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PSO based Congestion Management in Deregulated Power Systems using Optimal Allocation of TCSC

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ABSTRACT: Congestion in the transmission lines is one of the technical problems that appear particularly in the deregulated environment. One of the congestion management methodologies is installing Thyristor Controlled Series Compensator (TCSC) devices into the system. The major objective in applying TCSC is to increase power transfer capacity in critical tie-lines under contingency conditions. Under normal steady state conditions, it can be used to damp Sub-Synchronous Resonance by converting a part of the fixed compensation to controllable series compensation. In this paper, a novel method using Particle Swarm Optimization (PSO) algorithm is proposed to determine the optimal allocation of TCSC devices for maximizing the Available Transfer Capability (ATC) of power transactions between source and sink areas in the deregulated power system. The algorithm simultaneously searches the location, size and cost of TCSC devices. ATC is calculated using AC Power Transfer Distribution Factors (ACPTDF). The effectiveness of the proposed method is demonstrated using a modified IEEE 30 bus test system in normal and contingency conditions for the selected bilateral, multilateral and area wise transactions. The simulation results show that the introduction of TCSC devices in a right location could enhance ATC, reduced total losses and improve the line congestion as compared to that of the system without TCSC devices.

KEYWORDS: Available Transfer Capability, Independent System Operator, Thyristor Controlled Series Compensator, Particle Swarm Optimization, Power Transfer Distribution Factors.

1 INTRODUCTION

The power system operation faces new challenges due to deregulation and restructuring of the electricity markets. The deregulated power system consists of Generation companies (Gencos), Distribution companies (Discos), Transmission companies (Transcos) and Independent System Operator (ISO) with an open assess policy. The power flow pattern in deregulated environment is different from those in existing regulated one. All parties will try to get the benefits of cheaper source and greater profit margins leading to overloading and congestion of certain transmission corridors. The role of ISO is to relieve that congestion so that the system is maintained in a secure state. To relieve the congestion, ISO can use either cost-free or non-cost free means. In Cost-free means have advantages in that no extra cost is incurred in relieving the congestion and Gencos and Discos do not come in to picture [1-3]. In order to facilitate the electricity market operation and trade in the restructured environment, ample transmission capability should be provided to satisfy the demand of increasing power transactions. The conflict of this requirement and restrictions on the transmission expansion in the restructured electricity market has motivated the development of methodologies to estimate ATC of the existing transmission girds. For transmission networks, one of the major consequences of the non-discriminatory open-access requirement is a substantial increase of power transfers, which demand adequate ATC to ensure all economic transactions. Sufficient ATC should be guaranteed to support free market trading and maintain an economical and secure operation over a wide range of system conditions [4, 5]. However, tight restrictions on the construction of new facilities due to the increasingly difficult economic, environmental, and social problems, have led to a much more intensive shared use of the existing transmission facilities by utilities and independent power producers (IPPs). These concerns have motivated the development of strategies and methodologies to boost the ATC of the existing transmission networks. Various mathematical models have been developed by the researcher to determine the ATC of the transmission system based on conventional power system equations. Recently the distribution factors based on DC and AC power flow methods [6-9] have been proposed for calculating ATC. In this paper, the Power Transfer Distribution Factor (PTDF) using AC power flow are derived to calculate ATC using sensitivity properties of Newton Raphson Load Flow (NRLF) Jacobean.

Flexible Alternating Current Transmission Systems (FACTS) devices are proved to be very useful in achieving the control of power flows without disturbing the generation scheduling or topological changes and in addition these devices will also enhance the secured operation of power system [10, 11]. FACTS devices, despite minimizing line congestion and maximizing the transfer capability, assure that contractual constraints and targets are satisfied fairly. FACTS devices not only provide solutions for efficiently increasing transmission system capacity but also increase ATC, relieve congestion, improve reliability and enhance operation and control. Moreover, it is important to ascertain the location for placement of these devices because of their considerable costs. However, it is hard to determine the optimal allocation and parameters of FACTS devices due to the complicated combinatorial optimization. Thus, attention is paid in this current work to study a technique to optimally allocate the devices to enhance ATC. The task of calculating ATC is one of main concerns in power system operation and planning. ATC is determined as a function of increase in power transfers between different systems through prescribed interfaces. The insertion of such devices in electrical systems seems to be a promising strategy to increase ATC [12, 13]. In this paper, a TCSC is used for enhance the ATC and improving line congestion.

Some of the researchers have discussed the heuristic optimization algorithms that are used to locate FACTS devices in power systems [14-16], such as the Simulated Annealing (SA , Tabu Search (TS), Evolutionary programming (EP), Genetic Algorithm (GA) and recently Particle Swarm optimization (PSO) to solve simple and complex problems efficiently and effectively. However, unlike SA, TS, EP and GA, each individual in PSO flies in search space with a velocity which is dynamically adjusted according to its own flying experience and its companions flying experiences. The main merits of PSO are its fast convergence speed and it can be realized simply as less parameters need adjusting. The PSO algorithm was first introduced by Eberhart and Kennedy [17, 18]. In this paper, PSO technique is used to find optimal location and size of TCSC to achieve maximization of ATC, decrease the line congestion and total power loss. This paper is divided into several sections. Section 2 elaborates the Available Transfer Capability. Section 3 describes computational procedure for ATC determination while Section 4 presents mathematical model of the TCSC Device. Section 5 presents problem formulations of optimum allocation of TCSC devices. The procedure of PSO algorithm to allocate FACTS devices is discussed in Section 6. The simulation results are presented and discussed briefly in Section 7.

2 AVAILABLE TRANSFER CAPABILITY

Available Transfer Capability (ATC) is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above the already committed uses [7, 8]. ATC evaluation is important because it is the point where power system reliability meets electricity market efficiency. ATC can have a huge impact on market outcomes and system reliability, so the results of ATC are of great interest to all involved. ATC can be expressed as:

$$ATC = TTC - TRM - CBM - ETC \tag{1}$$

Where Total Transfer Capability (TTC) is the maximum transfer power that does not reach the limits, Existing Transmission Commitment (ETC) is the sum of the available transmission commitment between 2 areas, Transmission Reliability Margin (TRM) is the amount of transmission capability that is required to ensure that the interconnected system is secure under an acceptable range of uncertainty and Capacity Benefit Margin (CBM) is the amount of transmission that is reserved by the load to ensure access to the generation from interconnected systems to meet the requirement of the generation reliability. Utilities would have to determine adequately their ATC's to guarantee that system reliability is maintained while serving a wide range of transmission transactions. ATC between and within areas of the interconnected power system and ATC for critical transmission paths between these areas would be continuously updated and posted about changes in scheduled power transfers between the areas. ATC at base case, between bus *m* and bus *n* using line flow limit (thermal limit) criterion is mathematically formulated using AC Power Transfer Distribution Factors (ACPTDF).

3 ATC DETERMINATION USING AC POWER TRANSFER DISTRIBUTION FACTORS

AC Power Transfer Distribution Factors (ACPTDF) determines the linear impact of a transfer (or changes in power injection) on the elements of the power system. These values provide a linearized approximation of how the flow on the transmission lines and interfaces change in response to transaction between the seller and buyer. For a single area ATC, the transaction will be between seller bus and buyer bus present in the area and for multi-area ATC, the transaction will be between two areas. The proposed AC power transfer distribution factors method is used for calculation of ATC for a change in MW transaction at different operating conditions. Consider a bilateral transaction t_k between a seller bus *m* and buyer bus *n.* Line '*l*' carries the part of the transacted power and is connected between buses *i* and *j*. For a change in real power, transaction among the above buyer and seller by Δt_k MW, if the change in a transmission line quantity (real power flow) q_1 is Δq_1, power transfer distribution factors can be defined as,

$$PTDF_{ij,mn} = \frac{\Delta q_l}{\Delta t_k} \tag{2}$$

The transmission quantity q_l can be either real power flow from bus *i* to *j* (P_{ij}) (or) real power flow from bus *j* to bus *i* (P_{ji}). The above factors have been proposed to compute at a base case load flow with results using sensitivity properties of NRLF Jacobian. Consider full Jacobian in polar coordinates [J_T], defined to include all the buses except slack (including ΔQ-ΔV equations also for PV buses). We get the following

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J_T]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3}$$

In a base case load flow, if only one of the k^{th} bilateral transactions is changed by Δt_k MW, only the following two entries in the mismatch vector on RHS of (3) will be non zero.

$$\Delta P_i = \Delta t_k \qquad \Delta P_j = -\Delta t_k \tag{4}$$

With the above mismatch vector elements, the change in voltage angle and magnitude at all buses can be computed from (3) and (4) and, hence, the new voltage profile can be calculated. These can be utilized to compute all the transmission quantities q_l and hence the corresponding changes in these quantities, Δq_l, from the base case. Once the Δq_l for all the lines corresponding to a change in transaction Δt_k is known, PTDFs can be obtained from (2). These ACPTDFs, which are computed at a base load flow condition, have been utilized for computing change in transmission quantities at other operating conditions as well. ACPTDF is also calculated for multilateral transaction in which group of sellers have a bilateral contract with group of buyers. The change in multilateral transaction can be assumed to be shared equally by each of the sellers and buyers. However, the transaction amount can be shared in any pre-decided ratio in a deregulated environment. The mismatch vector for the multilateral transactions will have non zero entries corresponding to the buyer and seller buses. The rest of the procedure for calculation of ACPTDF will be the same as outlined above the bilateral transaction case. The ATC is then calculated as follows

$$ATC_{mn} = \min\left(T_{ij,mn}\right),\ ij \in N_L \tag{5}$$

Where $T_{ij,mn}$ denotes the transfer limit values for each line in the system. It is given by

$$T_{ij,mn} = \begin{cases} \dfrac{\left(P_{ij}^{\max} - P_{ij}^{0}\right)}{ACPTDF_{ij,mn}} & ; \quad ACPTDF_{ij,mn} > 0 \\ \infty \ (\text{infinite}) & ; \quad ACPTDF_{ij,mn} = 0 \\ \dfrac{\left(-P_{ij}^{\max} - P_{ij}^{0}\right)}{ACPTDF_{ij,mn}} & ; \quad ACPTDF_{ij,mn} < 0 \end{cases} \tag{6}$$

Where, P_{ij}^{max} is the MW power limit of a line between bus *i* and *j*, P_{ij}^{o} is the base case power flow in the line between bus *i* and *j*, $ACPTDF_{ij,mn}$ is the power transfer distribution factor for the line between bus *i* and *j* when a transaction is taking place between bus *m* and *n*. N_L is the total number of lines. ACPTDF as given in equation (6) is operating point dependent and computed using Jacobian inverse. $ACPTDF_s$ remain fairly constant for reasonable variations in power injections.

4 MODELING OF THYRISTOR CONTROLLED-SERIES CAPACITOR DEVICES

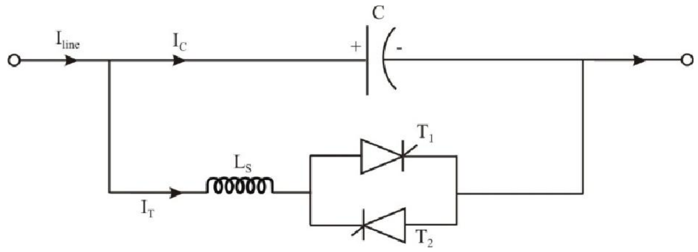

Fig 1. Basic structure of Thyristor controlled-series capacitor

Thyristor controlled-series capacitor (TCSC) is a series connected FACTS device in which a capacitor is connected in series with the transmission line and a parallel connection of thyristor-controlled inductor with the capacitor is shown in Fig 1. TCSC is connected in series with the line conductors to compensate for the inductive reactance of the line. It may have one of the two possible characteristics namely capacitive or inductive, respectively to decrease or increase the reactance of the line X_{line} respectively. The rating of TCSC is depends on transmission line where it is located. To prevent overcompensation, TCSC reactance is chosen between-0.8 X_{line} to 0.2 X_{line} Moreover, in order not to overcompensate the line, the maximum value of the capacitance is fixed at -0.8 X_{line} while that for inductance, it is 0.2 X_{line}. The rated value of TCSC where it is located is given by

$$X_{ij} = X_{Line} + X_{TCSC} \tag{7}$$

$$X_{TCSC} = \gamma_{TCSC} * X_{Line} \tag{8}$$

Where, X_{Line} is the reactance of the transmission line and γ_{TCSC} is the compensation factor of TCSC. The power flows in heavily loaded line can be reduced by TCSC through power flow control in the network. The power flow control with the TCSC is used to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactive correspondingly. Fig.2 shows a model of transmission line with one TCSC which is connected between bus-i and bus-j.

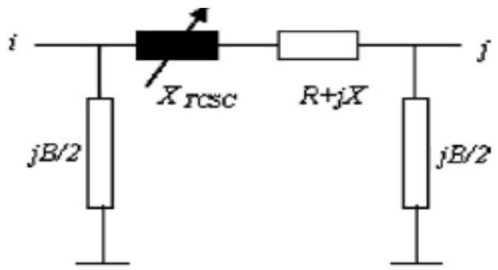

Fig.2 Single line diagram of power flow control with TCSC

The power flow equations of TCSC are given by

$$P_{ij} = V_i^2\, g_{ij} - V_i V_j\, (g_{ij} \cos_{ij} + b_{ij} \sin_{ij}) \tag{9}$$

$$Q_{ij} = V_i^2\, b_{ij} - V_i V_j\, (g_{ij} \sin_{ij} + b_{ij} \cos_{ij}) \tag{10}$$

Where, V_i and V_j are voltage of i^{th} and j^{th} bus respectively

5 PROBLEM FORMULATION

As stated in section 2, ATC is defined as the additional power that can be transmitted through a specified interface over and above the already committed transactions. The problem of ATC computation in bilateral and multilateral transaction can be formulated as an optimization problem in which the objective is to maximize the difference between TTC and ETC without violating the constraints. The aim of the optimization is to perform the best utilization of the existing transmission lines. The objective is to maximize the ATC i.e., uncommitted active transfer capacity of the prescribed interface, when a transaction is taking place between a seller bus (m) and buyer bus(n). The objective function to be maximized is expressed as

$$J = Maximize \ \ (ATC_{mn}) \tag{11}$$

Where ATC for each bilateral transaction between a seller at bus (m) and power purchaser at bus (n) satisfies the following power balance relationship:

$$P_{Di} - P_{Di}^{0} = 0, \qquad \forall_{i} \in t_{k} \tag{12}$$

It is subjected to

Eqn (13) and (14) as equality constraints such as the power flow equations at bus i,

$$P_{Gi} - P_{Di} - \sum_{j=1}^{nb} |V_i||V_j||Y_{ij}| \cos\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{13}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{nb} |V_i||V_j||Y_{ij}| \sin\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{14}$$

P_{Gi}, Q_{Gi} is real and reactive power generation at bus i, P_{Di}, Q_{Di} is real and reactive loads at bus i, $|V_i|, |V_j|$ Voltage magnitude at bus i and bus j. $|Y_{ij}|, \theta_{ij}$ is magnitude and phase parts of the ijth element of the bus admittance matrix. δ_i, δ_j is voltage angle of bus i and bus j, respectively. *nb* is the total number of buses. In Eqn (15), (16) and (17) are inequality constraints, which ensure the system real, reactive power flow and bus voltage limitations, respectively.

$$P_{Gi}^{\min} \ \le \ P_{Gi} \le \ P_{Gi}^{\max} \qquad for \ \ i = 1,2.......n_g \tag{15}$$

$$Q_{Gi}^{\min} \ \le \ Q_{Gi} \le \ Q_{Gi}^{\max} \qquad for \ \ i = 1,2,........n_g \tag{16}$$

$$V_b^{\min} \ \le \ V_b \le \ V_b^{\max} \qquad for \ b \ = 1,2....... \ n_b \tag{17}$$

The constraints on the TCSC devices used in this work are given below:

$$-0.8 \ X_{Line} \ \le X_{TCSC} \le 0.2 \ X_{Line} \ \ \ p.u. \tag{18}$$

Where, X_{TCSC} is the reactance added to the line by placing TCSC, X_{Line} is the Reactance of the line where TCSC is located. To prevent overcompensation, TCSC reactance is chosen between $-0.8X_{Line}$ to $0.2X_{Line}$.

The constraints on the installation cost of the corresponding TCSC devices are given by,

$$IC = C * S * 1000 \tag{19}$$

where *IC* denotes optimal installation cost of TCSC devices in US$. *C* represents cost of installation of TCSC devices in US $/KVar; S is the operating range of TCSC devices in MVAR and it is given by

$$S = |Q_1| - |Q_2| \tag{20}$$

Where Q_2 is the reactive power flow in the line after installing TCSC device in MVAR and Q_1 represents reactive power flow in the line before installing TCSC device in MVAR. The cost of installation of TCSC are taken from Siemens data base and reported in [21]. The cost of installation of TCSC devices are given by the following equations:

$$C_{TCSC} = 0.0015 \ S^2 - 0.713 \ S + 153.75 \tag{21}$$

6 OPTIMAL PLACEMENT OF TCSC USING PARTICLE SWARM OPTIMIZATION ALGORITHM

6.1 OVER VIEW OF PSO ALGORITHM

The Particle Swarm Optimization algorithm is a simple, fast and efficient population based optimization method which was proposed by by Kennedy and Eberhart [17]. The basic assumption behind the PSO algorithm is that birds find food by flocking and not individually. This leads to the assumption that information is owned jointly in the flocking. The swarm initially has a population of random solution. Each potential solution, called a particle (agent) is given a random velocity and is flown through the problem space. All the particles have memory and each particle keeps track of its previous best position (P_{best}) and the corresponding fitness value. The swarm has another value called (G_{best}), which is the best value of all P_{best}. It has been found to be extremely effective in solving a wide range of engineering problems and solves them very quickly. At each time step, the particle swarm optimization consists of velocity changes of each particle towards its P_{best} and G_{best} [19, 20]. After finding the best values, the particle updates its velocity and position according to the following equations:

$$V_i^{k+1} = w * V_i^k + C_1 * rand_1 * (P_{best_i} - S_i^k) + C_2 * rand_2 * (G_{best_i} - S_i^k) \quad (22)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \quad (23)$$

Where, Vi^{k+1} is the velocity of i^{th} individual at $(k + 1)^{th}$ iteration, Vi^k is the velocity of ith individual at k^{th} iteration, W is the inertia weight, C_1 and C_2 are the positive constants having values (0, 2.5), $rand_1$ and $rand_2$ are the random numbers selected between 0 and 1, P_{besti} is the best position of the i^{th} individual, G_{best} is the best position among the individuals (group best) and S_i^k is the position of i^{th} individual at k^{th} iteration. The acceleration coefficients C_1 and C_2 control how far a particle will move in a single iteration. Typically, these are both set to a value of 2.5. The velocity of each particle is modified according to (22) and the minimum and maximum velocity of each variable in each particle is set within the limits of V_{min} and V_{max} respectively. The position is modified according to (23). The inertia weight factor "w" is modified using (24) to enable quick convergence.

$$w = w_{\max} - \frac{(w_{\max} - w_{\min})}{iter_{\max}} * iter \quad (24)$$

Where w_{max} is the initial value of inertia weight equal to 0.9, w_{min} is the final value of inertia weight equal to 0.4, *iter* is the current iteration number and $iter_{max}$ is the maximum iteration number. Small values of *w* result in more rapid convergence usually on a suboptimal position, while a too large value may prevent divergence of solution. The PSO system combines two models; a social-only model and a cognition-only model. These models are represented by the velocity update, shown in (22).

6.2 STEP BY STEP ALGORITHM TO OPTIMALLY LOCATE TCSC FOR MAXIMIZING ATC USING PSO

Step 1: Input the data of Transmission line, generators buses and loads. Choose population size of particles, maximum number of iterations and convergence criterion. Define type of transactions.

Step 2: Select reactance setting and location (line number) of TCSC as control variables.

Step 3: Randomly generate population of particles with their variables in normalized form (i.e., between 0 to 1)

Step 4: Randomly install one TCSC devices in the Transmission line and check that TCSC device is not employed on the same line more than once in each iteration. Find demoralized value (actual value) of TCSC reactance and location of TCSC using the following Equation.

$$X_{Denormalized} = X_{\min} + (X_{\max} - X_{\min}) * X_{normalized} \quad (25)$$

Where X_{min}, X_{max} are minimum and maximum values of the variable X is TCSC reactance respectively. Demoralized value of location of TCSC is rounded to nearest integer during optimization. Modify the bus admittance matrix.

Step 5: Run Newton-Raphson load flow to get line flows, active power generations, reactive power generations, line losses and voltage magnitude of all buses.

Step 6: Calculate the ATC of each particle using Eqn (5).

Step 7: Calculate the objective function of each particle subject to satisfy the constraints using Eqn (11).

Step 8: Find out the global best (G_{best}) particles having maximum value of objective function in the population and personal best (P_{best}) of all particles.

Step 9: Update the velocity and position of each particle using Eqn (22) and (23).

Step 10: Go to Step 4 until maximum number of iterations are completed.

Step 11: The objective function of (G_{best}) particle is the optimized (maximum) value of ATC. Coordinates of (G_{best}) particle give optimal setting and location of TCSC respectively and also calculate cost of installation of TCSC using (21).

7 SIMULATION RESULTS AND OBSERVATIONS

This section present the details of the simulation study carried out on a modified IEEE 30-bus system for ATC computation under normal operating condition and line outage condition used for proposed approach. The test system consists of six generators and forty one lines as shown in Fig 3. The system data are in a per-unit system and taken from [21] and the base MVA value is assumed to be 100 MVA. Generators at buses 8, 11 and 13 are considered in area 1, while the remaining generators at buses 1, 2 and 5 are considered in area 2. The tie-lines existing between the two areas are shown in Fig 4. Transaction is carried out between Area 1 and Area 2. Three inequality constraints such as voltage limit, line thermal limit, and reactive power generation limit are considered. The voltage magnitude limit of each bus is assumed to be within 0.95 pu and 1.05 pu. The optimal location and size of TCSC devices are obtained using PSO Algorithm for maximizing ATC based on the selected bilateral, multilateral and area wise transactions. Installation cost of TCSC devices has also been calculated for each transaction with reference to ATC value and cost of installation. The simulations studies were carried out on Intel Pentium Dual Core, 2.40 GHz system in a MATLAB 2010a environment.

Case 1: Normal operating conditions

The test system results for different bilateral and multilateral transactions under normal operating conditions using proposed approach are given in Table 1 and Table 2. In bilateral transactions, five transactions between a seller bus in source area and buyer bus in sink area such as (11-27, 2-10, 5-20, 2-23 and 8-30) with the objective function (11) to maximize the ATC without and with TCSC device using PSO algorithm have been considered. Table 1 shows the test results of bilateral transactions for five transactions. Consider a bilateral transaction from bus 11 to bus 27, the ATC value is 40.06 MW without installing TCSC, whereas after installing TCSC the ATC value is increased to 43.38 MW without violating system constraints. The active power losses is 9.2 MW without placing TCSC, but it is reduced to 8.1 MW after placing TCSC and optimal location of TCSC is between bus 6 to bus 28. The optimal size (reactance) of TCSC is -0.035 p.u and negative sign indicates that TCSC operates in capacitive mode and the corresponding cost of installation of TCSC devices is 6.33 $\times 10^6$ US \$. From Table 1 and Fig 5, it can be clear that ATC values are increased for all possible bilateral transaction and active power losses are reduced after placing TCSC devices in right location. In multilateral transactions between a seller buses in source area and buyer buses in sink area such as (8, 13 - 27, 20 and 2, 8, 13 - 23, 27) with maximize the ATC is considered. A multilateral transaction from buses 8, 13 to buses 27, 20 consider. In this case the ATC value is 18.456 MW without installing TCSC, whereas after installing TCSC the ATC value is increased to 22.931 MW without violating system constraints and optimal location of TCSC is connected between bus 22 to bus 24 and size (reactance) of TCSC is -0.089 p.u and the corresponding cost of installation of TCSC devices is 8.56 $\times 10^6$ US \$ as shown in Table 2. The PSO convergence curve for this transaction utilizing TCSC devices is shown in Fig 6. From Table 2, it is obvious that TCSC is maximizing ATC and reducing power loss with minimum installation cost there by improving line condition for multilateral transactions also.

Case 2: contingency operating conditions

For a contingency case, the branch line outage between buses 9 and 10 is considered. In this case, the line connected between bus 9 and bus 10 is removed. The corresponding ATC values for the test system without and with TCSC for bilateral and multilateral transactions with line outage conditions are given in Tables 3 and 4 respectively. The active power loss for different bilateral transactions without and with TCSC devices is shown in Fig 7. From the Tables 3 and 4 and Fig 7 indicate that optimally placed TCSC devices by PSO significantly increase ATC, reduced active power losses under contingency conditions.

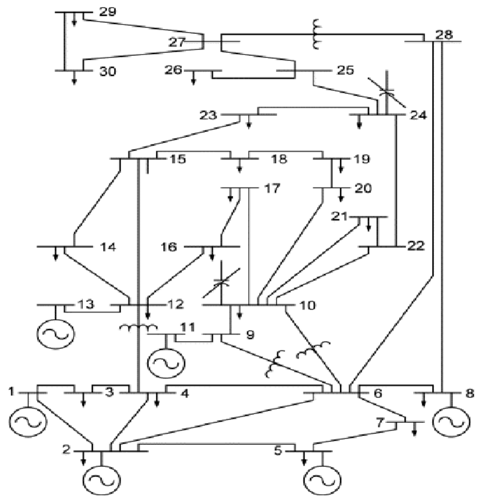

Fig 3. Single line diagram of the modified IEEE 30-bus system

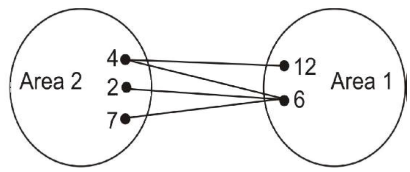

Fig 4. Tie-line between areas- IEEE 30 bus s

Table 1. ATC enhancement results for bilateral transactions under normal operating conditions

Transactions			ATC in MW		Placement of TCSC devices		Settings (X_{tcsc}) in p.u	Installation Cost (x10^6 US $)
No	Source bus	Sink bus	without TCSC	With TCSC	From bus	To bus		
T1	11	27	40.0689	43.3843	6	28	-0.0350	6.33
T2	2	10	78.4095	83.8036	16	17	-0.2898	1.36
T3	5	20	32.2021	36.9624	15	18	-0.1093	0.81
T4	2	23	20.1865	33.4703	15	23	-0.1262	8.06
T5	8	30	17.9993	20.8026	27	30	0.2696	0.06

Table 2. ATC enhancement results for multilateral transactions under normal operating conditions

Transactions			ATC in MW		Placement of TCSC devices		Settings (X_{tcsc}) in p.u	Installation Cost (x10^6 US $)
No	Source bus	Sink bus	without TCSC	With TCSC	From bus	To bus		
T1	8, 13	27, 20	18.456	22.931	22	24	-0.0895	8.56
T2	2, 8, 13	23, 27	11.765	17.183	15	23	-0.1132	6.26

Table 3. ATC enhancement results for bilateral transactions with line outage of 9-10

Transactions			ATC in MW		Placement of TCSC devices		Settings (X_{tcsc}) in p.u	Installation Cost (x10^6 US $)
No	Source bus	Sink bus	without TCSC	With TCSC	From bus	To bus		
T1	11	27	26.3458	31.2751	6	28	0.0297	8.22
T2	2	10	14.3888	22.4373	16	17	-0.0966	0.03
T3	5	20	13.2934	16.7312	15	18	-0.1093	0.99
T4	2	23	15.1709	16.9660	15	23	-0.1010	1.72
T5	8	30	17.7950	20.5497	27	30	0.2651	1.97

Table 4. ATC enhancement results for multilateral transactions with line outage of 9-10

Transactions			ATC in MW		Placement of TCSC devices		Settings (X_{tcsc}) in p.u	Installation Cost (x10^6 US $)
No	Source bus	Sink bus	without TCSC	With TCSC	From bus	To bus		
T1	8, 13	27, 20	10.803	11.387	15	18	-0.1496	0.21
T2	2, 8, 13	23, 27	8.7514	10.355	15	23	0.0694	0.07

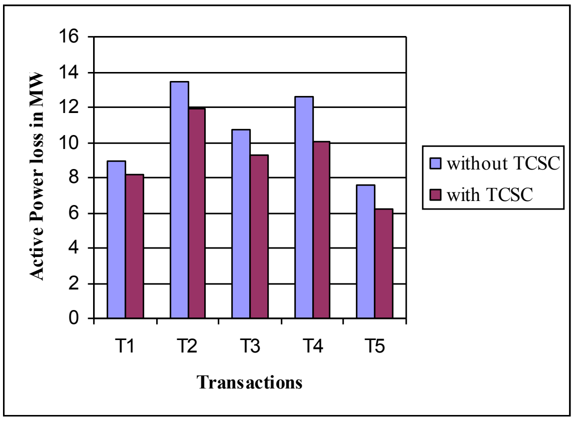

Fig 5. Active Power Loss (bilateral Transaction) for IEEE 30 bus system Base case

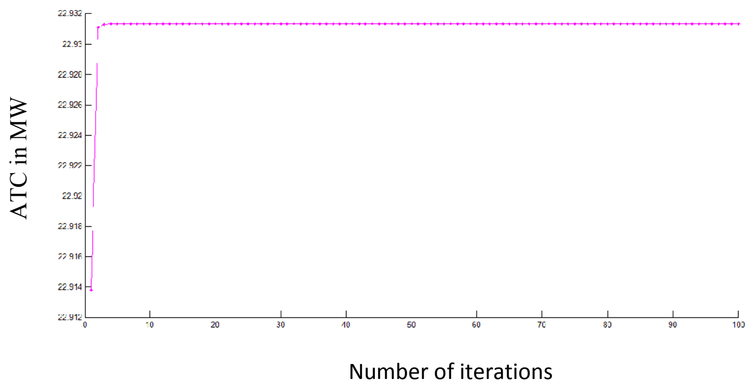

Fig 6. PSO convergence curve for multilateral transactions with TCSC under normal operating condition

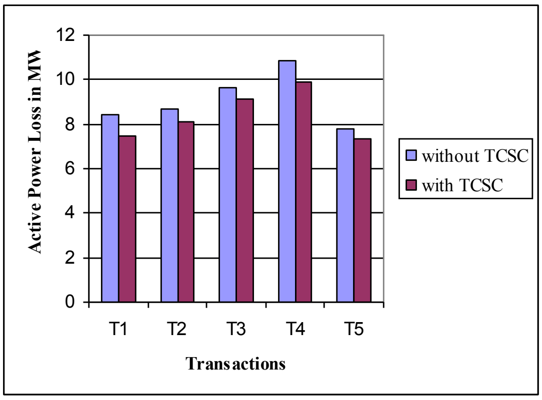

Fig 7. Active Power Loss (bilateral Transaction) for IEEE 30 bus system with line outage of 9-10

8 CONCLUSION

To facilitate the deregulated electricity market operation, control and trading, sufficient transmission line capability should be provided to satisfy increasing demand of power transactions reliably. PSO based algorithm has been is used to find optimal placement and setting of TCSC device for maximizing ATC and minimizing the active power losses of the competitive electricity market which consists of bilateral and multilateral transactions. The simulation results indicate that optimally placed TCSC by PSO could significantly increase ATC and reduced power losses under normal and contingency conditions. Moreover, PSO exhibits robust convergence characteristic so it could be used effectively to select optimal location of TCSC for enhancement of ATC, thereby improving transmission services of the competitive electricity market.

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