THE IMPACT OF TCSC ON TRANSMISSION COSTS IN WHOLESALE POWER MARKETS CONSIDERING BILATERAL TRANSACTIONS AND ACTIVE POWER RESERVES

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Abstract - In the electricity market operation, calculating transmission charges is a critical issue. Transmission costs relate to the issue of how much is paid and by whom, for the use of transmission system. For short-run transmission charges, difference of location marginal prices (LMP) on a network branch has much influence on the market participants, including bilateral transactions. When there is congestion in power systems, difference of location marginal prices on the branch becomes bigger. One of the measures to overcome network congestion is using thyristor controlled series capacitor (TCSC). In addition, the presence of price-sensitive loads, bilateral transactions and requirement of active power reserves in power systems complicate matters associated with transmission charges in the wholesale electricity market. In this paper, a method for determining the optimal location of TCSC has been suggested and the impact of TCSC compensation levels on transmission charges of bilateral contracts in the wholesale electricity market is analyzed. The calculated results are illustrated on a 6-bus system.

Key words - Location marginal prices (LMP); wholesale power markets; transmission costs; active power reserves; bilateral transactions; thyristor controlled series capacitor (TCSC); AC optimal power flow (ACOPF).

1. Introduction

Today, the electricity industry has changed from monopoly to competitive market mechanism in many countries around the world, including Vietnam. In the wholesale electricity market, the market participants are generation companies (GENCOS) and distribution companies (DISCOS). To maintain the frequency stability, sufficient active reserve must be ensured. Not only the reserve must be sufficient to make up for a generating unit failure, but the reserves must also be appropriately allocated among fast-responding and slow-responding units [5]. The reserve for frequency regulation is divided into 3 categories: regulation reserve (RR), spinning reserve (SR) and supplemental reserve (XR). Spinning reserve and supplemental reserve are components of contingency reserve (CR). Operation reserve encompasses contingency reserve (CR) and regulation reserve [5]. The market operator collects generating offers (increase in price), reserve offers by producers, load bids (decrease in price) by consumers and reserve bids by the market operator and clears the market by maximizing the social welfare [1]. Then, power output of generation units, power output of buying units and reserve capacity of generator units may be determined by one of the following methods: sequentially optimizing energy and reserve; co-optimization of energy and reserve [2]. Additionally, the firm bilateral and multilateral contracts are also incorporated into this optimization problem [3]. To make payments in the electricity market, location marginal price (LMP) are calculated. The difference in LMPs between two nodes of a branch is due to congestion and losses on that branch [4].

One of the measures to reduce the power flow on transmission lines congested is the use of Thyristor controlled series compensator (TCSC). The TCSC has many benefits, for instance, increasing power transfer limits, reducing power losses, enhancing stability of the power system, reducing production costs of power plants and fulfilling contractual requirements [6]. Moreover, the transmission charges of market participants and of bilateral transactions can be affected when installing TCSCs.

Recently, there has been growing interest in allocation of FACTS devices for achieving diverse objectives for transmission network. The impact of thyristor controlled series compensator (TCSC) on congestion and spot pricing is presented in [8]. Priority list method for TCSC allocation for congestion management has been proposed in [9]. However, these works have not taken into account active power reserves. This paper proposes a simple and efficient approach to determine the optimal placement of TCSC to reduce congestion index of the power system. In addition, the impact of compensation level of TCSC on LMPs and transmission charges of bilateral transactions in the wholesale electricity market when co-optimizing energy and active power reserve is also analyzed.

The next sections of the article are organized as follows. In section 2, the authors present optimization models to determine optimal placement of TCSC. Mathematical model of simultaneous optimization of the energy market and the active power reserve market, as well as methods to calculate the LMP are presented in section 3. Section 4 presents the methods for determining transmission costs in the electricity market and transmission charges of bilateral transactions. The calculated example for a 6 bus power system is presented and compared in section 5. Some conclusions are given in section 6.

2. Thyristor Controlled Series Capacitor (TCSC)

2.1. Static modeling of TCSC

Figure 1 shows a simple transmission line represented by its lumped PI equivalent parameters connected between bus i and bus j. The real and reactive power flow from bus i to bus j can be written as [3]:

$$P_{ij} = U_i^2 G_{ij} - U_i U_j \left[G_{ij} \cos\left(\delta_{ij}\right) + B_{ij} \sin\left(\delta_{ij}\right) \right] \quad (1)$$

$$Q_{ij} = -U_i^2 \left(B_{ij} + B_{sh} \right) - U_i U_j \left[G_{ij} \sin\left(\delta_{ij}\right) - B_{ij} \cos\left(\delta_{ij}\right) \right]$$

(2)

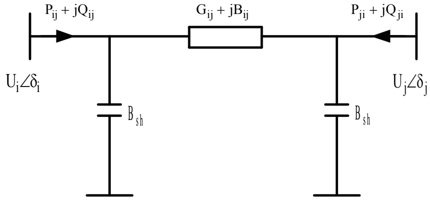

Figure 1. *Model of transmission line*

With a TCSC connected between bus i and bus j, the real and reactive power flow from bus i to bus j of a line are [6]:

$$P_{ij}^{C} = U_i^2 G_{ij}^{'} - U_i U_j \left(G_{ij}^{'} \cos\delta_{ij} + B_{ij}^{'} \sin\delta_{ij} \right) \quad (3)$$

$$Q_{ij}^{C} = -U_i^2 \left(B_{ij}^{'} + B_{sh} \right) - U_i U_j \left(G_{ij}^{'} \sin\delta_{ij} - B_{ij}^{'} \cos\delta_{ij} \right) \quad (4)$$

$$G_{ij}^{'} = \frac{R_{ij}}{R_{ij}^2 + \left(X_{ij} - X_C \right)^2}; \; B_{ij}^{'} = \frac{-\left(X_{ij} - X_C \right)}{R_{ij}^2 + \left(X_{ij} - X_C \right)^2} \quad (5)$$

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 Figure 2 [6].

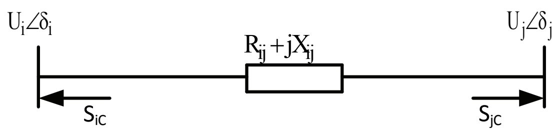

Figure 2. *Injection model of TCSC*

The real and reactive power injections at bus i and bus j can be expressed as follow [6]:

$$P_{iC} = U_i^2 \Delta G_{ij} - U_i U_j \left[\Delta G_{ij} \cos\left(\delta_{ij}\right) + \Delta B_{ij} \sin\left(\delta_{ij}\right) \right] \quad (6)$$

$$P_{jC} = U_j^2 \Delta G_{ij} - U_i U_j \left[\Delta G_{ij} \cos\left(\delta_{ij}\right) - \Delta B_{ij} \sin\left(\delta_{ij}\right) \right] \quad (7)$$

$$Q_{iC} = -U_i^2 \Delta B_{ij} - U_i U_j \left[\Delta G_{ij} \sin\left(\delta_{ij}\right) - \Delta B_{ij} \cos\left(\delta_{ij}\right) \right] \quad (8)$$

$$Q_{jC} = -U_j^2 \Delta B_{ij} + U_i U_j \left[\Delta G_{ij} \sin\left(\delta_{ij}\right) + \Delta B_{ij} \cos\left(\delta_{ij}\right) \right] \quad (9)$$

$$\Delta G_{ij} = \frac{X_C R_{ij} \left(X_C - 2X_{ij} \right)}{\left(R_{ij}^2 + X_{ij}^2 \right) \left[R_{ij}^2 + \left(X_{ij} - X_C \right)^2 \right]} \quad (10)$$

$$\Delta B_{ij} = \frac{-X_C \left[R_{ij}^2 - X_{ij}^2 + X_C X_{ij} \right]}{\left(R_{ij}^2 + X_{ij}^2 \right) \left[R_{ij}^2 + \left(X_{ij} - X_C \right)^2 \right]} \quad (11)$$

2.2. Optimal location of TCSC

The severity of the system loading under normal cases can be described by a real power line performance index, as given below [3, 7],

$$PI = \sum_{m=1}^{NL} \frac{w_m}{2n} \left(\frac{P_{Lm}}{P_{Lm}^{\max}} \right)^{2n} \quad (12)$$

where P_{Lm} is the active power flow on line m, $P_{Lm}^{\max}$ is the limit of active power flow on line m.

In this paper, the value of n has been taken as 2 (to avoid masking effect) and weighting factors w_m = 1 (the importance level of lines is similar).

To decrease congestion level of power transmission lines, TCSC should be placed in the line having the most negative sensitivity index b_k which is calculated below [7]:

$$b_k = \left. \frac{\partial PI}{\partial X_{Ck}} \right|_{X_{Ck}=0} \quad (13)$$

$$\frac{\partial PI}{\partial X_{Ck}} = \sum_{m=1}^{NL} w_m P_{Lm}^3 \left(\frac{1}{P_{Lm}^{\max}} \right)^4 \frac{\partial P_{Lm}}{\partial X_{Ck}} \quad (14)$$

$$\frac{\partial P_{Lm}}{\partial X_{Ck}} = \begin{cases} \left(SF_{mi} \dfrac{\partial P_i}{\partial X_{Ck}} + SF_{mj} \dfrac{\partial P_i}{\partial X_{Ck}} \right) & m \neq k \\ \left(SF_{mi} \dfrac{\partial P_i}{\partial X_{Ck}} + SF_{mj} \dfrac{\partial P_i}{\partial X_{Ck}} \right) + \dfrac{\partial P_j}{\partial X_{Ck}} & m = k \end{cases} \quad (15)$$

where SF_{mi}, SF_{mj} is the sensitivity of branch power flow m with respect to injected power i and j, respectively.

3. Co-optimization of Energy and active power reserves

3.1. Objective function

The objective function of co-optimization problem of energy and reserves in the wholesale electricity market is to minimize the total cost to supply minus total consumer benefit. This objective function is expressed as Eq. (16).

$$\begin{aligned} & \sum_{i=1}^{N_G} \sum_{b=1}^{N_{Gi}} \lambda_{Gib}.P_{Gib} \\ & + \sum_{i=1}^{N_G} \left(\lambda_{Gi}^{RR+}.P_{Gi}^{RR+} + \lambda_{Gi}^{RR-}.P_{Gi}^{RR-} + \lambda_{Gi}^{SR}.P_{Gi}^{SR} + \lambda_{Gi}^{XR}.P_{Gi}^{XR} \right) \\ & - \sum_{j=1}^{N_D} \sum_{k=1}^{N_{Dj}} \lambda_{Djk}.P_{Djk} - \sum_{b=1}^{N_{RR+}} \lambda_b^{RR+}.A_b^{RR+} - \sum_{b=1}^{N_{RR-}} \lambda_b^{RR-}.A_b^{RR-} \\ & - \sum_{b=1}^{N_{CR}} \lambda_b^{CR}.A_b^{CR} - \sum_{b=1}^{N_{OR}} \lambda_b^{OR}.A_b^{OR} \end{aligned} \quad (16)$$

where λ_{Gib} is price of the energy block b offered by generating unit i (constant), P_{Gib} is power of the energy block b offered by generating unit i (variable), λ_{Gi}^{RR+} is price of Up Regulation Reserve (RR) offered by generating unit i (constant), λ_{Gi}^{RR-} is price of Down Regulation Reserve offered by generating unit i (constant), λ_{Gi}^{SR} is price of Spinning Reserve (SR) offered by generating unit i (constant), λ_{Gi}^{XR} is price of Supplemental Reserve (XR) offered by generating unit i (constant), P_{Gi}^{RR+} is Up Regulation Reserve Power offered by generating i (variable), P_{Gi}^{SR} is Spinning Reserve Power offered by generating i (variable), P_{Gi}^{XR} is Supplemental Reserve Power offered by generating i (variable), λ_{Djk} is price of the energy block k bid by demand j (constant), P_{Djk} is power block b bid by demand j (variable), λ_b^{RR+} is price of Up Regulation Reserve block b bid by Area (constant), λ_b^{CR} is price of Contingency Reserve (CR) block b bid by Area (constant), λ_b^{OR} is price of Operation Reserve (OR) block b bid by Area (constant), A_b^{RR+} is Up Regulation Reserve Power block b bid by Area (variable), A_b^{CR} is Contingency Reserve Power block b bid by Area (variable), A_b^{OR} is Operation Reserve Power block b bid by Area (variable).

3.2. Constraints

3.2.1. Network equations

The state of a power system of n buses is determined by 2n nodal equations:

$$P_i = P_{Gi} - P_{Di} = \left|\dot{U}_i\right| \sum_{k=1}^{n} \left|\dot{U}_j\right| \left(G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij} \right)$$
$$Q_i = Q_{Gi} - Q_{Di} = \left|\dot{U}_i\right| \sum_{k=1}^{n} \left|\dot{U}_j\right| \left(G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij} \right) \quad (17)$$

3.2.2. Reserve balance

For each area or zone, the reserve balance is shown according to the following expressions:

$$\sum_{i=1}^{N_G} P_{Gi}^{RR+} = A^{RR+} \quad (18)$$

$$\sum_{i=1}^{N_G} P_{Gi}^{RR-} = A^{RR-} \quad (19)$$

$$\sum_{i=1}^{N_G} \left(P_{Gi}^{SR} + P_{Gi}^{XR} \right) = A^{CR} \quad (20)$$

$$\sum_{i=1}^{N_G} \left(P_{Gi}^{RR+} + P_{Gi}^{SR} + P_{Gi}^{XR} \right) = A^{OR} \quad (21)$$

3.2.3. Limits on generating active power of block b

$$0 \le P_{Gib} \le P_{Gib}^{\max} \quad (\forall i, b) \quad (22)$$

3.2.4. Limits on generator power

The limits on generator active and reactive power of power plants, considering all kinds of reserves are expressed as Eq. (23) – (24).

$$0 \le P_{Gi} + P_{Gi}^{RR+} + P_{Gi}^{SR} + P_{Gi}^{XR} \le P_{Gi}^{\max} \quad (\forall i)$$
$$P_{Gi} - P_{Gi}^{RR-} \ge P_{Gi}^{\min} \quad (23)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (24)$$

3.2.5. Limits on reserve capacity of generating units

These constraints are shown as the following equations (25) – (28):

$$0 \le P_{Gi}^{RR+} \le P_{Gi\max}^{RR+} \quad (25)$$

$$0 \le P_{Gi}^{RR-} \le P_{Gi\max}^{RR-} \quad (26)$$

$$0 \le P_{Gi}^{SR} \le P_{Gi\max}^{SR} \quad (27)$$

$$0 \le P_{Gi}^{XR} \le P_{Gi\max}^{XR} \quad (28)$$

3.2.6. Limits on elastic power of demand

In the wholesale electricity market, load is often represented by two components: constant load and price-sensitive load. Demand curve of the elastic demand can include multiple blocks and limits are expressed as Eq. (29) - (30).

$$P_{Dj}^{E\min} \le P_{Dj}^{E} \le P_{Dj}^{E\max} \quad (\forall j) \quad (29)$$

$$0 \le P_{Djk}^{E} \le P_{Djk}^{E\max} \quad (\forall j, k) \quad (30)$$

where P_{Dj}^{E} is the elastic power of demand j

3.2.7. Limits on Area reserve power of block b

Area demand curves of reserve power can include several blocks and the MW size of each block, indexed by b, is expressed as Eq. (31) – (34).

$$0 \le A_b^{RR+} \le A_{b\max}^{RR+} \quad (31)$$

$$0 \le A_b^{RR-} \le A_{b\max}^{RR-} \quad (32)$$

$$0 \le A_b^{CR} \le A_{b\max}^{CR} \quad (33)$$

$$0 \le A_b^{OR} \le A_{b\max}^{OR} \quad (34)$$

3.2.8. Spinning reserve percent constraint

For each area or zone, the spinning reserve (SR) usually accounts for at least SR% of contingency reserve (CR). This is due to the fact that the spinning reserve can only be provided by online units. Meanwhile, supplemental reserve (XR) is provided by online or offline fast-start units. This constraint is written as follows:

$$\sum_{i=1}^{N_G} P_{Gi}^{SR} \ge SR\%. \sum_{i=1}^{N_G} \left(P_{Gi}^{SR} + P_{Gi}^{XR} \right) \quad (35)$$

3.2.9. Branch flow limits

Branch flow limits are expressed as Eq. (36).

$$0 \le S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \le S_{ij}^{\max} \quad (36)$$

3.2.10. Voltage Limits

$$U_i^{\min} \le U_i \le U_i^{\max} \quad (37)$$

3.2.11. Limits on bilateral contracts

When generating unit i and consumer j have a bilateral contract with contract power P^b, this constraint is expressed as equations (38)-(39):

$$P_{Gi} \ge P_{Gi}^{b} \quad (38)$$

$$P_{Dj} = P_{Dj}^{E} + P_{Dj}^{F} \ge P_{Dj}^{b} \quad (39)$$

where P_{Dj}^{F} is the constant power of demand j, P_{Gi}^{b} is the amount of power contract of generating unit i, P_{Dj}^{b} is the amount of power contract of demand j.

The above-mentioned AC-based optimal problem (ACOPF) be solved using successive linear programming (SLP) method [3].

3.3. LMP Calculation and Components

Location Marginal Price (LMP) is determined according to following equation [3].

$$LMP_i = LMP_E - LF_i.LMP_E + \sum_l SF_{l-i}.\mu_l \quad (40)$$

4. Transmission costs of bilateral transactions

The main objective of any transmission pricing method is to recover the transmission cost plus some profit. In order to recover operating costs, short-run marginal cost pricing (SMRC) based method is used in this paper [4]. SMRC is the difference in location marginal costs of supply bus and delivery bus. The location marginal costs of two buses can be determined from the solution of co-optimization energy and active power reserves shown in section 3. The transmission cost of bilateral contracts can be calculated by multiplying the power transaction with SRMC to obtain SRMC-based transmission charge [4].

In addition, the transmission pricing associated with each line or group of lines is also calculated. This transmission cost depends the power flow on a line proportion to power being transmitted by each transaction and determined through the use the linear Power Transfer Distribution Factor (PTDF). The PTDF can be defined as:

$$PTDF_{ij-mn} = \frac{\Delta P_{ij}}{\Delta P^b_{mn}} \quad (41)$$

where m and n are seller bus and buyer bus, ΔP_{ij} is the change in power flow on line ij, ΔP^b_{mn} is the change in power transfer of the bilateral transaction between m and n.

These PTDFs, which are computed at the base load flow condition, are utilized for computing change in transmission qualities at other operating conditions as well. The transmission costs (TC) paid by bilateral transactions are calculated as (42) and (43).

$$TC^b_{ij} = \Delta P^b_{ij-mn}\left(LMP_j - LMP_i\right) \quad (42)$$

$$TC^b = \sum_{ij} TC^b_{ij} \quad (43)$$

where ΔP^b_{ij-mn} is the change in power flow on line ij when a power transfer of the bilateral transaction is changed between m and n.

5. Calculated results from a 6-bus system

5.1. Simulation Data

This section presents the calculated results using a 6 bus power system [3]. The energy offer prices of generating units and bid prices of price-sensitive demands include 5 blocks.

In terms of bilateral trade, two different bilateral transactions are carried out: between bus 1 and bus 6 with a contractual capacity of 20 MW, denoted as T1 (1, 6, 20); between node 2 and node 5 with a contractual capacity of 25 MW, denoted as T2 (2, 5, 25).

5.2. Optimal location of TCSC

The calculated b_k indices for the 6 bus system are shown in Table 1. From these results and the criteria for optimal location of TCSC expressed in section 2, TCSC is placed in line 2-6.

***Table 1**. Sensitivity b_k*

Line	$\frac{\partial P_i}{\partial X_{Ck}}$	$\frac{\partial P_j}{\partial X_{Ck}}$	b_k
1-2	-0.8830	0.8107	0.2679
1-4	-2.3154	2.2129	-0.8526
1-5	-1.2294	1.1625	0.0957
2-3	-0.0432	0.0401	0.0371
2-4	-4.5384	4.2975	1.4579
2-5	-0.6417	0.6118	-0.1375
2-6	-1.4067	1.3546	**-1.3442**
3-5	-0.9881	0.9188	-1.0195
3-6	-5.4084	5.2152	3.7894
4-5	-0.0713	0.0699	0.0456
5-6	0.0192	-0.0222	0.0189

When TCSC is located on the line 2-6, the impact of the control parameter of TCSC is shown in Figure 3. These results show that when the compensation level of TCSC is about 70% compared to the impedance of line 2-6, the PI index reaches the lowest value.

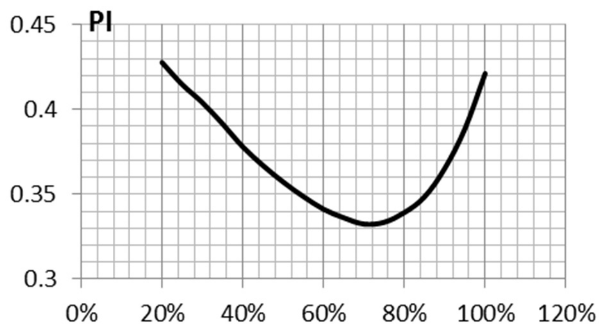

***Figure 3.** Effect of compensation level on PI indexes*

5.3. Impact of TCSC on transmission cost

Without TCSC, transmission charges of two bilateral transactions are given in Table 2. Table 2 shows that although the capacity of bilateral contract T1 is less than that of T2, transmission cost of contract T2 is nearly 4 times as high as that of T1.

***Table 2**. Transmission cost of bilateral contracts*

Line	LMP_j - LMP_i ($/MWh)	**T1 (1, 6, 20)**		**T2 (2, 5, 25)**	
		(MW)	($/h)	(MW)	($/h)
1-2	0.36	8.37	3.012	-3.66	-1.319
1-4	0.83	6.35	5.271	-1.12	-0.928
1-5	1.67	5.82	9.719	4.46	7.448
2-3	-1.36	3.10	-4.216	3.87	-5.263
2-4	0.47	-5.21	-2.447	4.70	2.209

2-5	1.31	0.00	0.000	7.12	9.327
2-6	5.37	10.26	55.118	6.12	32.851
3-5	2.67	-2.54	-6.792	4.94	13.190
3-6	6.73	5.53	37.217	-0.99	-6.629
4-5	0.84	1.13	0.951	3.94	3.310
5-6	4.06	4.21	17.076	-4.62	-18.78
Total transmission cost		**114.9 $/h**		**32.4 $/h**	

When TCSC is located on the line 2-6, the difference in LMP between node 2 and 5 (bilateral contract T2) is lowest when the control parameter of TCSC is approximately 52%. Additionally, the transmission charge of this transaction are given in Figure 4.

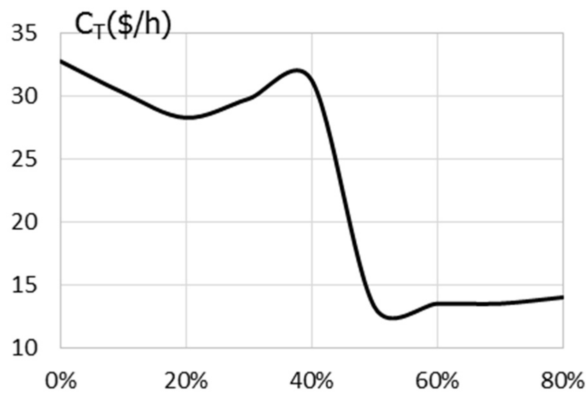

Figure 4. *Effect of compensation level on transmission cost of transaction T2*

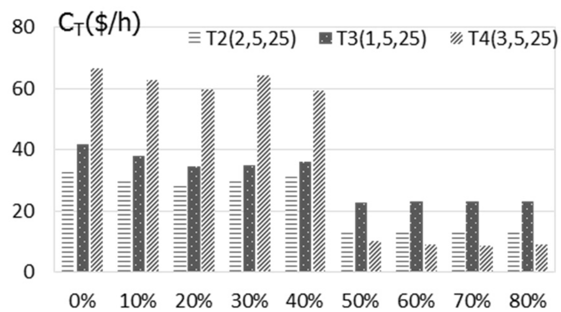

Figure 5. *The impact of seller bus on transmission cost*

The impact of the seller bus on transmission costs with different compensation levels is shown in Figure 5. The results show that with the same contractual capacity and the same compensation level, the position of seller bus can strongly affect transmission costs of the bilateral agreements.

6. Conclusion

This paper presents an approach to determine the optimal placement of TCSC to reduce congestion in the electric grid. Moreover, authors also presents the mathematical model of co-optimization problem of energy and active power reserve. The result of this optimization problem is location marginal price (LMP), the output capacity and reserve power of the generating units and the capacity of elastic loads. The influence of TCSC on LMPs, PI indices and transmission charges of bilateral agreements is also calculated and compared.

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