The Optimal Location and Compensation Level of Thyristor Controlled Series Compensator (*TCSC*) in Wholesale Electricity Markets considering Active Power Reserves

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Abstract

In the electricity market operation, when the congestion in power systems appears, total system cost increases, making the difference of locational marginal prices on the branch becomes bigger and generators can have market power. One of the measures to overcome network congestion is using thyristor-controlled series capacitor (TCSC). In this paper, a method for determining the optimal location and control parameters of TCSC in the wholesale electricity market, which consists of price-sensitive loads and ancillary services related to frequency control has been suggested. The sensitive method based on performance index is employed to optimally locate TCSC. The TCSC compensation level is appraised by co-optimization technique of energy and active power reserves with an objective function to maximize social welfare and minimize investment cost of TCSC. Moreover, this work has also made a comparison between additional social welfare and the investment cost of TCSC. The calculated results are applied on the North power system in Vietnam.

Keywords: Locational marginal prices (LMP), wholesale power markets, active power reserves, sensitive method, thyristor-controlled series compensator (*TCSC*), AC optimal power flow (ACOPF).

1. Introduction

Currently, the electricity industry in Vietnam has changed from competitive generation market to wholesale eletricity market mechanism. In the subsequent market, active power reserves become ancillary services. To control frequency and power flow among areas, sufficient active reserve must be ensured. Not only the reserve must be adequate to make up for a generating unit failure, but the reserves must also be appropriately allocated among fast-responding and slow-responding units. 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 [4], [5]. The market operator gathers generating offers, reserve offers by producers, load bids by consumers and reserve bids by the market operator, clearing the market by maximizing the social benefit [1], [3]. Moreover, locational marginal price (LMP) is calculated in order to make payments in the electricity market [1], [2].

To provide GENCOs and DISCOs with open access and enhance competitiveness among participants, demand on security and reliability of transmission network has increased enormously. Thyristor controlled series compensators (*TCSC*) have been evaluated to become one of measures which can considerably benefit modern power systems in term of increasing power transfer limits, reducing power losses, enhancing stability of the power system, reducing production costs of power plants, lessening the power flow on transmission lines congested and fulfilling contractual requirements [7].

There have been several works associated with location and compensation level of *TCSC* to accomplish diverse objectives. The approach based on sensitivity methods of reduction real power performance index has been proposed in [7]. Nevertheless, in [7] the value of control parameters has not been determined optimally. The influence of *TCSC* on congestion and locational marginal prices is analyzed in [8]. To manage congestion in transmission network, *TCSC* allocation using priority list method has been presented in [9]. However, these papers have not considered the investment cost of *TCSC*. Reference [10] proposes an approach to optimally locate and compute control reactance of *TCSC*, which takes into account investment cost. Nevertheless, these techniques have not regarded active power reserves in optimal problems. A procedure based a nonlinear mixed integer programming and a Bender's

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decomposition to simultaneously determine the optimal location and setttings of *TCSC* with the aim of reducing network congestion and generation costs in an optimization problem is proposed in reference [11]. Research in reference [12] determines the optimal placement of *TCSC* for improvement of wind energy utilization using probabilistic methodology.

In this paper, the optimal placement of *TCSC* is determined using an approach based on reducing congestion index of the power system. In addition, the step-by-step method is applied to achieve the optimal compensation level of *TCSC* in the wholesale electricity market. Social welfare along with LMPs are calculated according to co-optimization problems of energy and active power reserves.

The next sections of the article are organized as follows. In section 2, the authors present static models and investment cost 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 proposed in section 3. In section 4, the author demonstrates optimization models to Fig. out optimal placement of *TCSC* while section 5 shows an algorithm for determining parameter optimization of *TCSC*. The calculated example using POWERWORLD Simulator software for the North power system of Vietnam is presented and compared in section 6. Some conclusions are given in section 7.

2. Thyristor Controlled Series Compensator (*TCSC*)

2.1 Static modeling of TCSC

With a *TCSC* connected between bus i and bus j, the real and reactive power flow from bus i to bus j of a transmission line are [7]:

$$P_{ij}^{C} = U_i^2 G'_{ij} - U_i U_j \left(G'_{ij} \cos\delta_{ij} + B'_{ij} \sin\delta_{ij} \right) \quad (1)$$

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

$$G'_{ij} = \frac{R_{ij}}{R_{ij}^2 + \left(X_{ij} - X_{TCSC} \right)^2};\; B'_{ij} = \frac{-\left(X_{ij} - X_{TCSC} \right)}{R_{ij}^2 + \left(X_{ij} - X_{TCSC} \right)^2} \quad (3)$$

where X_{TCSC} is the reactance of *TCSC*, which is calculated as the following equation:

$$X_{TCSC} = k_{TCSC} . X_{ij} \quad (4)$$

where k_{TCSC} represents the compensation level of *TCSC*, which is positive if operating mode of *TCSC* is capacitive; otherwise negative when operating mode of *TCSC* is inductive.

The change in the line flow due to series compensation can be represented as a line without series compensation, with power injected at the receiving and sending ends of the line as shown in Fig. 1 [7].

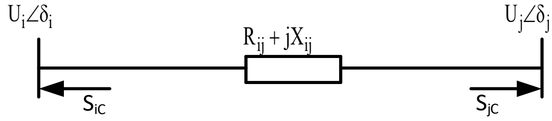

Fig. 1. Injection model of *TCSC*

The real and reactive power injections at bus i and bus j can be expressed as follow [7]:

$$P_{iC} = U_i^2 \Delta G_{ij} - U_i U_j \left[\Delta G_{ij} \cos\left(\delta_{ij}\right) + \Delta B_{ij} \sin\left(\delta_{ij}\right) \right] \quad (5)$$

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

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

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

$$\Delta G_{ij} = \frac{X_{TCSC} R_{ij} \left(X_{TCSC} - 2X_{ij} \right)}{\left(R_{ij}^2 + X_{ij}^2 \right) \left[R_{ij}^2 + \left(X_{ij} - X_{TCSC} \right)^2 \right]} \quad (9)$$

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

2.2 Investment cost of TCSC

The investment cost of *TCSC* can be calculated as follows [10]:

$$C_{TCSC} = 0.0015 Q_{TCSC}^2 - 0.7130 Q_{TCSC} + 153.75 \left(\$ / kVAr \right) \quad (11)$$

where C_{TCSC} is the total investment cost of *TCSC* in \$/kVAr and Q_{TCSC} is the operating reactive power of *TCSC* in MVAr.

The investment cost of *TCSC* in \$ is given by:

$$IC_{TCSC} = C_{TCSC} \times Q_{TCSC} \times 1000 \left(\$ \right) \quad (12)$$

The annual *TCSC* investment cost is determined using Eq. (13):

$$AIC_{TCSC} = IC_{TCSC} \frac{ir\left(1+ir\right)^{LT}}{\left(1+ir\right)^{LT} - 1} \left(\$ / year \right) \quad (13)$$

where AIC_{TCSC} is the annual investment cost of *TCSC*, ir is the interest rate and LT is the life time of *TCSC*. Assuming that ir = 5% and LT = 5 years.

The following equation is used to calculate the hourly *TCSC* investment cost (HIC_{TCSC}):

$$HIC_{TCSC} = \frac{AIC_{TCSC}}{8760}\left(\$/h\right) \quad (14)$$

3. Co-optimization of Energy and active power reserves with *TCSC*

3.1 Objective function

The objective function of co-optimization problem of energy and reserves including *TCSC* in the wholesale electricity market is to minimize the total cost to supply minus total consumer benefit and the investment cost of *TCSC* (so-called total system cost). This objective function is expressed as Eq. (15).

$$\begin{aligned}&\sum_{i=1}^{N_G}\sum_{b=1}^{N_{Gi}}\lambda_{Gib}.P_{Gib}\\&+\sum_{i=1}^{N_G}\left(\lambda_{Gi}^{RR+}.P_{Gi}^{RR+}+\lambda_{Gi}^{RR-}.P_{Gi}^{RR-}+\lambda_{Gi}^{SR}.P_{Gi}^{SR}+\lambda_{Gi}^{XR}.P_{Gi}^{XR}\right)\\&-\sum_{j=1}^{N_D}\sum_{k=1}^{N_{Dj}}\lambda_{Djk}.P_{Djk}-\sum_{b=1}^{N_{RR+}}\lambda_b^{RR+}.A_b^{RR+}-\sum_{b=1}^{N_{RR-}}\lambda_b^{RR-}.A_b^{RR-}\\&-\sum_{b=1}^{N_{CR}}\lambda_b^{CR}.A_b^{CR}-\sum_{b=1}^{N_{OR}}\lambda_b^{OR}.A_b^{OR}+HIC_{TCSC}\end{aligned} \quad (15)$$

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:

$$\begin{aligned}P_i = P_{Gi} - P_{Di} = \left|\dot{U}_i\right|\sum_{k=1}^{n}\left|\dot{U}_j\right|\left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right)\\Q_i = Q_{Gi} - Q_{Di} = \left|\dot{U}_i\right|\sum_{k=1}^{n}\left|\dot{U}_j\right|\left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right)\end{aligned} \quad (16)$$

3.2.2 Reserve balance

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

$$\sum_{i=1}^{N_G}P_{Gi}^{RR+} = A^{RR+} \quad (17)$$

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

$$\sum_{i=1}^{N_G}\left(P_{Gi}^{SR} + P_{Gi}^{XR}\right) = A^{CR} \quad (19)$$

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

3.2.3 Limits on generating active power of block b

$$0 \le P_{Gib} \le P_{Gib}^{\max} \quad \left(\forall i, b\right) \quad (21)$$

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. (22) – (23).

$$\begin{aligned}&0 \le P_{Gi} + P_{Gi}^{RR+} + P_{Gi}^{SR} + P_{Gi}^{XR} \le P_{Gi}^{\max} \quad \left(\forall i\right)\\&P_{Gi} - P_{Gi}^{RR-} \ge P_{Gi}^{\min}\end{aligned} \quad (22)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (23)$$

3.2.5 Limits on reserve capacity of generating units

These constraints are shown as the following equations (24) – (27):

$$0 \le P_{Gi}^{RR+} \le P_{Gi\max}^{RR+} \quad (24)$$

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

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

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

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. (28) - (29).

$$P_{Dj}^{\mathrm{E}\min} \le P_{Dj}^{E} \le P_{Dj}^{\mathrm{E}\max} \quad \left(\forall j\right) \quad (28)$$

$$0 \le P_{Djk}^{E} \le P_{Djk}^{\mathrm{E}\max} \quad \left(\forall j, \mathrm{k}\right) \quad (29)$$

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. (30) – (33).

$$0 \le A_b^{RR+} \le A_{b\max}^{RR+} \quad (30)$$

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

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

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

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:

$$\sum_{i=1}^{N_G} P_{Gi}^{SR} \ge SR\%.\sum_{i=1}^{N_G}\left(P_{Gi}^{SR} + P_{Gi}^{XR}\right) \quad (34)$$

3.2.9 Branch flow limits

Branch flow limits are expressed as Eq. (35).

$$0 \le S_{ij} = \sqrt{P_{ij}^2 + Q_{ij}^2} \le S_{ij}^{\max} \quad (35)$$

3.2.10 Voltage Limits

$$U_i^{\min} \le U_i \le U_i^{\max} \quad (36)$$

3.2.11 Limits on reactance of TCSC

A coefficient which represents the compensation level of *TCSC* is usually chosen from -0.2 to 0.7:

$$-0.2 \le k_{TCSC} \le 0.7 \quad (37)$$

Some problems associated with the series resonance can occur in power systems when choosing 100% compensation.

The above-mentioned AC-based optimal problem with reserves (ACOPF Reserve) can be solved using successive linear programming (SLP) method [2].

3.3 LMP Calculation and Components

Locational Marginal Price (LMP) is determined according to following equation [1], [2].

$$LMP_i = LMP_E - LF_i.LMP_E + \sum_l SF_{l-i}.\mu_l \quad (38)$$

4. 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 blow [7],

$$PI = \sum_{m=1}^{NL} \frac{w_m}{2n}\left(\frac{P_{Lm}}{P_{Lm}^{\max}}\right)^{2n} \quad (39)$$

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 has been set to1 (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]:

$$b_k = \left.\frac{\partial PI}{\partial X_{Ck}}\right|_{X_{Ck}=0} \quad (40)$$

$$\frac{\partial PI}{\partial X_{Ck}} = \sum_{m=1}^{NL} w_m P_{Lm}^3 \left(\frac{1}{P_{Lm}^{\max}}\right)^4 \frac{\partial P_{Lm}}{\partial X_{Ck}} \quad (41)$$

$$\frac{\partial P_{Lm}}{\partial X_{Ck}} = \begin{cases} \left(SF_{mi}\dfrac{\partial P_i}{\partial X_{Ck}} + SF_{mj}\dfrac{\partial P_i}{\partial X_{Ck}}\right) & m \ne k \\ \left(SF_{mi}\dfrac{\partial P_i}{\partial X_{Ck}} + SF_{mj}\dfrac{\partial P_i}{\partial X_{Ck}}\right) + \dfrac{\partial P_j}{\partial X_{Ck}} & m = k \end{cases} \quad (42)$$

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

5. Parameter optimization algorithm of *TCSC*

Determining the rating and cost of *TCSC* is based on optimal power flow with reserves sequentially, in which optimization is done by varying the reactance of *TCSC* step by step manner between the specified ranges and obtaining optimal solutions.

The step-by-step procedure described above encompasses main steps as follows:

1) Input parameters of power systems, consisting of configuration, line data, bus data, offer of generating units for energy and reserves, demand curve by the elastic load and bid of Area for reserves.

2) Determine the location of *TCSC* using Equations (40)-(42).

3) Solve OPF Reserve problem defined in (15)-(36) without including *TCSC* and save the optimal value of objective function.

4) Set the value of *TCSC* reactance

$$X_{TCSC}^{line} = k_{TCSC}^{\min} X_{line} \quad (43)$$

5) Solve OPF Reserve problem with *TCSC* and obtain the optimal value of objective function.

6) Update the reactance of *TCSC* by changing small increment (Δk_{TCSC} = 0.5%) and set it to

$$X_{TCSC} = X_{TCSC}^{\min} + \Delta k_{TCSC} X_{line} \quad (44)$$

Get the value of the objective functions for all k_{TCSC} between the specified ranges.

7) Determine the minimum value of the objective function with *TCSC*.

8) Determine the optimal compensation of *TCSC*, reactance of *TCSC*, investment cost of *TCSC* and social benefit.

6. Results obtained with the North system of Vietnam

This section presents the calculated results using the North power system of Vietnam in 2013, in which it is assumed that there are 5 elastic demands, namely HA DONG, NAM DINH, SOC SON, BAC NINH, PHO NOI. The energy offer prices of generating units and bid prices of price-sensitive demands which include 3 blocks are shown in Table 1.

The calculated b_k indices for the North system are shown in Table 2. From these results and the criteria for optimal location of *TCSC* expressed in section 4, *TCSC* is placed in line HOA BINH – XUAN MAI.

When *TCSC* is located on the line HOA BINH-XUAN MAI, the optimal control parameter and investment cost of *TCSC* is shown in Table 3. These results show that when the compensation level of *TCSC* is 32.5% compared to the reactance of line HOA BINH-XUAN MAI, the social welfare reached the highest value.

The total system cost with *TCSC* is 3,318,048,577 VND/h, which is 101,851,423 VND/h lower than that without *TCSC*. This additional benefit is by far higher than the investment cost of *TCSC* (1,948,576.59 VND/h). The additional welfare after investment recovery of *TCSC* is 99,902,846.82 VND/h. Therefore, the investment cost recovery of *TCSC* in the network is obtained. Additionally, an improvement in the total system cost is approximately 3%.

The impact of *TCSC* on Locational Marginal Prices in various buses is shown in Fig. 2.

Table 1. Energy Offers of Generator and Elastic Load

	HAI PHONG GEN			HA DONG LOAD		
Block	1	2	3	1	2	3
Power (MW)	450	100	100	60	60	60
Price (VND/kWh)	1300	1350	1400	1550	1500	1450

Table 2. Sensitivity b_k

Line		b_k
HOA BINH	T500 HOA BINH	0.0416
HOA BINH	NHO QUAN	-0.7452
HOA BINH	**XUAN MAI**	**-2.4499**
HOA BINH	HA DONG	-0.4023
HOA BINH	CHEM	5.3342
T500 HOA BINH	T500 NHO QUAN	-1.9489
T500 SON LA	T500 HOA BINH	-1.2292
NHO QUAN	T500 NHO QUAN	0.6452
T500 SON LA	T500 NHO QUAN	0.8975
T500NHO QUAN	T500 HA TINH	0.0194
T500 NHO QUAN	T500 THUONG TIN	-2.2264
HA DONG	NHO QUAN	-0.4378
NHO QUAN	BA CHE	0.0598
NINH BINH	NHO QUAN	-0.3219
PHU LY	NHO QUAN	0.8665
HA DONG	XUAN MAI	-0.8812
HA DONG	CHEM	-1.9887
HA DONG	PHU LY	-0.1074
HA DONG	THUONG TIN	-0.2011
SON LA	T500 SON LA	0.0000
T500 HIEP HOA	T500 SON LA	-0.0087
T500 SON LA	T500 HIEP HOA	-0.0063
NINH BINH	BA CHÈ	-0.0245
BA CHÈ	BIM SON	-0.0138
NINH BINH	NAM ĐINH	-0.2957
HUNG ĐONG	BIM SON	0.0137
HUNG ĐONG	HA TINH	0.0124
HA TINH	T500 HA TINH	0.0497
NAM ĐINH	THAI BINH	0.1488
DONG HOA	THAI BINH	0.1569
DONG HOA	VAT CACH	0.0142
THUONG TIN	T500 THUONG TIN	-0.7999
MAI DONG	THUONG TIN	-0.0001
PHO NOI	THUONG TIN	0.0504
ND PHA LAI	THUONG TIN	-0.1386
T500 QUANG NINH	T500 THUONG TIN	0.0027
DINH VU	ND HAI PHONG	-0.0151
DONG HOA	DINH VU	-0.0120
ND HAI PHONG	VAT CACH	0.0233
DONG HOA	ND PHA LAI	0.0715
ND PHA LAI	DONG HOA	0.0716
PHO NOI	ND PHA LAI	-0.2424
ND PHA LAI	TRANG BACH	-0.0332
BAC GIANG	ND PHA LAI	0.4335
BAC NINH	ND PHA LAI	-0.0949
HIEP HOA	ND PHA LAI	-0.0156
TRANG BACH	UONG BI	-0.0025
TRANG BACH	SON DONG	0.0112
TRANG BACH	HOANH BO	-0.0512
HOANH BO	SON DONG	0.0036
QUANG NINH	HOANH BO	-0.0227
QUANG NINH	T500 QUANG NINH	0.0010
ND CAM PHA	QUANG NINH	-0.0037
THAI NGUYEN	BAC GIANG	-0.0219
SOC SON	BAC NINH	0.1528
HIEP HOA	BAC NINH	-0.0050
SOC SON	THAI NGUYEN	-0.0537
SOC SON	HIEP HOA	-1.2239
TD TUYEN QUANG	THAI NGUYEN	-0.0172
THAI NGUYEN	HIEP HOA	-0.0217
TD TUYEN QUANG	HIEP HOA	0.0031
HIEP HOA	T500 HIEP HOA	-0.0098

Table 3. Optimal parameters of *TCSC*

S.N.	*TCSC* parameters	Optimal
1	Location	HOA BINH-XUAN MAI
2	Compensation level (k_{TCSC})	32.5%
3	Operating mode	Capacitive
4	Reactance of *TCSC* (X_{TCSC}) in p.u	0.010923
5	Reactive power (Q_{TCSC}) in MVAr	23.87308
6	Investment Cost (VND/h)	1,948,576.59

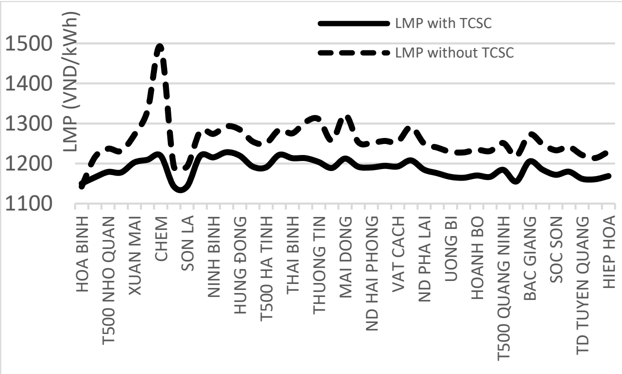

Fig. 2. Locational Marginal Prices

The results show that the difference in LMP among buses reduces reasonably when locating *TCSC* in line HOA BINH-XUAN MAI ($LMP_{max} - LMP_{min}$ = 1228.26 – 1142.76 VND/kWh) compared to when *TCSC* is not used ($LMP_{max} - LMP_{min}$ = 1490.55 – 1142.52 VND/kWh).

In addition, the value of average LMPs without *TCSC* is 1257.24 VND/kWh, which is 69.78 VND/kWh higher than that with *TCSC* located in line HOA BINH-XUAN MAI.

7. Conclusion

This paper presents an approach to determine the optimal placement and operating point of *TCSC* in order to reduce congestion and increase the social benefit. Moreover, authors the presents the mathematical model of co-optimization problem of energy and active power reserve considering investment cost of *TCSC*. The result of this optimization problem is the location marginal price (LMP), the output capacity and reserve power of the generating units and the capacity of elastic loads. The calculated results reveal a noticeable improvement in LMPs, the social welfare in the North system of Vietnam. Besides, the application of *TCSC* in transmission networks is sufficient due to *TCSC* investment recovery. In this paper, the optimal location and settings of *TCSC* device regardless of demand uncertainty have been considered solely for the single interval (1 h). It can also be developed for the multiple intervals (8760 hours in one year). Additionally, a variety of uncertain resources such as load, wind power (WT) and photovoltaics (PV) can be integrated in this proposed model. These could be the future research topics on the application of *TCSC* devices.

References

[1] Hongyan Li, Leigh Tesfatsion, ISO Net surplus collection and allocation in wholesale power markets under LMP, IEEE Trans. Power Systems, 26 (2011) 627-641.

[2] V. Sarkar and S. A. Khaparde, Optimal LMP Decomposition for the ACOPF Calculation, IEEE Trans. Power Systems, 26 (2011) 1714-1723.

[3] Marco Zugno, Antonio J. Conejo, A robust optimization approach to energy and reserve dispatch in electricity markets, European Journal of Operational Research, (2015) 659-671.

[4] J. Frunt, W. L. Kling, J. M. A. Myrzik, Classification of reserve capacity in future power systems, International Conference on the European Energy Markets, (2009) 1-6.

[5] Xingwang Ma, Yonghong Chen, Jie Wan, MIDWEST ISO Co-Optimization based real-time dispatch and pricing of energy and ancillary services, 2009 IEEE General Meeting.

[6] Santiago Grijalva, Peter W. Sauer, James D. Webber, Enhancement of linear ATC Calculations by the incorporation of reactive power flows, IEEE Trans. Power Systems, 18 (2003) 619-624.

[7] Seyed Abbas Taher, Hadi Besharat, Transmission Congestion Management by Determining Optimal Location of FACTS Devices in Deregulated Power Systems, American Journal of Applied Sciences 5 (2008) 242-247.

[8] N. Acharya and N. Mithulananthan, Influence of *TCSC* on congestion and spot price in electricity market with bilateral contract, Elect. Power Syst. Res., 77 (2007) 1010-1018.

[9] N. Acharya and N. Mithulananthan, Locating series FACTS devices for congestion management in deregulated electricity market, Elect. Power Syst. Res., 77 (2007) 352-360.

[10] R.S. Wibowo, N. Yorino, M. Eghbal, Y. Zoka, and Y. Sasaki, FACTS devices allocation with control coordination considering congestion relief and voltage stability, IEEE Trans. Power System, 26 (2011) 2302-2310.

[11] O. Ziaee, F. Choobineh, Optimal location – allocation of *TCSC* devices on a transmisison network, IEEE Trans. Power System, 32 (2017) 94-102.

[12] A. Kapetanaki, V. Levi, M. Buhari, J. A. Schachter, Maximization of Wind Energy Utilization through corrective scheduling and FACTS deploying, IEEE Trans. Power System, 32 (2017) 4764-4773.