Congestion Management in a Deregulated Power System with Thyristor Controlled Series Capacitor

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Abstract

This paper presents congestion management in deregulated power systems. In a deregulated environment, every buyer wants to buy power from the cheapest generator available, irrespective of relative geographical location of buyer and seller. As a consequence of this, the transmission corridors evacuating the power of cheaper generators would get overloaded if all such transactions are approved. Congestion management is a mechanism to prioritize the transactions and commit to such a schedule which would not overload the network. The congestions in the transmission lines are determined by optimal power flow solution, which is carried based primal liner programming method and congestion in the transmission lines have been alleviated by optimal placement of thyristor controlled series capacitor. A method to determine the optimal location of thyristor controlled series capacitor has been suggested based on real power flow performance sensitivity index based approach. The effectiveness of proposed method has been demonstrated on modified IEEE-14 and 30 bus test systems.

1. Introduction

The privatization and deregulation of electricity markets has a very large impact on almost all the power systems around the world. Competitive electricity markets are complex systems with many participants who buy and sell electricity. In competitive market, system security plays a vital role from the market/system point of view. When power producers and consumers of electrical energy desire to produce and consume in total amount that would cause the transmission system to operate at or beyond one or more transfer limits, the system is said to be congested [1]. Congestion is a technical problem, which occurs frequently in deregulated power Systems due to transmission line insufficient transfer capabilities and line outages in the systems, and competition among the power consumers and power producers [2].

Congestion management is a mechanism to prioritize the transactions and commit to such a schedule which would not overload the network. Despite these measures, congestion can still occur in real time following a forced outage of transmission line. The system operator then handles this situation by means of real time congestion management. Thus, congestion management involves precautionary as well as remedial action on system operator's part [3]. The scope of transmission congestion management in the deregulated environment involves defining a set of rules to ensure control over generators and loads in order to maintain acceptable level of system security and reliability [4]. Congestion in transmission line is relied by load curtailment, generation rescheduling, built new parallel transmission line and connect Flexible AC Transmission System (FACTS) devices in the systems [5-6].

FACTS devices provide new control facilities, both in steady state power flow control and dynamic stability control [7-8]. The possibility of controlling power flow in an electric power system without generation rescheduling or load curtailment changes can improve the performance considerably [9]. Using controllable components such as controllable series capacitors and phase shifters line flows can be changed in such a way that thermal limits are not violated, losses minimized, stability margin increased, contractual requirement fulfilled etc, without violating specified power dispatch [10].

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 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 [11-12].

This paper is describes congestion management in deregulated power system with thyristor controlled series capacitor. The congestion problem is occurred in IEEE 14 and 30 Bus systems due to competition in consumers in deregulated environment, which is determined by optimal power flow solution based on primal liner programming method. The bus data, line data and generation data are taken of IEEE 14 and 30 bus systems from [13]. The remedial action has been taken by thyristor controlled series capacitor (TCSC), and the optimal placement of TCSC is found by real line flow sensitivity index, where which line have most negative real power line flow sensitivity is the best location for placement of TCSC.

This paper is organized as follows: Section 2 deals with congestion management. Section 3, presents Thyristor Controlled Series Capacitor (TCSC) has been modeled in the systems. Section 4, describes sensitivity approach method. Section 5, presents simulations results at various operating conditions. Section 6, concludes the paper.

2. Congestion Management

The basic principle for the transmission congestion management could be illustrated with the help of the traditional spot pricing theory. In this framework, the central dispatcher optimally dispatches the generators such that the social welfare is maximized while satisfying the operation and security related constraints. Specifically, the dispatcher solves the following optimization problem with optimal power flow solution, which is carried by primal linear programming method to maximize the social welfare, where changes system controls to enforce liveried constraints while minimize the cost:

$$\min(\sum_{i=1}^{N_G} C_g(P_{g_i}) - \sum_{i=1}^{N_D} B_d(P_{d_i}) \quad (1)$$

Subjected to

$$P_{gi} - P_{di} = \sum_{j=1}^{N_B} |V_i||V_j||Y_{ij}|\cos(\delta_i - \delta_j - \theta_{ij}) \quad (2)$$

$$Q_{gi} - Q_{di} = \sum_{j=1}^{N_B} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \quad (3)$$

$$P_{gi,min} \le P_{gi} \le P_{gi,max} \quad (4)$$

$$Q_{gi,min} \le Q_{gi} \le Q_{gi,max} \quad (5)$$

$$P_{di,min} \le P_{di} \le P_{di,max} \quad (6)$$

$$Q_{di,min} \le P_{di} \le P_{di,max} \quad (7)$$

$$V_{i,min} \le V_i \le V_{i,max} \quad (8)$$

$$T_{ij} \ge 0 \quad (9)$$

Where, P_{gi} , Q_{gi} are real and reactive power generations and P_{di} , Q_{di} are real and reactive power demand at bus i. $P_{gi,min}$, $P_{gi,max}$ and $Q_{gi,min}$, $Q_{gi,max}$ are real and reactive power minimum and maximum generation limits at bus i. $P_{di,min}$, $P_{di,max}$ and $Q_{di,min}$, $Q_{di,max}$ are real and reactive power minimum and maximum demand limits at bus i.

The objective function $C_{g_i}(P_{g_i})$ is cost function for generating real power P_{g_i}, and $B_{di}(P_{di})$ is demand function at bus i. T_{ij} is the bilateral transaction between suppliers at node i and consumer at node j. By solving above optimization problem the generation schedule can be obtained and with this schedule lines flow can be found. Then check whether all line flows are within the maximum limits are not, if any (one or more) of line flow exceeds the limit that the line is said to be congested and it has to be relieved as quickly as possible. Here congestion is relieved by thyristor controlled series capacitor has been placed in optimal location of the system.

3. Static Modelling of TCSC

The effects of FACTS devices like TCSC on the network can be seen as a controllable reactance inserted in the related transmission line. The model of the network with TCSC is shown in Fig.1.

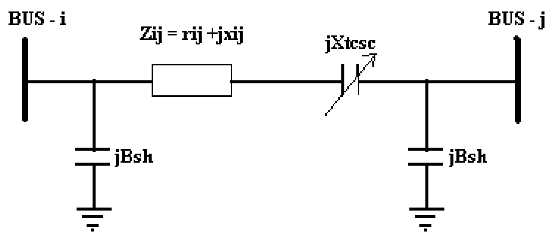

Fig.1. Modelling of transmission line with TCSC

During steady state the TCSC can be considered as a static capacitor/ reactor offering impedance jX_{TCSC}. The basic idea behind series capacitive compensation is to decrease the overall effective series transmission line impedance from sending end to receiving end. Since losses are neglected, the impedance of TCSC is purely reactive. The capacitive reactance of TCSC is obtained from equation (10) is given by

$$X_{TCSC} = \frac{X_C}{\left(1 - \frac{X_C}{X_{TCR}}\right)} \quad (10)$$

Where X_C and X_{TCR} are capacitive and inductive reactance of TCSC. Moreover, to avoid over compensation of the line, the working range of the TCSC is considered to be (-0.5X_L and 0.5X_L), where X_L is total line inductive reactance before connecting TCSC. The controllable reactance X_{TCSC} is directly used variable to be implemented in the power flow equations. The real and reactive power flow equations of the branch k flowing from bus i to j can be expressed as:

$$P_{ij}^c = V_j^2 G_{ij}^c - V_i V_j \left[G_{ij}^c \cos(\delta_{ij}) + G_{ij}^c \sin \delta_{ij}\right] \quad (11)$$

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

$$Q_{ij}^c = -V_j^2 (B_{ij}^c + B_{sh}) + V_i V_j \left[G_{ij}^c \sin(\delta_{ij}) + B_{ij}^c \cos \delta_{ij}\right] \quad (13)$$

Where $G_{ij}^c = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_{TCSC})^2}$ and $B_{ij}^c = \frac{-(x_{ij} - x_{TCSC})}{r_{ij}^2 + (x_{ij} - x_{TCSC})^2}$

The TCSC can improve maximum power transfer capacity of line as well as improve the voltage profile of the system; it is assumed that only one TCSC per lines is allowed because considerable cost of TCSC.

4. Method of Optimal Location of TCSC

The real power flow power flow performance index sensitivity approach method is taken for finding optimal location of TCSC, to relieve congestion problem in the system. The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index, as given below

$$PI = \sum_{m=1}^{N_L} \frac{W_m}{2n} \left(\frac{P_{Lm}}{P_{Lm}^{max}}\right)^{2n} \quad (14)$$

Where P_{Lm} the real power is 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 the lines. PI will be high, when all the lines are within their limits and reach a small value when there is congestion. Thus, it provides a good measure of severity of the line congestion for given state of the test system. 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 congestion. By most of the operational standards, the system with one huge violation is much more severe than that with many small violations. The congestion can be an avoided using lower order performance index that is $n < 1$.

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

$$b_k = \frac{\partial PI}{\partial x_{ck}} | x_{ck} = 0 \quad (15)$$

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

$$\frac{\partial PI}{\partial x_{ck}} = \sum_{m=1}^{N_L} w_m P_{Lm}^3 \left(\frac{1}{P_{Lm}^3}\right)^4 \frac{\partial P_{Lm}}{\partial x_{ck}} \quad (16)$$

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

$$P_{Lm} = \begin{cases} \sum_{\substack{n=1 \\ n \neq s}}^{N} S_{mn} P_n & for\ m \neq k \\ \sum_{\substack{n=1 \\ n \neq s}}^{N} S_{mn} P_n + P_j & for\ m = k \end{cases} \quad (17)$$

Using equation (17), the following relation can be derived as bellow

$$\frac{\partial P_{Lm}}{\partial x_{ck}} = \begin{cases} \left(S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}}\right) & for\ m \neq k \\ \left(S_{mi} \frac{\partial P_i}{\partial x_{ck}} + S_{mj} \frac{\partial P_j}{\partial x_{ck}}\right) + \frac{\partial P_j}{\partial x_{ck}} & for\ m = k \end{cases} \quad (18)$$

The terms $\frac{\partial P_i}{\partial x_{ck}} \Big/ x_{ck=0}$ and $\frac{\partial P_j}{\partial x_{ck}} \Big/ x_{ck=0}$ can be derived as bellow

$$\frac{\partial P_i}{\partial x_{ck}} \Big/ x_{ck=0} = \frac{\partial P_{ic}}{\partial x_{ck}} \Big/ x_{ck=0}$$

$$= -2(V_i^2 - V_i V_j \cos \delta_{ij}) \frac{r_{ij} x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} + V_i V_j \cos \delta_{ij} \frac{r_{ij}^2 - x_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2} \quad (19)$$

$$\left.\frac{\partial P_j}{\partial x_{ck}}\right/_{x_{ck}=0} = \left.\frac{\partial P_{jc}}{\partial x_{ck}}\right/_{x_{ck}=0}$$

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

The location of TCSC can be based on static or dynamic performance of the system. The sensitivity factor method is generally used to find the best location to enhance the static performance of the system. Here in *PI* method, TCSC should be placed in a line having most negative sensitivity index.

5. Test Results

5.1 IEEE 14 Bus Systems

IEEE 14 Bus system has been considered as test bus in deregulated power system. Data of test bus system is taken form [13]. Fig.2 shows, modified IEEE14 bus system has been congested in line 10 (between buses 5-6), congestion in the system has been created by the load increases 50 percentages at each bus. Solve Optimal Power Flow (OPF) solution with primal linear programming method; IEEE 14 bus systems have total Demand (259.3 MW & 78.9 MVAR), Generation (268 MW & 103.3 MVAR) and Loss (8.72 MW & 24.37 MVAR). After OPF solution check whether all line flows are within the maximum limits are not, where the line 10 (between buses 5-6) is congested due to transfer limit exceeds. Congested system the marginal cost per unit is different at each bus, total generation cost of the system per hour is: 2907.80 $/h. The remedial action has been taken by TCSC is connected at optimal location in the system. Here the placement of the TCSC is fund by real power sensitivity performance index approach. Find the *PI* value with respect to TCSC is connected each line of the system, were the X_{TCSC} = $0.4X_L$. The values of *PI* are given in table I.

Table I

Line No	From bus	To bus	*PI* sensitivity
1	1	2	-3.135
3	2	3	-2.77
7	4	5	-2.288
8	**4**	**7**	**-4.030**
9	4	9	-1.9675
15	7	9	-1.5087
17	9	14	-0.9525

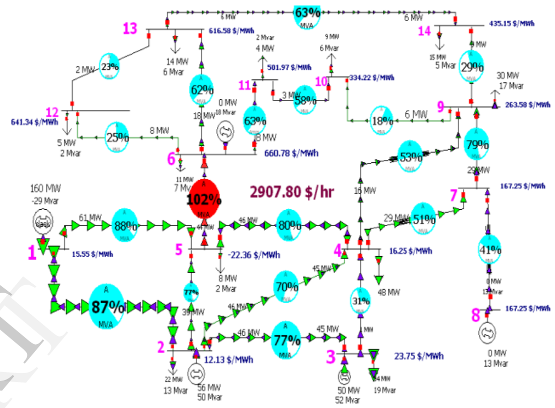

Fig.2.Modified IEEE 14 bus system is congested in line 10 (between buses 5-6)

From table I, the line 8 (between buses 4-7) has most negative *PI* sensitivity, which the best placement of TCSC to connect in the system.

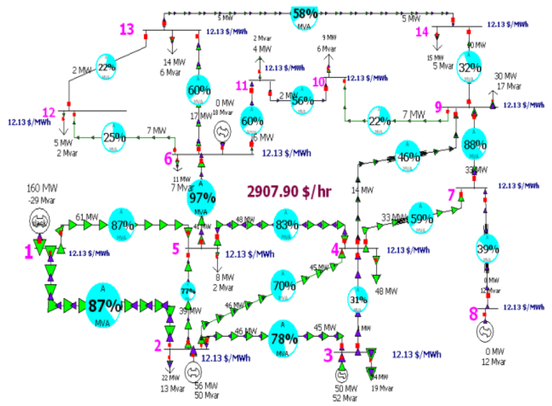

Fig.3 Congestion is relieved in modified IEEE 14 bus system in line 10 (between buses 5-6)

Fig.3 a show, the congestion is alleviated in line 10 by TCSC has been connected in the line 8 (between buses 4-7). Here congestion is reduced as well as voltage profile of the system improved, voltage profile is improved by reducing reactive power loss in the system from 24.37 MVAR to 23.47 MVAR.

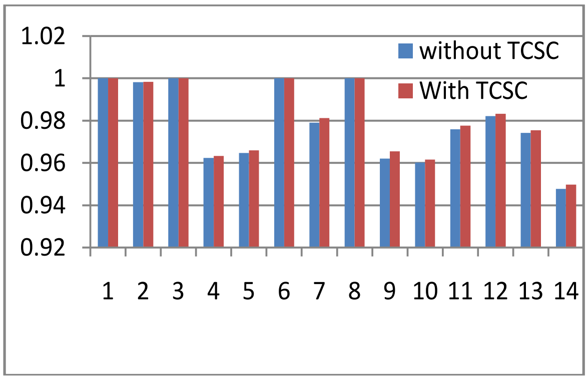

Fig.4 IEEE 14 Bus system voltage profile

Fig.4 shows, IEEE 14 Bus systems voltage profile with and without TCSC. Here the values of voltage are given in per unit (p.u) on Y-axis and buses on X-axis. Compare to with and without TCSC, in with TCSC case the voltage profile of the system little bit improved.

5.2 IEEE 30 Bus System

IEEE 30 Bus system has been taken as test bus in deregulated power system. Data of test bus system has been taken form [13]. Fig.5 shows, modified IEEE30 bus system has been congested, congestion is created in the system by the load increases 50 percentages at each bus. Solve Optimal Power Flow (OPF) solution with primal linear programming method; IEEE 30 bus systems have total Demand (290 MW & 130 MVAR), Generation (300 MW & 140.1 MVAR) and Loss (11.07 MW & 10.08 MVAR). After OPF solution check whether all line flows are within the maximum limits are not, where the line 4 (between buses 2-5) is congested due to transfer limit exceeds. Congested system the marginal cost per unit is different at each bus, total generation cost of the system per hour is: 3893.78 $/h.

The remedial action has been taken by TCSC is connected at optimal location in the systems. Here the placement of the TCSC is fund by real power sensitivity performance index approach. Find the *PI* value with respect to TCSC is connected each line of the system, were the $X_{TCSC} = 0.4X_L$. The values of *PI* are given in table II. From table II, the line 5 (between buses 2-6) has most negative *PI* sensitivity, which the best placement to connect TCSC in the system.

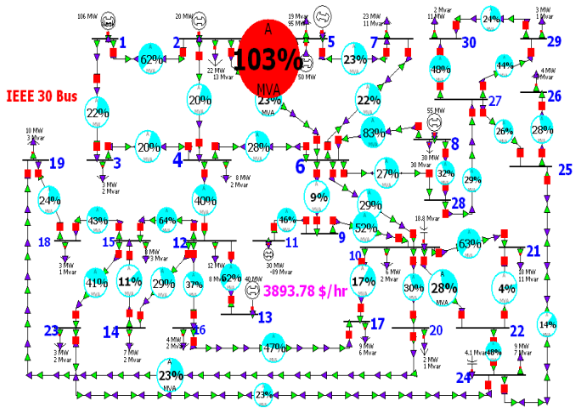

Fig.5.Modified IEEE 30 bus system is congested line 4 (between buses 2-5)

Table II

Line No	From bus	To bus	*PI* sensitivity
2	1	3	-6.342
3	2	4	-7.053
5	**2**	**6**	**-9.872**
8	4	12	-4.814
11	6	8	-5.731
13	6	10	-3.889

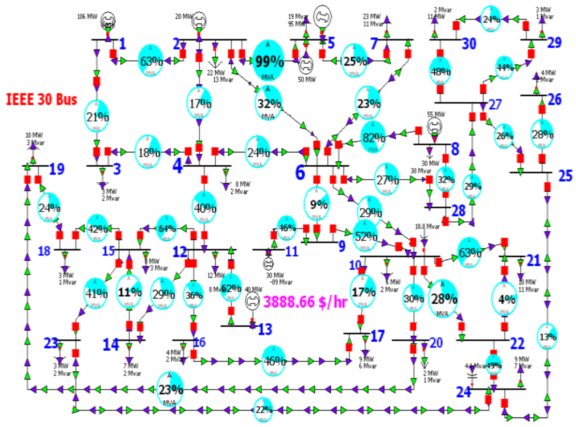

Fig.6 Congestion is relieved in modified IEEE 30 bus system in line 4 (between buses 2-5)

Fig.6 is shown, the congestion has been alleviated in line 4 (between buses 2-5) in the system by TCSC has been connected in the line 5 (between buses 2-6). Here congestion is reduced in the system as well as improved voltage profile by reducing real power loss from 11.07 MW to 10.60 MW, and reactive power loss from 10.08 MVAR to 9.76 MVAR of the system.

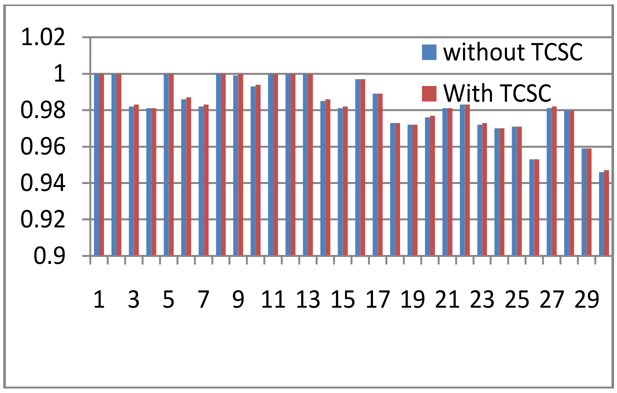

Fig.7 IEEE 30 Bus system voltage profile

Fig.7 shows, IEEE 30 Bus systems voltage profile with and without TCSC. Here the values of voltage are given in per unit (p.u) on Y-axis and buses on X-axis. Compare to with and without TCSC, in with TCSC case the voltage profile of the system little bit improved.

6. Conclusion

Congestion management is an important issue in deregulated power systems. IEEE 14 and 30 bus test systems have been modeled in deregulated environment. Congestion has been created by increased load at bus in the system and congestion in the transmission is determined by optimal power flow solution, which is carried by primal linear programming method.

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.

The results presented in this paper show that real power performance sensitivity index along with TCSC should effectively used for determining optimal location of TCSC. The congestion in transmission lines of IEEE 14 and 30 bus test systems have been alleviated by connected TCSC at optimal location in the systems.

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