_{TCSC} = 0.0015S^2 - 0.7130S + 153.75 \quad (23)$$

where:

1. C_{TCSC} - cost of TCSC in $/kVAr.
2. S - operating range in MVAr, $S = Q_2 - Q_1$

Q_1 and Q_2 - reactive power flow through a branch before and after device installation, respectively. The capital cost of TCSC was obtained using (23) as:

$C_{TCSC} = \$6,387.13.$

It is assumed that savings made due to TCSC utilization go towards paying the initial capital cost. Table 8 shows savings attained when TCSC is installed in the system.

Savings	$/hr	$/yr
TCSC	34.51	302,307.6

Table 7: Savings

From simulations,$Q_2 = 83.1MVAr,\ Q_1 = 80.81MVAr$, hence $S = 2.29MVAr$. With assumed utilization factor of 0.6 (Shi, 2006), the payback period for TCSC is approximately 1 month.

5. CONCLUSION AND RECOMMENDATIONS

In this paper, a method for optimal placement of TCSC was presented, with aim of reducing congestion. Simulations were done on the WSCC 9-bus test system. In relation to congestion, the voltage profile and transmission line loading were investigated. It is observed that installation of TCSC reduced line loading, but did not significantly affect the voltage profile. The payback period for TCSC was found to be very short. Further investigations should be carried out with series FACTS devices distributed along the transmission network, to see if a better voltage profile would be attained.

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