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Optimal Location of TCSC for Social Welfare Maximization in Deregulated Electricity Market

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Abstract

In a competitive electricity market, congestion leads to decreasing Social Welfare. Hence, congestion management, Social Welfare Maximization is one of the technical challenges for Independent System Operator (ISO). The congestion can be eliminated /alleviated by improving transfer capability of the network. Thyristor controlled series compensators (TCSC), with its ability to directly control the power flow can be very effective to improve the operation of transmission network. In which, proper location of TCSC plays key role for enhancement of system performance. This paper applied min cut algorithm to determine proper location of TCSC. Result simulation on IEEE 14-bus, IEEE 30 - bus system show that the proposed method is capable of finding the best location for TCSC installation to eliminate congestion and maximum Social Welfare.

Keywords: Congestion, Social Welfare, TCSC, FACTS, Min cut algorithm.

INTRODUCTION

Since the last three decades, many electrical power utilities have been forced to change their way of operation and business, from monopolistic structure to competitive market structure. In Vietnam, the roadmap for the application of electricity markets has also been approved by the Prime Minister. Currently, we are applying pilot steps and then moving towards a perfect competitive electricity market. The creating electricity market has brought many social benefits. However, it also causes the system to frequently congestion. Congestion has a direct impact on trading contracts and electricity prices, while prices in some areas increase while others decrease. Consequently, it distorts the market and reduces social welfare. Therefore, in order to eliminate congestion, maximum social welfare, need to build new transmission lines. This is often difficult from regulating state and environmental policies. Thus, rebalancing power flow to increase the use of available capacity of the existing lines to satisfy the increased power demand is on of important problems. Along with the development of the electronics industry, FACTS devices have a significant influence in controlling the power flows.

Among FACTS devices, TCSC is a very common device because it can be connected directly to the line in the system. TCSC is used to redistribute the power flow, enable the existing system to improve its transfer capability. Hence, the installation of TCSC on the transmission system is the best alternative to eliminate congestion and maximum social welfare. In which, determining location of TCSC is a important issue because TCSC is a costly device and it can adversely affect system stability unless properly located optimal.

Various methods have been proposed to achieve these different objectives via optimal location of FACTS devices. Gerbex et al. [1] have used a genetic algorithm to seek the optimal location of FACTS devices in a power system. Optimizations have been performed on the location of the device as well as their values. However, in [1] the number of devices to be installed is decided arbitrarily not by optimization. The impact of TCSC on congestion and spot pricing is presented in [2]. The paper demonstrated that theTCSC could reduce congestion as well as the losses. References [3] and [4] have proposed optimal allocation methods for TCSC to eliminate the line overloads, where sensitivity index is introduced for ranking the optimal placement. Priority list method for TCSC allocation for congestion management has been proposed in [5]. In [6], an efficient genetic algorithm technique was proposed for optimal size and location of TCSC in deregulated market for congestion management with aim of maximizing the social welfare cost. A new fuzzy-based genetic algorithm (Fuzzy-GA) for alleviating congestion and maximizing social benefit in a double-sided auction market by locating and sizing of one Thyristor-Controlled Series Capacitor (TCSC) unit [7]. In [8], A genetic algorithm for finding the optimal location and size of this device is proposed for congestion management with the aim of increasing social welfare. A novel and efficient differential evolution and evolutionary programming techniques for social welfare maximization by optimal location of various FACTS devices in pool electricity market based on contingency analysis is introduced [9].

This paper has applied the minimum cut methodology for determining bottleneck of power system. The basic idea of the algorithm is to find the cut that has the minimum cut value over all possible cuts in the network. That is the cut which contains bottleneck branches with sum of capacity through it's smallest. Therefore, if the minimum cut is identified, the branch that has the ability to contribute to adjust impedance will be recognized and only that branch is able to install TCSC

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to help the congested branch This method can limit the search space. Using this method, the number of branches which need to be investigated to determine the position placement TCSC has been significantly decreased

STATIC MODEL OF TCSC

The effect of TCSC on the network can be seen as acontrollable reactance inserted in the related transmission line [5]. Series capacitiv ecompensation works by reducing the effective series impedance of the transmission line by canceling part ofthe inductive reactance. Hence the power transferred is increased. In this case study,TCSC only operates as acapacitor. The model of the network with TCSC is shown in Fig.1.TCSC can be considered as a static reactance $-jX_{TCSC}$ under steady state.

TCSC is integrated in the OPF problem by modifying the line data.The maximum compensation by TCSC is limited to 70% of the reactance ofthe uncompensated line where TCSC is located. A new line reactance (X_{new}) is given as follows.

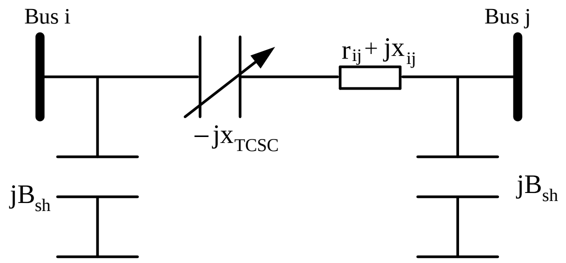

Figure 1. Model of transmission line with TCSC

$$X_{New} = X_{ij} - X_{TCSC} \quad (1)$$

$$X_{New} = (1- L)X_{ij} \quad (2)$$

Where $L=X_{TCSC}/X_{ij}$ is the degree of series compensation and X_{ij} is the line reactance between bus-i and bus-j.

The power flow equations of the line with a new reactance can be derived as follows.

$$P_{ij} = V_i^2 G_{ij} - V_i V_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) \quad (3)$$

$$Q_{ij} = -V_i^2 B_{ij} - V_i V_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) \quad (4)$$

$$P_{ji} = V_j^2 G_{ij} - V_i V_j (G_{ij} \cos\delta_{ij} - B_{ij} \sin\delta_{ij}) \quad (5)$$

$$Q_{ji} = -V_j^2 B_{ij} + V_i V_j (G_{ij} \sin\delta_{ij} + B_{ij} \cos\delta_{ij}) \quad (6)$$

Where $G_{ij} = \frac{R_{ij}}{R_{ij}^2 + X_{New}^2}$ and $B_{ij} = \frac{X_{New}}{R_{ij}^2 + X_{New}^2}$

THE IMPACT OF TCSC ON SOCIAL WELFARE

Price, surplus and congestion charge

In a market economy, the supply and demand rule plays a decisive role in the market. There, The producer try to produce well to bring a lot of profit, while customers consume the product to serve the needs to be able to make the best profit from the use of the product. Producer profit is known as producer surplus and customer profit is known as consumer surplus. Producer surplus is the difference between the invoice received from the sale and the cost of production, while customer surplus is the difference between the price of the customer willing to pay and the actual price paid. It shows the net profit of customers who can buy all the products to fully meet their needs at market price levels. Gross producer surplus and customer surplus represent the total market value and are considered social surplus or so called social welfare.

The ultimate goal of social welfare is to use the best prices in the market. This price is determined according to the market supply and demand rules and is considered as a criterion for assessing economic efficiency. Assuming the market is considering a perfectly competitive market, a balanced price will be reached at the point at which the supply and demand intersect. This is the point at which the cost of production (marginal cost) corresponds to the willingness (demand curve). However, in the electricity market, this trade off would be distorted if transmission constraints were violated. Other constraints such as voltage limitation and transmission limitation can also distort the market. The effect of such constraints restricts competition and reduces market efficiency. At the same time it also reduces producer surplus and customer surplus. The reduced surplus will be transferred to the ISO market operator. This is the congestion charge.

Consider a simple two-bus system, with the generator at bus 1 and load at bus 2. The line limit between bus 1 and bus 2 is P_{limit}. For this simple case, the line is assumed to be lossed. The supply and demand curves are shown in Figure 2

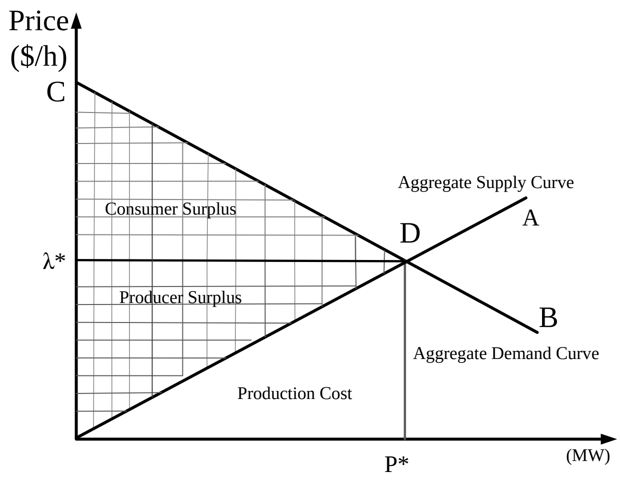

Figure 2. Producer surplus and customer surplus under unconstrained case

When ignoring line constraints, the equilibrium point is at λ* ($/MWh) and P* (MW). However, when considering the line limit as shown in Figure 3, there is a price difference between the two. At the generator bus, the price falls down and at the consumer bus the price goes up. This result reduced the producer surplus and customer surplus as show in Fig. 3.

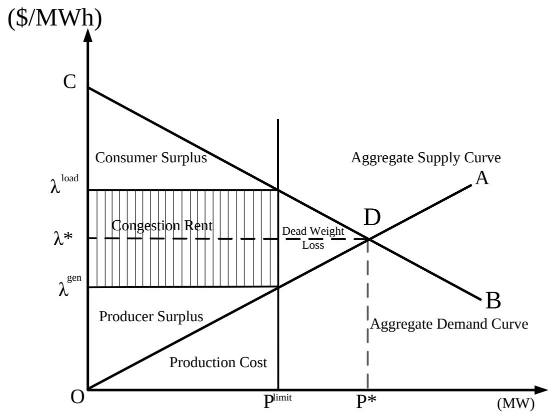

Figure 3. Surplus under constrained case without TCSC

This has caused social loss. Because the price is determined at the generator bus and load bus corresponding. The result is a surplus for the market operator (ISO). This surplus is known as the congestion rent. It is used to compensate for the losses or to reinforce transmission grid or transfer to the participants based on market rules.

Market prices for a given amount of power can be determined by solving the optimal problem with the objective of maximizing social welfare to satisfy limited constraints. From there, producer surplus (PS), consumer surplus (CS) and ISO income can be determined.

$$Min\left(\sum_{i\in N_g} C_{gm}(P_{gm}) - \sum_{i\in N_d} B_{dn}(P_{dn})\right)$$

Where $C_{gm}(P_{gm}) = a_m P_{gm}^2 + b_m P_{gm} + c_m$ and $B_{dn}(P_{dn}) = a_n P_{dn}^2 + b_n P_{dn} + c_n$ is the cost of the generator function and the profit function of the customer

Subject to

- Power balance equation

$$P_i(V,\delta) + P_{di} - P_{gi} = 0 \qquad i = 1,..., N_b \qquad (8)$$

$$Q_i(V,\delta) + Q_{di} - Q_{gi} = 0 \qquad i = 1,..., N_b \qquad (9)$$

- Power generation limit

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \qquad i = 1,....., N_g \qquad (10)$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \qquad i = 1,....., N_g \qquad (11)$$

- Bus voltage limits

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1,....., N_b \qquad (12)$$

- Apparent line flowlimit

$$S_l \le S_{l,\max} \qquad l = 1,....., N_l \qquad (13)$$

Producer Surplus (PS)

$$PS = \sum_{i\in N_{gm}} \frac{1}{2}(\lambda_m - b_{gm})(P_{gm} - P_{gm}^{\min}) \qquad (14)$$

Customer surplus (CS)

$$CS = \sum_{i\in N_{dn}} \frac{1}{2}(b_{dn} - \lambda_n)(P_{dn} - P_{dn}^{\min}) \qquad (15)$$

Merchandize surplus ISO

$$MS = \sum_{i\in N_{dn}} \lambda_n P_{dn} - \sum_{i\in N_{gm}} \lambda_m P_{gm} \qquad (16)$$

Where:

λ_m is the spot price at generator bus m

λ_n is the spot price at load bus n

b_{gm} is the linear coefficient in the quadratic generator bid function

b_{dn} is the linear coefficient in the quadratic demand function

P_{gm} is the real power output of the generator bus m

$P_{gm}^{\min}$ is the lower limit of the generator m

P_{dn} is the real power demand at load bus n

$P_{dn}^{\min}$ is the lower limit of the load n

Impact of TCSC

When TCSC is installed at the proper location with suitable size, congestion will be reduced. Simulation result for the two bus system is shown in Figure 4.

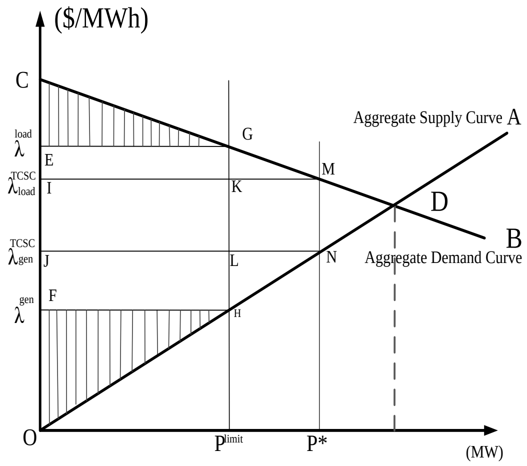

Figure 4. Surplus under constrained case with TCSC

In un-congested zone, where generally generator is located, price increases. However, in the congested zone, where load is lacated, price decreases. The congestion rent that ISO receives from market participants due to LMP difference at the source and sink zone is also reduced. This results in increasing producer surplus and customer surplus. As shown in Figure 4, the maximum power that can be transferred over the line without TCSC is P_{limit} and the price at the generator bus and load bus is λ_{gen} and λ_{load} respectively. The congestion rent that ISO receives is given by the area EGHFE, which is the difference in price multiplied by the maximum power flow through the link; P_{limit} x (λ_{load} - λ_{gen}). The consumer and producer surplus are given by triangle EGCE and FHOF, respectively. TCSC can quickly rebalance power by controlling the power flow through un-congested transmission line, improving transfer capability to eliminate congestion. It is given by P_{TCSC}. Price at two positions also change. The price at the load bus is reduced λ_{TCSC}^{load} and the price at the generator bus increases λ_{TCSC}^{gen}, so that the nodal price spread is small. The effect is that both the producer and customer surplus increases and is given by the area IMCI and JNOJ respectively. The congestion rent is also changing and is reflected in the IMNJI area. Before installing TCSC, the congestion rent was in the EGHFE area, which was larger than IMNJI. Social welfare is increased by the use of TCSC indicated in the GMNHG.

OPTIMAL LOCATION OF TCSC

The TCSC optimization position proposed in this paper is determined through the system bottleneck. The bottleneck is where the largest capacity can be transferred from source to load. As the system increases the load, the bottleneck is the first to occur congestion. Therefore, to eliminate or reduce congestion, the transmission capability at the bottleneck should be considered. In addition, the power distribution does not depend on the carrying capacity of the line but depends on the impedance. This results in the bottleneck being overloaded although the carrying capacity of the bottleneck may be greater than the capacity requirement. Therefore, replacing TCSC on the bottleneck branch to adjust the line impedance is a quick method of rebalancing power by controlling the power flow through these branches to eliminate overload. Or, in other words, using TCSC to prevent congestion means redistributes power flow to increase the use of available capacity of the existing lines.

The use of the maximum power flow method to determine the minimum cut of any network has been introduced in [10]. Based on this method, it determined the minimum cut of the power system has been proposed [11-12]. However, a new algorithm that used to determined minimum cut has proposed in this paper. The basic idea of the algorithm is to find the cut that has the minimum cut value over all possible cuts in the network. That is the cut which contains bottleneck branches with sum of capacity through its smallest. Therefore, if the minimum cut is identified, the branch that has the ability to contribute to adjust impedance will be recognized and only that branch is able to install TCSC to help the congested branch.

Modeling power network using min cut approach

The network is modeled as a directed graph G (N, C), in which there is only one peak s without input supply called the corresponding transmitter source for the transmitter, only one peak t without output supply as the corresponding revenue source for the load. Set node N, corresponding to the bus in the network. The branch power line between bus i, j ∈ N is represented by a supply of cij ∈ C. Each supply is denoted by S_{ij}, which represents the maximum permissible power flow of that line and is referred to as the flow in the graph. Each output line of the transmitter is the maximum capacity of the transmitter, each input line of the source is the demand for the load. Equivalent modeling of the network Figure 5 is shown in Figure 6a. Some possible min cut of the network Figure 5 shows in Figure 6b. Flow chart for determining the minimum cut of the network and the TCSC location for maximum social welfare is shown in Figures 7 and 9 respectively.

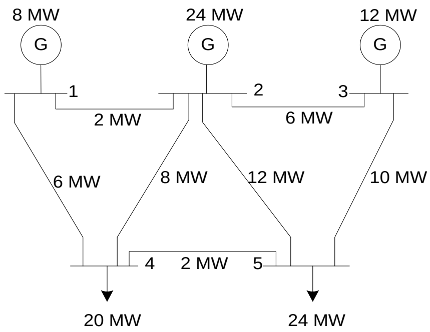

Figure 5. Five-bus power system

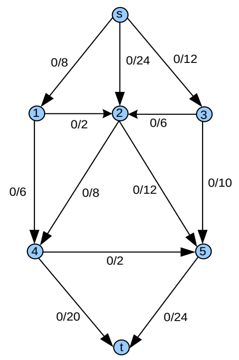

Figure 6a.. Equivalent modeling

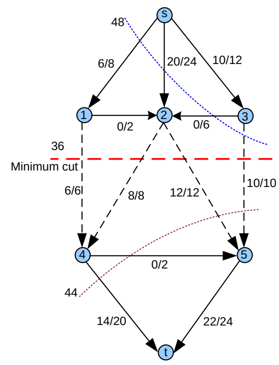

Figure 6b. Some possible cuts

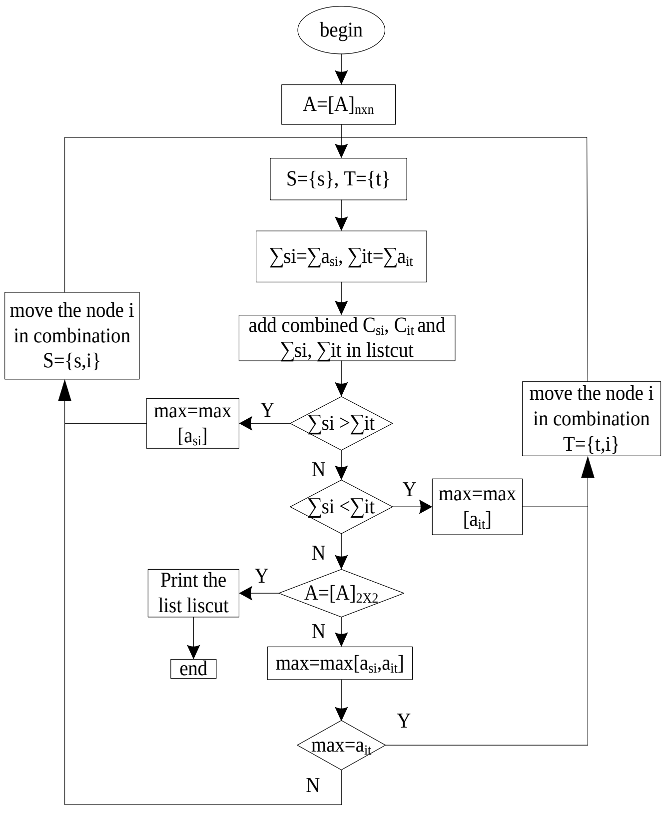

Figure 7. Flow chart of algorithm for determining the minimum cut

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Simulation results on IEEE 14-bus system

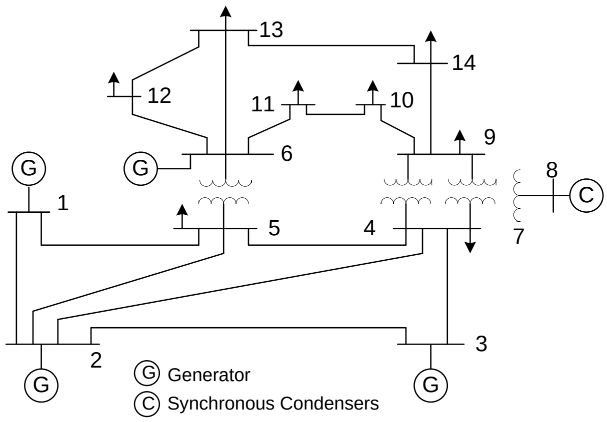

Figure 8. The IEEE 14-bus System

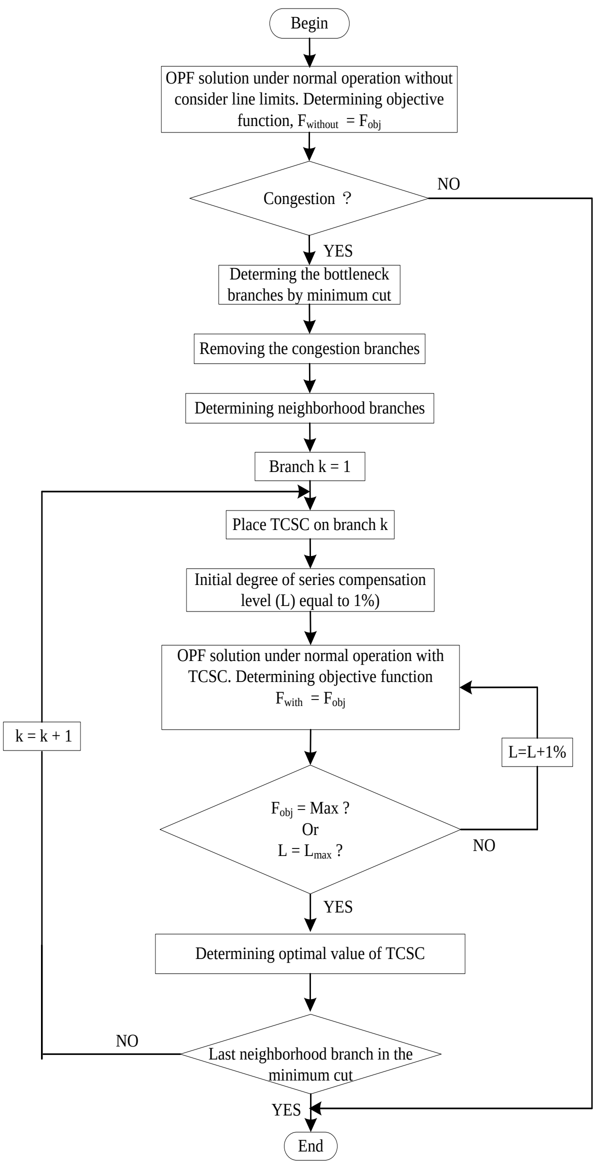

Figure 9. Flow chart for determining TCSC to maximize social profit

The IEEE 14-bus system was used to investigate the effect of TCSC on social welfare and the profitability of participants in the market. The IEEE 14 bus system consists of 5 generators and 20 lines, as shown in Figure 8. The generator and load data for Table 1 - Table 3. A Matpower 4.0 software package [13-14] was used to resolve the optimal power flow in this study.

Table 1: Generator cost function and customer profit function

Gen no		a	b	c
1	G1	0.0245	1	0
2	G2	0.0351	1	0
3	G3	0.0389	1	0
6	G4	0.0372	1	0
8	G5	0	0	0
4	L1	- 0.015	15	0
5	L2	- 0.015	15	0
9	L3	- 0.010	15	0
10	L4	- 0.015	20	0
11	L5	- 0.015	20	0
12	L6	- 0.018	20	0
13	L7	- 0.018	20	0
14	L8	- 0.018	20	0

$$C_{gm}(P_{gm}) = a_m P_{gm}^2 + b_m P_{gm} + c_m$$

$$B_{dn}(P_{dn}) = a_n P_{dn}^2 + b_n P_{dn} + c_n$$

Table 2: generator data

Generator	P_{max}	P_{min}	Q_{max}	Q_{min}
1	150	20	40	- 40
2	500	50	50	- 40
3	500	50	40	- 40
6	100	20	24	- 6
8	0	0	24	- 6

Table 3: Load data

Load	P_d (MW)	Q_d (MVAR)
4	107.6	52.1
5	116.2	56.3
9	5.0	2.4
10	20.8	10.1
11	20.7	10.5
12	26	12.6
13	5.0	2.4
14	29.4	14.2

From the results in Table 4 (column 2), it can be seen that, by ignoring the line limit, the maximum social welfare obtained 2212.9$ / h. At this value of social welfare, line 6-13 are congested as shown in Table 5 (column 3) and Figure 10 at the line 13. Clearly the power system can not operate in this case because security was violated. However, overloads on the 6-13 line have been eliminated by redispatch the power of generator output. This condition will prevent loads to be served from generators obtained from the cheapest combination of generator outputs and resulted in price changes at the bus, especially at bus prices that connection to the congested line as shown in Figure 11. The line limit, congestion has made social welfare, customer surplus and producer surplus decrease, while ISO income is increased as in Table 4 (column 4). Redispatching the power of generator output to eliminate overloads in this case is necessary to ensure security in operating the system, but is probably not acceptable by suppliers and customers in the electricity market. Therefore, the use of TCSC device to improve transfer capability, eliminating congestion while still achieving maximum profitability is one of the main concerns of researchers today.

From the simulation results in Table 4 it can be seen that the maximum welfare was improved when TCSC was installed at line 6-12. This is the line in the minimum cut and is also neighborhood line of the overloaded line 6–13 as shown in Table 6. The installation of TCSC on this branch to modify the impedance is a quick method of rebalancing power to eliminate overload and provide cheap power to customers. From Table 5 and Figure 10 it can be seen that the power flow on branches 6-13 has now decreased, while the power flow on branch 6-12 has increased. TCSC reduced the impedance of the 6-12 line from 0.25581 pu to 0.21581 pu so the power flow on this branch increased.

Table 7 was constructed to examine a number of different TCSC location. It can be seen from Table 7, lines 6-12 and lines 6-11 is also the best location to install TCSC. When TCSC installed in this position, social welfare was the greatest.

Table 4: Results of the social welfare optimization of the 14-bus IEEE system

Excess	Ignore the line limit	Consider the line limit	With TCSC
Social welfare	2212.9 $/h	1849.7 $/h	2212.8 $/h
Producer Surplus	581.6 $/h	580.6 $/h	581.4 $/h
Consumer surplus	1540.9 $/h	1416.8 $/h	1541.2 $/h
Income ISO	90.43 $/h	328.5 $/h	90.15 $/h
Power loss	14.14 MW	14.99 MW	14.11 MW
Location TCSC	-	-	line 6-12
Size	-	-	0.04 pu

Table 5. The branch power of IEEE 14-bus system

Line i-j	MVA Limit	Ignore the line limit	With TCSC
1-2	80	50.21	50.21
1-5	80	69.34	69.32
2-3	80	7.12	7.10
2-4	80	71.75	71.72
2-5	80	71.77	71.76
3-4	80	77.10	77.05
4-5	80	11.08	11.01
4-7	42	22.61	22.59
4-9	25	11.00	10.97
5-6	42	5.0	4.87
6-11	42	31.13	31.06
6-12	25	23.03	24.10
6-13	**30**	**31.03**	**29.95**
7-8	30	23.15	23.15
7-9	30	21.86	21.77
9-10	25	19.39	19.40
9-14	25	17.79	17.64
10-11	25	9.72	9.63
12-13	25	6.92	5.83
13-14	25	17.72	17.92

Table 6. The minimum cut of IEEE 14 bus system

Line	Minimum cut	Lines is considered for placing TCSC
1	6 - 13	Overloaded line
2	**6 - 12**	Neighborhood line
3	6 - 11	Neighborhood line

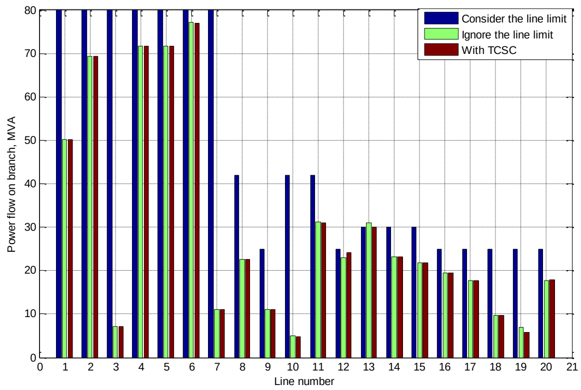

Figure 10. The power flow on branch after placing TCSC devices in IEEE 14 bus system

Table 7. Cost optimization results when TCSC installed at different locations

Line	i-j	Total cost $/h
2	6-12	2212.8
3	6-11	2210.3
4	11-10	1857.6
5	12-13	1869.2
6	9-14	1889.4
7	13-14	1879.7

The comparison between Table 7 and Table 6 shows that the branches in the minimum cut are the suitable location of TCSC to eliminate congestion and maximum social welfare.

From the above analysis, it can be seen that in the electricity market, customers can buy electricity at the same price regardless of the location of consumption. However, the transmission and congestion constraints have increased the bus price (Figure 11) and prevent consumers from buying electricity at lower prices from suppliers and making economic activity in the electricity market effective. Therefore, the installation of TCSC on the branch of the minimum cut and neighborhood line of the overloaded line is one of the effective methods to eliminate congestion and maximum social welfare. In addition, this method also reduces the search space TCSC installation location. In this study, the TCSC installation location has decreased from 20 branches to 2 branches as shown in Table 6. This is one of the challenges for researchers in using TCSC to optimize operation the system.

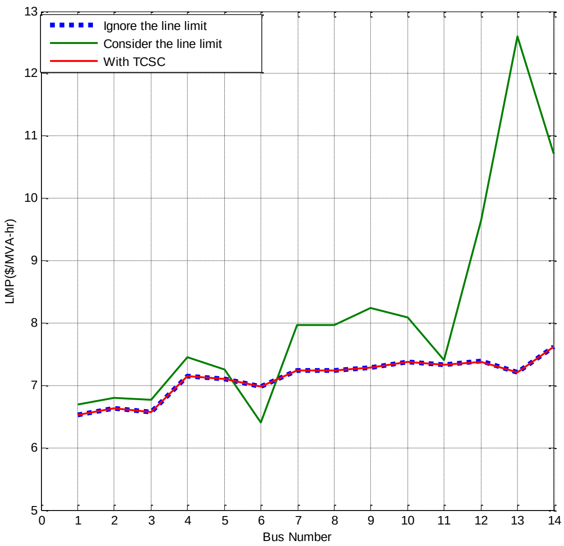

Figure 11. The nodal price of IEEE 14 bus system

Simulation results on IEEE 30-bus system

The proposed methodology has been implemented on IEEE 30 - bus system which is shown in Fig. 4. The network and load data for this system are taken from [8]

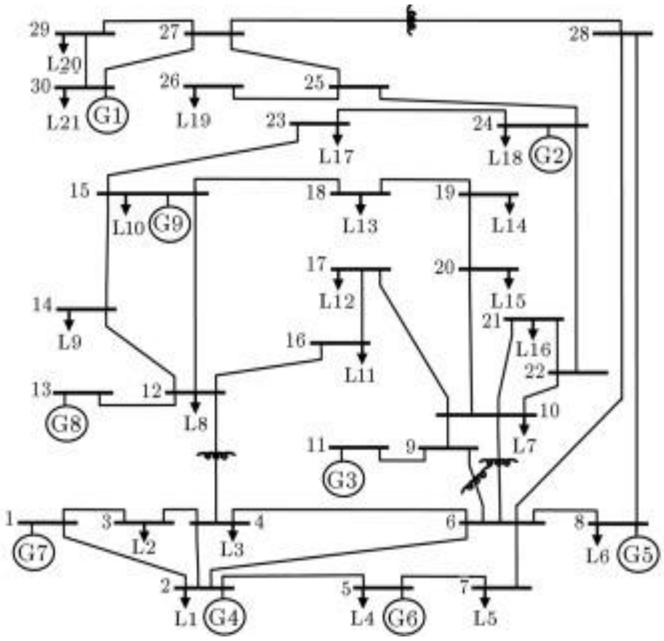

Figure 12. The IEEE 30-bus System

Table 8: Optimization problem result with and without TCSC

Gen No	Generation schedule without TCSC (MW)	Generation schedule with TCSC (MW)
1	10	10
2	5	5
3	5	5
4	10.75	10
5	50	50
6	50	50
7	59.91	84.52
8	10	17.83
9	45.13	55.41
Social welfare	7855.12 $/h	8002.9 $/h
Total Generation cost	6370.05 $/h	6223.1 $/h

The obtained results without using TCSC for maximizing the social welfare are presented in table II. In this case, the maximum social welfare is 7855.12 $/h. Also, the generation cost is 6370.05 $/h. By placing TCSC in bottleneck branch (line is neighborhood of the overloaded line and is in minimum cut) as shown in Table 9, maximizing the social welfare is obtained 8002.9 $/h. From Table 8, it can be seen that, the social welfare increases form

7855.12$/h to 8002.9 when TCSC is installed in line 1-2. The detail results by optimal setting TCSC parameters are presented in Table 8

Table 9 : The minimum cut of IEEE-30 bus system

Line	Minimum cut	Lines is considered for placing TCSC
1	6 - 8	Not neighborhood line
2	8 - 28	Not neighborhood line
3	3 - 4	Overloaded line
4	**1 -2**	Neighborhood line
5	1- 3	Overloaded line

The comparison of the results obtained by proposed method and Ref [8] it is observed that, the number of branches which need investigated to determine the location of TCSC has been significantly decreased while social welfare is achieved nearly same value.

Table 10: Social Welfare obtained by proposed method and [8] algorithm in IEEE 30-bus system

TCSC	Proposed method	Results reported in [8]
Location TCSC	Line 1-2	Line 1-2
Compensation value (pu)	60.28%	60.13%
Social Welfare	8002.9 $/h	8000.5 $/h

CONCLUSION

Managing congestion, maximizing social welfare using TCSC device is a major issue in the competitive electricity market. Proper location of TCSC plays key role in optimal power flow solution and enhancement of system performance without violating the security of the system. Therefore, it is important to determine the optimal location to install this device.

This paper has proposed a new algorithm in determining minimum cut of power system for installation TCSC. Using this method, the search space has been limited so the number of branches needed to survey to determine the location of TCSC has been significantly reduced. Only a few branches in the minimum cut need to be considered in detail to evaluate the best position. The simulation results presented demonstrate the effectiveness of the proposed method.

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