Enhancing Total Transfer Capability via Optimal Location of TCSC in Deregulated Electricity Market

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Abstract. In deregulated electricity market, most of the power transferred through the wheeling transaction. Hence, it is very important and necessary to determine the transfer capability of the transmission system before the power dispatch. Series FACTS devices such as Thyristor controlled series compensators (TCSC), with its ability to directly control the power flow can be very effective to total transfer capability of transmission network. Proper location of TCSC plays key role in improving total transfer capability (TTC). From the viewpoint, this paper focuses on the evaluation of the impact of TCSC on TTC via optimal location. Evaluation total transfer capability using TCSC requires a two-step approach. First, the optimal location of the TCSC in the network must be ascertained by Min cut algorithm and then, the mathematical formulation of TTC using Repeated Power Flow (RPF) with fixed TCSC parameters is solved. The proposed method is tested and validated for locating TCSC in IEEE 14-, IEEE-30 bus test systems. Results show that the proposed method is capable of finding the best location for TCSC installation to improve total transfer capability.

Keywords: Deregulated power system, FACTS, TCSC, RPF and TTC.

1 Introduction

Deregulation of power system has brought the trading of significant amounts of electrical energy and major changes in the system operation and control. In open access environment, consumers are allowed to choose their provider for electrical energy and consequently one and more transactions are possible in the transmission system. Therefore, the system Operator should have knowledge about power dispatch and total transfer capability (TTC).

TTC is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above all ready committed uses. According to the report of NERC [1], TTC is defined as the amount of electric power that can be manner while meeting all of specific set of defined pre and post contingency system condition transferred over the interconnected transmission network in a reliable. TTC can be calculated by several power flow solution methods such as 1) linear ATC (LATC) method [2], 2) continuation power flow (CPF) method

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[3], 3) repetitive power flow (RPF) method [4], and 4) optimal power flow (OPF) based methods [5].

In practice, an infinite transfer capacity of the network is impossible due to transfer limit of the transmission lines. Various factors, such as environmental, right-of-way and cost constraints have limited the expansion of the transmission networks. This makes transmission lines are often driven close to or even beyond their thermal limits in order to satisfy the increased power demand and trades due to increase of the unplanned power exchanges. If the exchanges were not controlled, some lines located on particular paths may become overloaded and this has led to bottleneck on the power system. The existence of bottlenecks in the transmission line affects direct on market transactions and decrease transfer capability of power system [6]. Using TCSC seems to be a promising strategy to eliminate /alleviate the transmission congestion and to increase available transfer capability of the existing lines. This device is not an alternative to constructing new transmission networks or upgrading transmission links but make it possible to use existing transmission network up to or close to their thermal limits.

Because of cost for these devices is high and effectiveness of the controls for different purposes mainly depends on the location of control device [7]. Therefore, optimization of location of the FACTS controllers has become the important issue for system Operators in the electricity market. Determining the bottleneck of power system plays key role in reducing search space and number of FACTS devices need to be installed. However, it is difficult to implement if there is not an effective method. This paper has applied Min cut algorithm that can be used to determined bottleneck in such effective away.

Various sensitivity methods are used to determine the optimal locations of FACTS devices to achieve different objectives. In [8], Genetic algorithm (GA) was used to determine the optimal location and parameter of TCSC for maximizing power transfer capability. Evolutionary Programming (EP) was proposed to obtain optimal placement of multi-type FACTS devices for simultaneously maximizing the total transfer capability whereas minimizing the total system real power loss and the results are better when compared to loss sensitivity index method [9]. In [10], Particle Swarm Optimization (PSO) is used to determine the optimal allocation of multitype FACTS controllers to enhance power transfer capability of power transactions between sources and sink areas in power systems. In [11], the real power flow performance index (PI) was used to determine the suitable locations of TCSC and TCPAR for TTC enhancement. In [12], RPF method combined with the sensitivity index of the loading margin to transmission line impedances were used to determine the location of TCSC for maximizing TTC.

In this paper, TCSC, which is one of the most effective FACTS devices, is selected to study. The objective of this paper is to improve transfer capability through the optimal utilization of TCSC. Proper location of TCSC is determined base on bottleneck of power system. In order to evaluate the suitable location of TCSC, the Min-cut algorithm has been proposed to determine optimal location of TCSC. The proposed method can identify the weakest location of the system in terms of transfer capability of the lines and therefore helps the System Operators to operate the system in a more secure and sufficient way.

2 Problem Formulations Using RPF with TCSC

Repeated power flow (RPF) enables transfers by increasing, the complex load with uniform power factor at every load bus in the sink area and increasing the injected real power at generator buses in the source area in incremental steps until limits are incurred [4].

The mathematical formulation of TTC using RPF without TCSC can be expressed as follows:

Maximize λ

Subject to:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} V_i V_j (G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) = 0 \tag{1}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} V_i V_j (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) = 0 \tag{2}$$

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{3}$$

$$S_{ij} \leq S_{ij}^{max} \tag{4}$$

Where

λ is scalar parameter representing the increase in bus load or generation. $\lambda = 0$ (λ_0) corresponds to no transfer (base case) and $\lambda = \lambda_{max}$ corresponds to the maximal transfer. P_{Gi} and Q_{Gi} are the real and reactive power generation at bus i; P_{Di} and Q_{Di} are the real and reactive power demand at bus i; V_i and V_j are the voltage magnitude at bus i, j; G_{ij}, B_{ij} are real and imaginary part of the ij^{th} element of bus admittance matrix; δ_{ij} is the voltage angle difference between bus i and bus j; S_{ij} is the apparent power flow of transmission line i; n is bus number of the system.

In the above power flow equations (1) and (2), P_{Gi} (generator real output in source area), P_{Di} (real load in sink area), and Q_{Di} (reactive load in sink area) are changed in the following way [13]:

$$P_{Gi} = P_{Gi}^0 (1 + \lambda K_{Gi}) \tag{5}$$

$$P_{Di} = P_{Di}^0 (1 + \lambda K_{Di}) \tag{6}$$

$$Q_{Di} = Q_{Di}^0 (1 + \lambda K_{Di}) \tag{7}$$

Where: P_{Gi}^0 is original real power generation at bus which is in source area; P_{Di}^0, Q_{Di}^0 are original real and reactive load demand at bus which is in sink area; K_{Gi}, K_{Di} are constants used to specify the change rate in generation and load as λ varies.

TTC level in each case (normal or contingency case) is calculated as follows

$$TTC = \sum_{i \in Sink} P_{Di}(\lambda_{max}) - \sum_{i \in Sink} P_{Di}^0 \tag{8}$$

Where

$\sum_{i \in Sink} P_{Di}(\lambda_{max})$ is sum of load at sink area when $\lambda = \lambda_{max}$; $\sum_{i \in Sink} P_{Di}^{0}$ is sum of load at sink area when $\lambda = 0$.

The effect of TCSC on the network can be seen as a controllable reactance inserted in the related transmission line. Series capacitive compensation works by reducing the effective series impedance of the transmission line by canceling part of the inductive reactance. Hence the power transferred is increased. The model of the network with TCSC is shown in Figure 1.

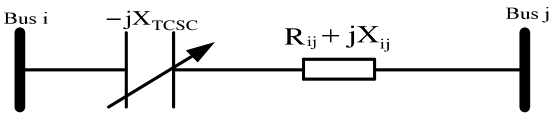

Fig. 1. Model of transmission line with TCSC

The maximum compensation by TCSC is limited to 70% of the reactance of the un-compensated line where TCSC is located. A new line reactance (X_{new}) is given as follows.

$$X_{New} = X_{ij} - X_{TCSC}$$

$$X_{New} = (1\text{- }k)X_{ij}$$

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

The formulation of TTC using RPF with TCSC can be represented as follows:

Maximize λ

Subject to:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} V_i V_j (G_{ij}^{new} \cos\delta_{ij} + B_{ij}^{new} \sin\delta_{ij}) = 0 \quad (9)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} V_i V_j (G_{ij}^{new} \sin\delta_{ij} - B_{ij}^{new} \cos\delta_{ij}) = 0 \quad (10)$$

$$V_i^{min} \le V_i \le V_i^{max} \quad (11)$$

$$S_{ij} \le S_{ij}^{max} \quad (12)$$

Where

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

3 Optimal Location of TCSC

Because of cost for these devices is high, the best location of TCSC is an important issue in the deregulated electricity markets. In order to reduce search space and improve transfer capability, TCSC need to be installed at the bottleneck location of power system. This is the location that demonstrates maximum possible power flow from source(s) to sink(s). When the system load is increased, the bottleneck is the first location where congestion occurs. Therefore, in order to eliminate/alleviate congestion, the transfer capability at the bottleneck should be examined.

3.1 Min Cut Algorithm

Using the Min-cut algorithm to find the minimum cut has been introduced in [14]. In this paper, the Min-cut algorithm will be used to determine the minimum cut 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 its smallest. In other words, the power system can satisfy sufficient the power to the loads, but due to the limit of the minimum cut, so maximum possible power flow from source(s) to sink(s) equals the minimum cut value for all the cuts in the network. Therefore, if the minimum cut is identified, the branch that has the ability to install TCSC will be recognized.

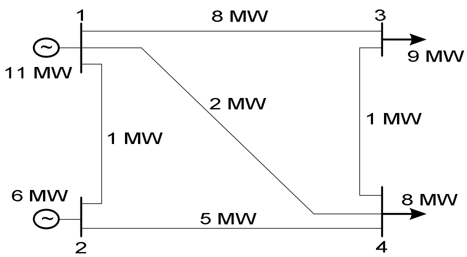

Fig. 2. Example power system with generators of 11 at 1 and 6 at 2 and loads of 9 and 8

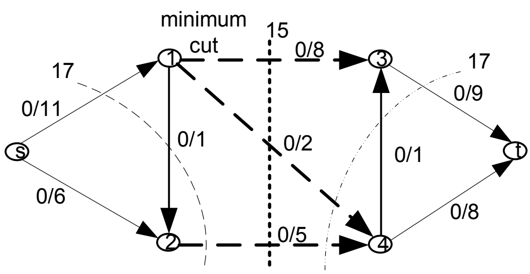

Fig. 3. The modeling of an example power system

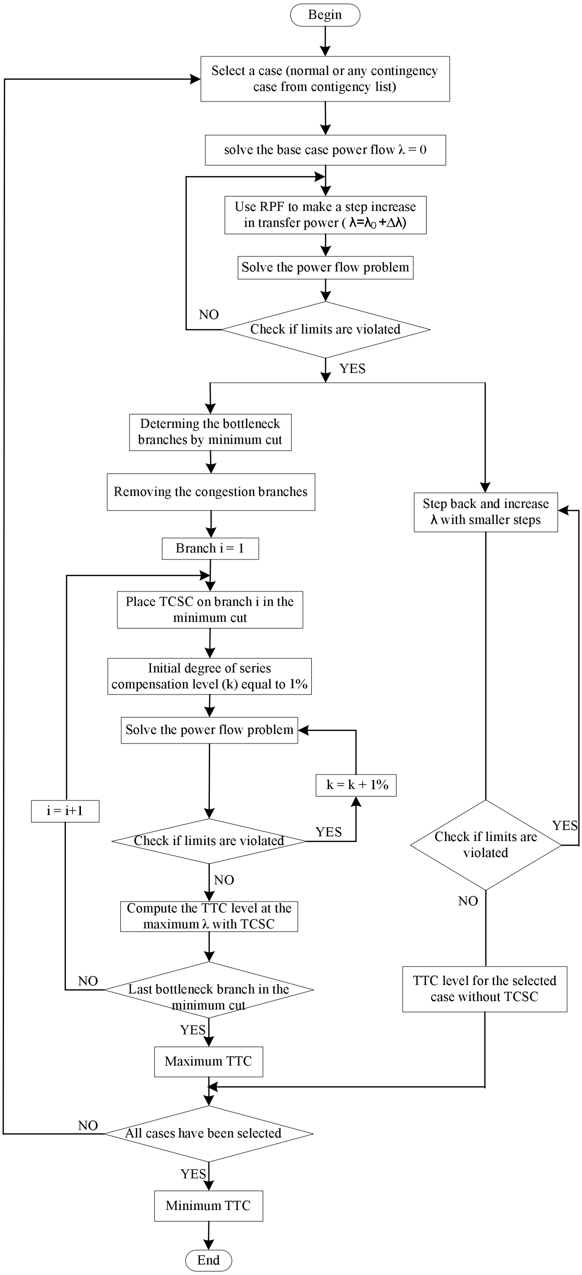

Fig. 4. Flow chart for power transfer capability with TCSC and without TCSC

3.2 Modeling Power Network Using Min Cut Algorithm

The power system is modeled as a directed network G(N,A) where defined by a set N of n nodes and a set A of m directed arcs. Each arc $a_{ij} \in A$ has a capacity u_{ij} that shows the maximum amount that can flow between node i and j. The Min cut algorithm is added two nodes, the virtual source and the virtual sink, representing the combination of the generators and loads, respectively. Each line out of the virtual source has a maximum flow that matches the generation of the connected node, and each line into the virtual sink represents the load demanded by the connected node. The modeling of an example power system depicted in Figure 2 is shown in Figure 3. The details for determination the bottleneck of power system by Min cut algorithm can refer in [15]. The flow chart of the proposed method for the calculation of total transfer capability with and without TCSC is given in Figure 4.

4 Case Study and Discussions

The proposed method for the optimal location of the TCSC to evaluate TTC has been implemented on IEEE 14- and IEEE 30- bus test systems. The TTC is computed for a set of source/sink transfers (bus to bus, area to area, contingencies).

4.1 IEEE 14-Bus Test System

System data can be found in [8].

Table 1. TTC from bus to bus without and with TCSC placed in best location in the minimum cut

Source/Sink Bus No.	TTC (MW) without TCSC	Violated limits	TTC with TCSC	TCSC Location	Compensation	Minimum cut
1/9	51.3	Line 8	69.98	Line 9	-0.086	Line 8, 9,11,12
1/10	45.9	Line 8	63.75	Line 12	-0.075	Line 8, 9,11,12
1/12	32.6	Line 8	48.13	Line 9	-0.122	Line 8, 9,11,12
1/13	32.8	Line 8	49.52	Line 9	-0.122	Line 8, 9,11,12
1/14	41.3	Line 8	58.36	Line 12	-0.115	Line 8, 9,11,12
1/4	239.7	Line 1	256.11	Line 3	-0.074	Line 1, 3,4,5
1/3	164.6	Line 2	216.84	Line 6	-0.083	Line 2, 3,5,6

According to Table 1, when TCSC is not placed, the TTC (from bus to bus) can only be achieved as shown in Table 1(Column 2). With this TTC level, it was found that the some lines in Table 1 (Column 3) are violated line thermal limit. This impeded transfer capability of power system. Therefore, by placing TCSC on proper location (the branch with great capacity in the minimum cut) to redirect the power flow through un-congested transmission line(s) is a method which rapidly rebalances the power and improve TTC.

When the minimum cut is not considered, there are 20 possible locations to place one unit of TCSC. However, the number of branches which need to be investigated to determine the location of TCSC has significantly been decreased after the minimum cut is considered. Observation of Table 1 shows that the location in Column 5 is the best location for placement TCSC since it giving maximum TTC. It can be observed from Table 1 (Column 4) that, after optimal placement of TCSC, the TTC has been improved which is more than as compared with the result in [8].

4.2 IEEE 30-Bus Test System

The network and load data for IEEE 30-bus are given in [16].

Table 2. Test results of bilateral transaction from bus 2(area 1) to bus 21(area 3) of the IEEE 30 bus test system

Objectivefunction	Without TCSC	With TCSC	TCSC Location	TCSC setting (p.u.)	Minimum cut
Max. TTC	26.68	33.42	Line 28-27	-0.3369	Line 28-27, 10-9, 10-6

Table 2 shows the test results of bilateral transaction from bus 2 to bus 21. From this Table it can be observed that, TTC in the case without TCSC is obtained 26.68 MW. However, it is improved after installing TCSC at suitable location by using the minimum cut. As per the procedure mentioned in the previous sections, line 28-27 is one of the lines in the minimum cut which have a direct effect on TTC. Therefore this line is selected to install TCSC. The degree of series compensation for improving TTC was taken as -0.3369 pu. According to the Table 2 it can see that, the TTC in the case with TCSC is increased to 33.42MW without violating system constraints.

Table 3. Test results of multilateral transaction from area 3 to area 2 of the IEEE 30 bus test system

Case	TTC level without TCSC	TTC without TCSC	TCSC Location	TCSC setting (p.u.)	TTC level with TCSC	TTC with TCSC	Minimum cut
Normal	76.52		Line 23-24	-0.1143	85.6		
Largest generator G6 outage in area 2	56.23	56.23	Line 10-17	-0.2109	62.41	62.41	Line 10-17, 10-20, 23-24
Tie-line 23-24 outage	56.85		Line 10-20	-0.1148	65.25		

Furthermore, results of multilateral transaction from area 3 to area 2 are showed in Table 3. It was observed from this Table that, TTC value in the case without TCSC is obtained 56.23 MW. However, it is increased to 62.41 MW after placing TCSC on the line in the minimum cut. Optimal TCSC setting is -0.2109 p.u and location is line 10-17.

It can be observed from Table 3 (Column 3) and Table 3 (Column 7) that, the proposed method also captures the best location for the placement of TCSC as compared with the result in [16]. However, the number of branches which need to be investigated to determine the location of TCSC has reduced which is less than as compared with [16].

5 Conclusions

In deregulated power systems, System Operators face the challenge of finding effective ways of enhancing total transfer capability for congestion management. TCSC has been considered one of the effective methods to solve this issue. An efficient solution for the transfer capability enhancement in deregulated electricity market has been presented.

The study results on IEEE14- and IEEE 30-bus system have proved the effectiveness of the method. The proposed method is capable of finding the best location for TCSC installation to enhance the TTC. Only some lines in the minimum cut need to be examined in detail to assess the best location. Using this method, the search scope is limited hence the number of branches which need to be investigated to determine the location of TCSC has been significantly decreased.

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