ADVANCES in NATURAL and APPLIED SCIENCES

ISSN: 1995-0772
EISSN: 1998-1090
2016 September 10(13): pages 81-92

Published BY **AENSI Publication**
http://www.aensiweb.com/ANAS
Open Access Journal

Optimal Allocation of TCSC and SVC devices for Congestion Management in deregulated power systems

[1]K. Vetrivel, [2]S.Ganapathy, [3]K. Uma Rao

[1]Assistant Professor, National Power Training Institute / PSTI, Bangalore, Karnataka, India.
[2]Professor, Department of Electrical Engineering, Annamalai University, Tamil nadu, India.
[3]Professor, Department of Electrical and Electronics Engineering, RV Institute of Technology, Bangalore, India.

Received 7 June 2016; Accepted 12 September 2016; Available 20 September 2016

Address For Correspondence:
K. Vetrivel, Assistant Professor, National Power Training Institute / PSTI, Bangalore, Karnataka, India
Email: eluswamy@gmail.com, Phone no: +91-9449017475

Copyright © 2016 by authors and American-Eurasian Network for Scientific Information (AENSI Publication).
This work is licensed under the Creative Commons Attribution International License (CC BY).
http://creativecommons.org/licenses/by/4.0/

Open Access

ABSTRACT

Congestion management is one of the most important issues for secure and reliable system operations in a deregulated electricity market. This paper investigates the use of Flexible AC Transmission Systems (FACTS) devices, such as Thyristor Controlled Series Compensators (TCSC) and Static Var Compensator (SVC), to maximize power transfer transactions during normal and contingency conditions. The introduction of FACTS devices in a right location could enhance Available Transfer Capability (ATC) and result in reduction of total losses and improved stability of the system. The major objective in applying TCSC is to increase power transfer capacity in critical tie-lines under contingency conditions. The goal of SVC is a power quality device, which has the ability to provide fast-acting reactive power compensation on electrical systems where it is connected. Particle Swarm optimization (PSO) algorithm is used as an optimization tool to determine the location and controlling parameters of TCSC and SVC. The effectiveness of the proposed method is demonstrated using a modified IEEE 30 bus test system without and with TCSC/SVC in normal and contingency conditions for the selected bilateral, multilateral and area wise transactions. Test results indicate that the proposed PSO algorithm is efficiently used for optimal placement of TCSC and SVC for maximizing ATC, and reducing real and reactive power losses.

KEYWORDS: Available Transfer Capability Congestion management Particle Swarm Optimization Static Var Compensator Thyristor Controlled Series Compensator

INTRODUCTION

The competitive environment has increased the electricity trade by many folds and caused the power to flow over the transmission corridors by unexpected amounts and directions. During certain periods, transmission system is unable to accommodate desired energy transactions, which leads to the congestion in the transmission system. Transmission system congestion is tackled by the Independent System Operator (ISO) of electricity markets by curtailments or adjustments in scheduled transactions. In deregulated electricity market transmission congestion occurs when there is insufficient transmission capacity to simultaneously accommodate all constraints for transmission of a line and causes a huge revenue loss to market participants [1-3]. The objective of the congestion management is to take actions (or) control measures in relieving congestion of transmission network and increasing the power transferring capabilities. With open access to the transmission system by competing generators, the pattern of generations and the line flow can change drastically over a few hours. Under such situations, the ISO requires more direct means of controlling the power flow. Also, large increase in power demand, competition among various market players and scarce natural resources are some factors due to

To Cite This Article: K. Vetrivel, S.Ganapathy, K. Uma Rao., Optimal Allocation of TCSC and SVC devices for Congestion Management in deregulated power systems. **Advances in Natural and Applied Sciences**. 10(13); Pages: 81-92

which transmission systems operate very near to their thermal and stability limits. Due to economic, environment and political reasons, it may not be practical to build new transmissions line to relieve congestion. An alternative option is to use flexible AC Transmission systems (FACTS) devices for congestion management. FACTS devices are solid state converters that have the capability of control of various electrical parameters in transmission networks [4]. In addition to conventional control applications, the devices can also be used to mitigate problem of congestion. Fast power flow control is the main application of FACTS devices, which can help us to achieve the above objectives. FACTS devices influence the system by switched or controlled shunt compensation, series compensation or phase shift control. These devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. Thyristor Controlled Series Compensator (TCSC) and Static Var Compensator (SVC) are two FACTS devices that flexibly control line impedance and susceptance respectively. These 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 [5-7]. Nowadays, because of the deregulation of the power industry the continuous increase of the load increases the necessity of calculation of ATC of a system to analyze the system security. The open access of power system network may create the overload on the power system network more frequently. In power system network, since ATC is an available transfer capability, and unless the calculations of ATC are being used optimally by the power transmission companies, huge amount of power losses will occur in the power system network. The result of this will be a challenging task for power system operation people to manage the system in secured condition. The Determination and enhancement ATC are important issues in deregulated operation of power systems [8]. Various mathematical models have been developed by the researchers to determine the ATC of the transmission system based on conventional power system equations. Recently, the distribution factors based on DC or AC power flow methods [9, 10] have been proposed for calculating ATC. In this paper, the Power Transfer Distribution Factor (PTDF) using AC power flows are derived to calculate ATC using sensitivity properties of Newton Raphson Load Flow (NRLF) Jacobian. 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.

In congestion management, the objective function is nonlinear mixed integer which requires a complex optimization tool to solve the allocation problem. Many researchers have discussed the heuristic optimization algorithms used to locate FACTS devices in power systems [11-14], such as the Genetic Algorithm (GA), Evolutionary programming (EP), Biogeography Based Optimization (BBO) and recently a Particle Swarm optimization (PSO) to solve simple and complex problems efficiently and effectively. However, unlike GA, EP and BBO each individual in PSO flies in search space with a velocity that is dynamically adjusted according to its own flying experience and its companions flying experiences [15-17]. The prime advantage of PSO algorithm is its fast convergence and simplicity in implementation, as the number of parameters that are dynamically adjusted is less. In this paper, PSO technique is used to find the optimal location and size of TCSC/ SVC to achieve maximization of ATC, decrease the line congestion and total power loss.

2. Available Transfer Capability:

According to NERC definition; ATC is defined as a measure of the transfer capability in the physical transmission network, for transfers of power for further commercial activity, over and above already committed uses. Practically, ATC is determined as a function of increase in power transfers between different systems through prescribed interfaces. The flows in transmission line increase as the transfers increase. The calculation of ATC involves three major components which are Total Transfer Capability (TTC), Transmission Reliability Margin (TRM) and Capacity Benefit Margin (CBM). The TRM is the amount of transmission capacity necessary to ensure that the interconnected system is secure under a reasonable range of routine uncertainty, while the CBM is the transmission capacity reserved by load serving entities to ensure access to generation from interconnected systems to meet the generation reliability requirement. Obviously, the TTC minus the base flow and appropriate transmission margin is the ATC for the selected interfaces. Therefore, mathematically, ATC can be expressed as

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

The ETC is the sum of the Existing Transmission Commitment between two areas or known as base case flow. The effects of contingencies are taken into account in ATC determination. Generally, the information of base case is from a contingency case, a real time state estimate or a future postulated system condition. ATC between and within areas of the interconnected power system and ATC for critical transmission paths between these areas would be continuously updated by posting 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) described in section 3.

3. Determination Of Atc Using Acptdf:

AC Power Transfer Distribution Factors (ACPTDF) [9, 10] 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 a transaction between the seller and buyer. For a single area ATC, the transaction will be between a seller bus and a buyer bus present in the area and for multi-area ATC, the transaction will be between two areas. The proposed ACPTDF 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 (PTDF) 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 the full Jacobian in polar coordinates [J_T], defined to include all the buses except slack (including ΔQ-ΔV equations for PQ 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

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

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

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

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*, AC$PTDF_{ij,mn}$ 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 is computed using Jacobian inverse. $ACPTDF_s$ remain fairly constant for reasonable variations in power injections

4. Modeling Of Facts Devices:

4.1 Modeling of Static VAR Compensator (SVC) devices:

Static Var Compensators have their output adjusted to exchange inductive or capacitive current in order to control a power system variable such as the bus voltage. It provides fast reactive power and voltage regulation support. The SVC is a combination of fixed capacitors and reactors. In the most general state, SVC is composed of a Thyristor Controlled Reactor (TCR) which is parallel with a Fixed Capacitor (FC) bank. The control of the fire angle of the Thyristor enables the SVC to answer the network in all instances. The main structure of the SVC for one phase is shown in Fig 1(a). In practice, a SVC can be considered as a variable reactance whose

reactance can be varied by varying the firing angle of the TCR. The SVC susceptance (B_{svc}) can be controlled to operate the SVC in either inductive or capacitive mode, within the limits of operation. The equivalent circuit of SVC is shown in Fig 1 (b). From Fig 1(b) we can write

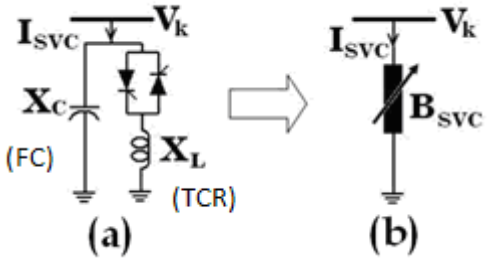

Fig. 1: The equivalent circuit of a SVC

$$I_{SVC} = jB_{SVC} \times V_K \tag{7}$$

The reactive power injected by the SVC into bus K is given by

$$Q_{SVC} = V_K^2 \times B_{SVC} \tag{8}$$

Suitable control of this equivalent reactance allows voltage magnitude regulation at the SVC point of connection. The SVC will inject or absorb reactive power (Q_{SVC}) at a selected bus. It injects reactive power into the system if $Q_{SVC}<0$ and absorbs reactive power from the system if $Q_{SVC}>0$. Operating range of SVC is normally ±100MVar.

4.2 Thyristor controlled-series capacitor Devices:

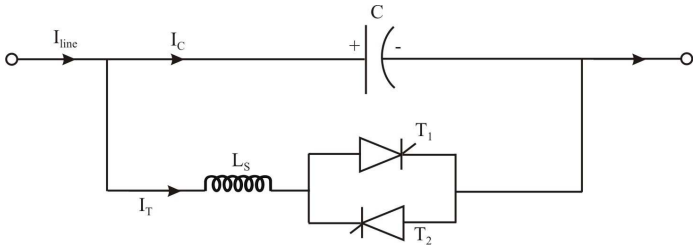

Fig. 2: Basic structure of Thyristor controlled-series capacitor

The TCSC configuration is similar to that of an SVC, namely a parallel combination of FC and TCR; it is connected in series with the line as shown in Fig 2. The TCSC is operated mostly in the capacitive mode, in a region to avoid resonance between the fixed capacitor C and the TCR (refer Fig 2). It is operated in the inductive mode during faults, to protect the capacitor. The rating of the TCSC depends on transmission line where it is located. To prevent overcompensation, TCSC reactance is chosen between $-0.8X_{Line}$ (capacitive) to $0.2X_{Line}$ (inductive). The reactance of the line where TCSC is located is given by

$$X_{ij} = X_{Line} + X_{TCSC} \tag{9}$$

$$X_{TCSC} = \gamma_{TCSC} * X_{Line} \tag{10}$$

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 TCSC is used to decrease or increase the overall line effective series transmission impedance, by adding a capacitive or inductive reactive correspondingly. Fig.3 shows a model of transmission line with one TCSC connected between bus-i and bus-j.

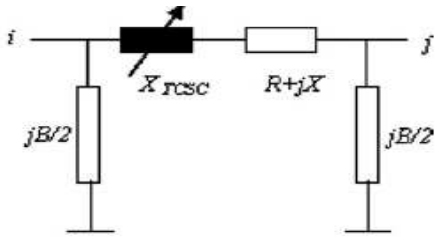

Fig. 3: Single line diagram of power flow control with TCSC

The power flow equations of TCSC are given by

$$P_{ij} = V_i^2 \, g_{ij} - V_i V_j \, (g_{ij} \cos_{ij} + b_{ij} \sin_{ij}) \tag{11}$$

$$Q_{ij} = V_i^2 \, b_{ij} - V_i V_j \, (g_{ij} \sin_{ij} + b_{ij} \cos_{ij}) \tag{12}$$

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 objective of the optimization problem is to maximize the utilization of 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

$$J = Maximize \;\; (ATC_{mn}) \tag{13}$$

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

$$P_{Gm} - P_{Dn} = 0 \tag{14}$$

Where P_{Gm} is active power generation at bus *m* in a source area and P_{Dn} is active power demand at bus *n* in a sink area It is subjected to

(i) Equality constraints, which reflects the power flow equations at bus i,

$$P_{Gi} - P_{Di} - \sum_{j=1}^{nb} |V_i| |V_j| |Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{15}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{nb} |V_i| |V_j| |Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{16}$$

P_{Gi}, Q_{Gi} are real and reactive power generation at bus i, P_{Di}, Q_{Di} are real and reactive loads at bus i, $|V_i|, |V_j|$ Voltage magnitude at bus i and bus j. $|Y_{ij}|, \theta_{ij}$ are magnitude and phase parts of the ijth element of the bus admittance matrix. δ_i, δ_j are voltage angle of bus i and bus j, respectively. *nb* is the total number of buses.

(ii) Inequality constraints, which enforce the system real and reactive power flow and bus voltage limits, given by.

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad for \;\; i = 1,2.....n_g \tag{17}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad for \;\; i = 1,2,.....n_g \tag{18}$$

$$V_b^{\min} \le V_b \le V_b^{\max} \qquad for \; b = 1,2..... n_b \tag{19}$$

Where n_g is the number of generators, n_b is number of buses

(iii) The constraints on the FACTS devices as

$$-0.8 \, X_{Line} \le X_{TCSC} \le 0.2 \, X_{Line} \quad p.u. \tag{20}$$

$$-100\ M\ \text{var} \le Q_{SVC} \le 100\ M\ \text{var} \tag{21}$$

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. TCSC reactance is restricted between $-0.8X_{Line}$ to $0.2X_{Line}$. Q_{SVC} is the reactive power injected at the bus by placing SVC.

(iv) The constraints on the installation cost of the corresponding FACTS devices are given by,

$$IC = C * S * 1000 \tag{22}$$

where *IC* denotes optimal installation cost of FACTS devices in US$, *C* represents cost of installation of FACTS devices in US $ / KVar. The cost of installation of TCSC and SVC are taken from Siemens data base. The cost of installation of the FACTS devices are given by the following equations:

$$C_{TCSC} = 0.0015\ S^2 - 0.713\ S + 153.75 \tag{23}$$

$$C_{SVC} = 0.0003\ S^2 - 0.3051\ S + 127.38 \tag{24}$$

Where S is the operating range of FACTS devices in Mvar and it is given by

$$S = |Q_1| - |Q_2| \tag{25}$$

Where Q_2 is the reactive power flow in the line after installing FACTS device in Mvar and Q_1 represents reactive power flow in the line before installing FACTS device in Mvar.

6. Optimal Placement Of Facts Devices Using Pso Algorithm:

6.1 Over view of PSO algorithm:

The Particle Swarm Optimization is a population-based stochastic optimization algorithm which was introduced by Kennedy and Eberhart [15]. High quality, solutions with shorter calculation time and stable convergence characteristics can be obtained by PSO as compared to other stochastic methods. In PSO, the potential solutions, called particles, are flown through the problem space by following the current optimal particles. Each individual in PSO flies in the search space with a velocity which is dynamically adjusted according to its own flying experience and its companions flying experiences. Each individual keeps track of its coordinates in the problem space, which are associated to the best solution (fitness) it has achieved so far. This value is called P_{best}, while the overall best value obtained so far by any particle in the population, the so-called G_{best}, and its location is tracked by the global version of the particle swarm optimizer. At each time step, the particle swarm optimization consists of velocity changes of each particle towards its P_{best} and G_{best} [15,16]. After finding the best values, the particle updates its velocity and position according to the following equations:

$$V_i^{k+1} = w * V_i^k + C_1 * rand_1 * (P_{best_i} - S_i^k) + C_2 * rand_2 * (G_{best_i} - S_i^k) \tag{26}$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \tag{27}$$

Where, Vi^{k+1} is the velocity of i^{th} individual at $(k + 1)^{th}$ iteration, Vi^k is the velocity of i^{th} 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 (26) 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 (27). The inertia weight factor "w" is modified using (24) to enable quick convergence.

$$w = w_{\max} - \frac{(w_{\max} - w_{\min})}{iter_{\max}} * iter \tag{28}$$

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 (26).

6.2 Step by Step algorithm to optimally locate FACTS 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 of TCSC, MVar rating of SVC and location of TCSC/ SVC as control variables.

Step 3: Randomly generate population of particles with their variables in normalized form.

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

$$X_{Denormalized} = X_{\min} + (X_{\max} - X_{\min}) * X_{normalized} \quad (29)$$

Where X_{min}, X_{max} are minimum and maximum values of the variable X respectively. Denormalized value of location of TCSC is rounded to nearest integer during optimization. For constant active power flow and supply voltage of V_K, the required capacitive VAR of SVC is the difference between the pre compensation VAR and the required compensated VAR as given by (30) and modify the bus admittance matrix.

$$Q_{SVC} = Q_{required} - Q_{uncompensated} \quad (30)$$

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 Eq (5).

Step 7: Calculate the objective function of each particle subject to satisfy the constraints using Eq (13).

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 Eq (26) and (27).

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 FACTS devices respectively and also calculate cost of installation of FACTS devices using (23 and (24)).

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 4. The system data are in a per-unit system and taken from [9] and the base MVA value is taken 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 5. Transaction is carried out between Area 1 and Area 2. Three inequality constraints on voltage limit, real, 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 FACTS devices are obtained using PSO Algorithm for maximizing ATC based on the selected bilateral, multilateral and area wise transactions. Installation cost of FACTS devices has also been calculated for each transaction with reference to ATC value and cost of installation. The simulations studies have been carried out on an Intel Pentium Dual Core, 2.40 GHz system in a MATLAB 2010a environment. The results are presented in the following sections.

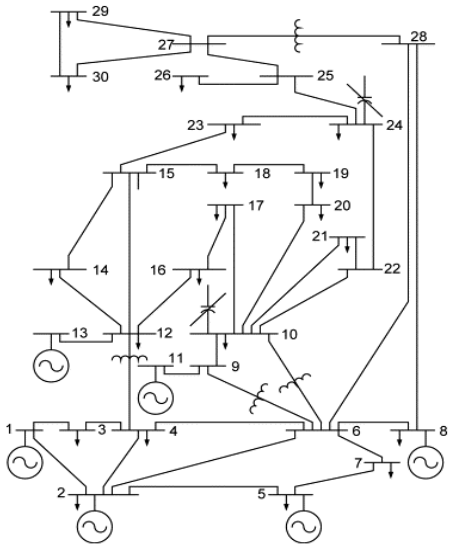

Fig. 4: Single line diagram of the modified IEEE 30-bus system

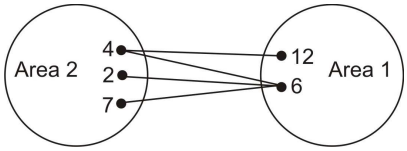

Fig. 5: Tie-line between areas- IEEE 30 bus system

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 (11-27, 2-10, 5-20, 2-23 and 8-30) with the objective function as in (13) are considered. Table 1 shows the results of ATC before and after the allocation of FACTS devices. A single type FACTS device such as TCSC or SVC is installed in the test system to study the effectiveness of the devices in enhancing ATC for different bilateral transactions. From Table 1, it can be observed that for a bilateral transaction from bus 5 to bus 20, the ATC value is 32.21 MW without installing FACTS devices, whereas after installing TCSC or SVC, the ATC value is improved by 14.78 % and 5.2 % respectively without violating system constraints. The optimal location of TCSC is between buses 15 to 18. The optimal size (reactance) of TCSC is -0.1093 p.u and negative sign indicates that TCSC operates in capacitive mode. By considering SVC device, the optimal location of SVC is at bus 18 and rating of the SVC is - 13.117 Mvar and negative sign indicate that SVC injects reactive power into the system. The active and reactive power losses for the base case and with TCSC or SVC are tabulated in Table 1. The comparative studies of active and reactive losses without and with TCSC/SVC are also plotted in Fig 6 and 7. It can be observed that the active power losses is 10.71 MW without placing FACTS devices , but it is reduced to 13.06 % and 8.25 % after placing TCSC and SVC respectively. It can be observed the reactive power loss is -3.23 Mvar without placing TCSC/ SVC devices but it is reduced to 5.61 % and 11.2 % by placing TCSC and SVC devices respectively. The corresponding optimum cost of installation of TCSC devices and SVC devices is 0.81 $x10^6$ US $ and is 1.25 $x10^6$ US $ respectively as shown in Fig 8. From Fig 8, it can be observed that the cost of installation of TCSC is less than SVC.

Multilateral transactions between seller buses in source area and buyer buses in sink area such as (8, 13 - 27, 20 and 2, 8, 13 - 23, 27) which maximize the ATC have also been considered. Table 2 shows the results for multilateral transaction between 8-27 and 13-20. The active power losses is 8.91 MW without placing FACTS devices , but it is reduced to 8.65 % after placing TCSC and optimal location of TCSC is between bus 22 to bus 24. The optimal size (reactance) of TCSC is -0.0892 p.u and negative sign indicates that TCSC operates in capacitive mode and the corresponding cost of installation of TCSC devices is 6.33 $x10^6$ US $. The active power loss is also reduced 4.21 % by considering SVC device connected at bus 18 and rating of the SVC is - 21.56 Mvar and negative sign indicate that SVC injects reactive power into the system and the corresponding installation cost of TCSC devices is 7.56 $x10^6$ US $. Moreover, the reactive power loss is -8.53 Mvar without placing TCSC/ SVC devices but it is reduced to 4.08 % and 6.45 % by placing TCSC and SVC devices respectively. The corresponding different multilateral transactions results are shown in Table 2. From Table 1, 2 and Figs. 6-8, it can be clear that ATC values are increased for all possible transactions and power losses is reduced after placing FACTS devices in right location. The results also show that TCSC could enhance ATC much higher than SVC. The active power loss and installation Cost is reduced with use of TCSC device but reactive power loss is more as compare with SVC.

Case 2: contingency operating conditions:

For a contingency case, the branch line outage between buses 9 and 10 is considered. The corresponding ATC values for the test system without and with FACTS devices for bilateral and multilateral transactions with line outage conditions are given in Tables 3 and 4 respectively. The active and reactive power loss for different bilateral transactions without and with FACTS devices are shown in Figs. 9 and 10 respectively and the corresponding installation cost of FACTS devices is shown in Fig 11. Tables 3, 4 and Figs. 9-11 indicate that optimally placed FACTS devices by PSO significantly increase ATC and reduce active power losses. Moreover, TCSC enhances ATC much higher than SVC. The active power loss and installation Cost is reduced with use of TCSC device but reactive power loss is more as compared to SVC under contingency conditions.

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

Transactions			Placement of FACTS devices		Settings of FACTS devices		% improvement in ATC		% decrease in active power loss		% decrease in reactive power loss	
No	Source bus	Sink bus	TCSC (line)	SVC (bus)	TCSC (X_{tcsc})	SVC (Mvar)	TCSC	SVC	TCSC	SVC	TCSC	SVC
T1	11	27	6-28	22	-0.0350	- 9.891	8.27	2.91	11.13	4.08	5.31	13.9

T2	2	10	16-17	6	-0.2898	84.675	6.88	0.86	11.26	9.04	7.54	13.6
T3	5	20	15-18	18	-0.1093	- 13.117	14.78	5.20	13.06	8.25	5.61	11.2
T4	2	23	15-23	23	-0.1262	- 9.815	16.26	5.84	18.52	12.4	6.11	15.9
T5	8	30	27-30	30	0.2696	62.944	15.57	5.92	17.16	9.17	5.85	12.6

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

Transactions			Placement of FACTS devices		Settings of FACTS devices		% improvement in ATC		% decrease in active power loss		% decrease in reactive power loss	
No	Source bus	Sink bus	TCSC (line)	SVC (bus)	TCSC (X_{tcsc})	SVC (Mvar)	TCSC	SVC	TCSC	SVC	TCSC	SVC
T1	8, 13	27, 20	22-24	18	-0.0895	-21.555	18.82	13.65	8.65	4.21	4.08	6.45
T2	2,8, 13	23, 27	15-23	23	-0.1132	-22.381	19.87	11.36	7.18	4.07	5.14	8.65

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

Transactions			Placement of FACTS devices		Settings of FACTS devices		% improvement in ATC		% decrease in active power loss		% decrease in reactive power loss	
No	Source bus	Sink bus	TCSC (line)	SVC (bus)	TCSC (X_{tcsc})	SVC (Mvar)	TCSC	SVC	TCSC	SVC	TCSC	SVC
T1	11	27	6-28	28	0.0297	- 30.25	18.71	9.21	9.75	3.99	4.65	7.99
T2	2	10	16-17	17	-0.0966	35.827	19.67	9.79	7.45	4.12	5.26	9.11
T3	5	20	15-18	18	-0.1093	- 63.416	25.86	9.80	5.58	4.43	2.61	8.77
T4	2	23	15-23	23	-0.1010	16.814	11.83	6.26	14.8	7.36	5.29	10.5
T5	8	30	27-30	30	0.2651	75.931	15.48	8.17	6.21	3.67	4.09	10.6

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

Transactions			Placement of FACTS devices		Settings of FACTS devices		% improvement in ATC		% decrease in active power loss		% decrease in reactive power loss	
No	Source bus	Sink bus	TCSC (line)	SVC (bus)	TCSC (X_{tcsc})	SVC (Mvar)	TCSC	SVC	TCSC	SVC	TCSC	SVC
T1	8, 13	27, 20	15-18	18	-0.1496	- 2.643	5.41	1.32	6.51	4.18	3.97	5.71
T2	2,8, 13	23, 27	15-23	23	0.0694	- 83.112	18.32	11.25	6.28	3.87	4.89	7.64

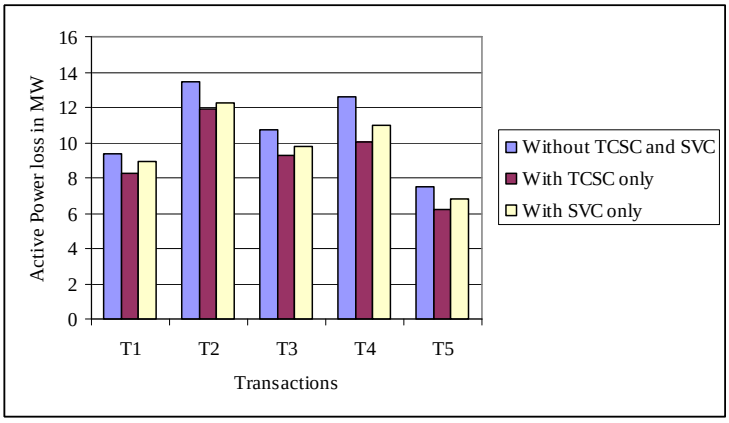

Fig. 6: Active Power Loss (bilateral Transaction) for IEEE 30 bus system Base case

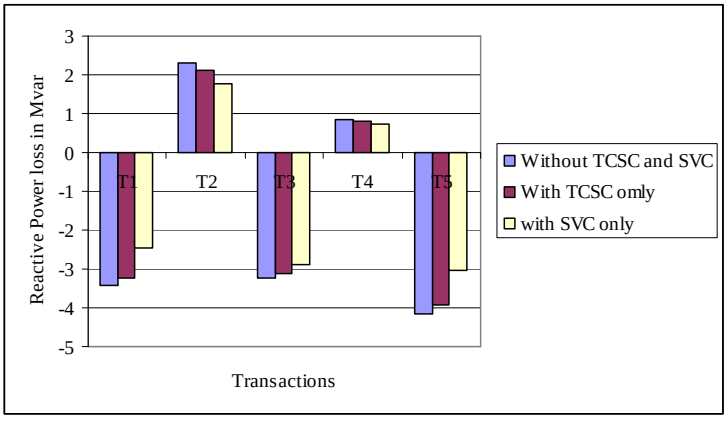

Fig. 7: Reactive Power Loss (bilateral Transaction) for IEEE 30 bus system Base case

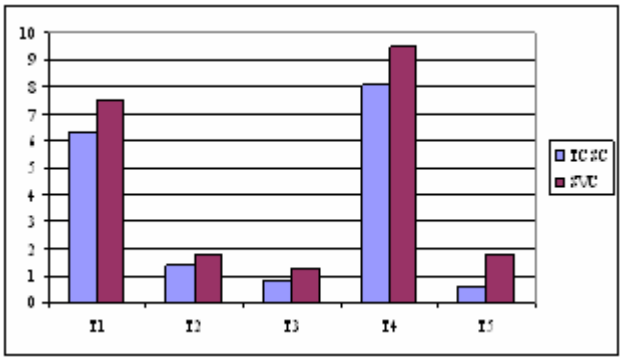

Fig. 8: Installation Cost (bilateral Transaction) for IEEE 30 bus system

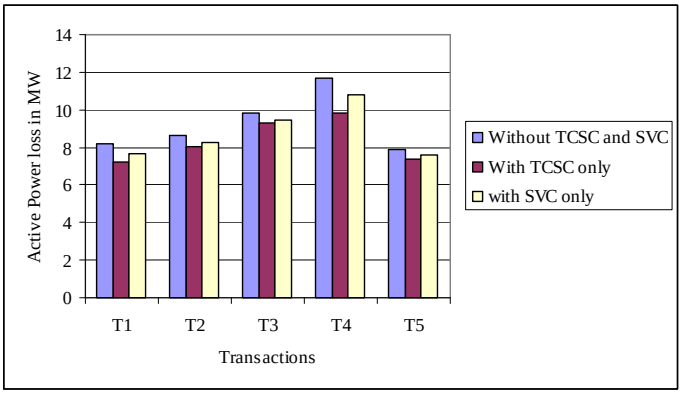

Fig. 9: Active Power Loss (bilateral Transaction) for IEEE 30 bus system with line outage of 9-10

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

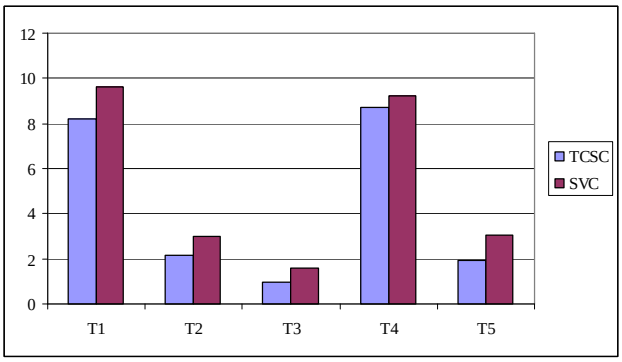

Fig. 11: Installation Cost (bilateral Transaction) for IEEE 30 bus system with line outage of 9-10

Conclusion:

The present research work has been undertaken to illustrate the application of FACTS devices to relieve transmission congestion in heavily loaded systems. The PSO algorithm has been used to obtain the optimal location and control parameters of TCSC and SVC to enhance ATC and minimizing the power losses of the competitive electricity market. Simulations have been carried out using IEEE 30-bus system. Extensive case studies have been conducted. The results obtained on test system reveal that the ATC values are enhanced with suitable parameters of TCSC and SVC using PSO which gives the better enhancement of ATC under normal as well as line outage case. However, the improvement with TCSC is found to be better. Both the devices also reduce the active and reactive power losses. The TCSC is more effective than the SVC in reducing the active power loss, while the SVC is better at reducing reactive power loss, due to a better voltage profile maintained with SVC. Thus, we can conclude that both TCSC and SVC are effective in transmission congestion management and existing installations can be used to enhance ATC, over and above normal control objective, wherever congestion occurs. Moreover, the proposed PSO algorithm is able to find out the optimal location, parameters of FACTS devices in less computational time and with relatively small number of iterations. A multi type FACTS devices can improve some different system parameter in a multi objective optimization problem is consider in future study.

ACKNOWLEDGEMENT

The authors wish to thank the authorities of Annamalai University, Annamalainagar, Tamilnadu, India for the facilities provided to prepare this paper.

REFERENCES

1. Tuan, L.A., K. Bhattacharya and J. Daalder, 2005. Transmission congestion management in bilateral markets: an interruptible load auction solution. Electric Power Systems Research, 74(3): 379-389.
2. Rajalakshmi, L., M.V. Suganyadevi and S. Parameswari, 2011. Congestion Management in Deregulated Power System by Locating Series FACTS Devices. International Journal of Computer Applications, 13(8): 19-22.
3. Md Sarwar and Anwar Shahzad Siddiqui, 2016. An approach to locational marginal price based zonal congestion management in deregulated electricity market. Frontiers in Energy, 10(2): 240-248.
4. Sambasivarao, N., J. Amarnath and V. Purnachandrarao, 2013. Congestion Management using FACTS devices in Deregulated Power System. International Journal of Research in Engineering and Technology, 2 (11): 90-95.
5. Mohamad idris, R., A. Khairuddin and M.W. Mustafa, 2010. Optimal Allocation of FACTS Devices in Deregulated Electricity Market Using Bees Algorithm. WSEAS Transactions on power systems, 5(2): 108-119.
6. Sharma, P.R., A. Kumar and N. Kumar, 2007. Optimal location for shunt connected FACTS devices in a series compensated long transmission line. Turkish Journal of Electrical Engineering, 15(3): 321-328.
7. Imran Khan, M.A. Mallick, Malik Rafi and Mohammad Shadab Mirza, 2015. Optimal placement of FACTS controller scheme for enhancement of power system security in Indian scenario. Journal of Electrical Systems and Information Technology, 2: 161-171.
8. Nireekshana, T., G. Kesava Rao and S. Sivanaga Raju, 2016. Available transfer capability enhancement with FACTS using Cat Swarm Optimization. Ain Shams Engineering Journal, 7: 159-167.
9. Manikandan, B.V., S. CharlesRaja and P. Venkatesh, 2011. Available Transfer Capability Enhancement with FACTS Devices in the Deregulated Electricity Market. Journal of Electrical Engineering & Technology, 6(1): 14-24.
10. Indhumathy, K., N.B. Rajesh and J. Jaya Priya, 2013. Assessment of Available Transfer Capability (ATC) Using Linear Sensitivity Factors under Deregulated Environment. International Journal of Engineering and Technology, 5(3): 3029-3035.
11. Ippolito, Lucio, La Cortiglia, Antonio Petrocelli and Michele, 2006. Optimal allocation of FACTS devices by using multi-objective optimal power flow and genetic algorithms. International Journal of Emerging Electric Power Systems, 7(2): 1-19.
12. Anju Gupta and P.R. Sharma, 2014. Application of GA for Optimal Location of FACTS Devices for Steady State Voltage Stability Enhancement of Power System. I.J. Intelligent Systems and Applications, 3: 69-75.
13. Venkatesh, P., R. Gnanadass and Narayana Prasad Padhy, 2003. Comparison and application of Evolutionary programming techniques to combined economic emission dispatch with line flow constraints. IEEE Transactions on Power systems, 18(2): 688-697.
14. Karthikeyan, K. and P.K. Dhal, 2016. Transient Stability Analysis by Optimal Location and Tuning of SVC using Biogeography based Optimization. Advances in Natural and Applied Sciences, 10(3): 215-223.

15. Kennedy, J. and R. Eberhart, 1995. Particle Swarm Optimization. Proceeding. IEEE international conference Neural Networks, pp: 1942-1948.
16. AlRashidi, M.R., M.E. El-Hawary, 2009. A survey of Particle Swarm Optimization Applications in electric power systems. IEEE Transactions on Evolutionary Computation, 13(4): 913-918.
17. Ajilly Ann John, Tibin Joseph and Sasidharan Sreedharan, 2013. Allocation of FACTS Devices For Congestion Relief Using Particle Swarm Optimization. International Journal of Engineering Research & Technology, 2(8): 2395-2401.