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OPTIMAL DISTRIBUTION OF MULTIPLE FACTS DEVICES FOR AVAILABLE TRANSFER CAPABILITY ENHANCEMENT IN A RESTRUCTURED POWER SYSTEM

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ABSTRACT
In this paper presents the various combinations of power electronics devices such as Thyristor Controlled Series Capacitor (TCSC), Static Var Compensator (SVC) and Unified Power Flow Controller (UPFC) are tried to develop multiple FACTS devices. A novel method using Flower Pollination Algorithm (FPA) is proposed to determine the optimal allocation of FACTS devices for maximizing the Available Transfer Capability (ATC) of power transactions between source and sink areas in the restructured power system. This algorithm concurrently searches the optimal types, placement and tuning the parameters of multiple FACTS devices in order to enhance the available transfer capability (ATC). An IEEE30 bus system is used to demonstrate the effectiveness of the algorithm as an optimization tool to enhance ATC. The simulation results illustrate that the multiple FACTS devices in a precise location could augment ATC reduction of total losses and improve the line congestion. Moreover, the proposed FPA technique is an effectiveness to get better the searching for the optimal location, size and installation cost of multiple FACTS devices as compared with Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) technique.

Keywords: Available Transfer Capability, Flower Pollination Algorithm (FPA), Static Var Compensator, Thyristor Controlled Series Capacitor, Unified Power Flow Controller

1. INTRODUCTION
In competitive electricity markets are complex systems with many participants who buy and sell electric power and it will lead to transmission lines to function outside their capacities causing congestion. The electric utilities are mandatory to relive the congestion consecutively to get better the ATC of power transactions amid generators and loads in the restructured power system. The ATC may be decide to some main factors such as power transfer among areas, system load level, the boundary imposed on the transmission network and load distribution in the network, etc and this information will be supportive for power marketers (Wu). Many researchers have proposed the computation of ATC with power flow sensitivity scheme based on Power Transfer Distribution Factors (PTDFs), with DC load flow approach (Christie and others).. The DC load flow based approaches are fast, but are based on DC load flow assumptions. The more accurate method for computation of ATC based on PTDFs using AC load flow approach has been reported in (Kumar and Kumar). In this method transmission system can be restricted by voltage, thermal and stability limits.

In recent years, the impacts of FACTS devices are good choice ATC enhancement and system loss minimization in the competitive electric power systems (Bhattacharyya). It can reduced the number of new construction of transmission lines and improve the utilization rate of transmission lines. FACTS devices make it possible to use circuit reactance, voltage magnitude, and phase angle as controls to redistribute line flow and regulate voltage profile in order to increases ATC, relieve congestion, improve reliability and enhances operation and control (Esmaeili and Esmaeili). However, it is hard to determine the optimal allocation and parameters of FACTS devices due to the complicated combinatorial optimization. Thus, attention is paid to this current work to study a technique to optimally allocate the devices to enhance ATC.

Artificial Intelligence (AI) based genetic algorithm (GA), particle swarm optimization (PSO) and harmony search algorithm (HSA) techniques are used simultaneously searches the optimal allocation includes optimal types (series and parallel), locations, installation cost and parameters setting of FACTS devices in order to improve the ATC of power transactions between generators and loads without violating system constraints (Nireekshana and others). A newly developed flower pollination algorithm (FPA) is a Meta-heuristic optimization technique based on pollination of flowers. It has only one key parameter p (switch probability) which makes the algorithm easier to implement and faster to reach optimum solution (Yang). FPA technique has unique capability such as extensive domain search with excellence and consistency solution (Yang and others). In this study, FPA is used to find the optimal location, types and control parameters of multiple FACTS devices to achieve maximization of ATC, decrease the line congestion and total power loss.

2. STATIC MODELING OF FACTS DEVICES
The power flow equations of the line connected between bus i and bus j having series impedance $r_{ij} + jx_{ij}$ and without any FACTS devices are given b

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$$P_{ij} = V_i^2 g_{ij} - V_i V_j (g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}) \quad (1)$$

$$Q_{ij} = -V_i^2 (b_{ij} + B_{sh}) - V_i V_j (g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}) \quad (2)$$

Where V_i, V_j are the magnitudes voltage at bus-i and bus-j, δ_{ij} is the angle difference between bus-i and bus-j and $g_{ij} = \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2}$, $b_{ij} = \frac{-x_{ij}}{r_{ij}^2 + x_{ij}^2}$

Similarly, the active power (P_{ji}) and reactive power (Q_{ji}) flow from bus-j and bus-i in the line given by

$$P_{ji} = V_j^2 g_{ij} - V_i V_j (g_{ij} \cos\delta_{ij} - b_{ij} \sin\delta_{ij}) \quad (3)$$

$$Q_{ji} = -V_j^2 (b_{ij} + B_{sh}) + V_i V_j (g_{ij} \sin\delta_{ij} + b_{ij} \cos\delta_{ij}) \quad (4)$$

2.1 Static Var Compensator (SVC)

SVC is a shunt connected devices used to absorb reactive power from the bus or to inject reactive power to the bus where it is connected. The output is adjusted to exchange capacitive or inductive current in order to control bus voltage. It provides fast reactive power and voltage regulation support. The static model of SVC is shown in Fig.1. The control of the firing angle of the Thyristor enables the SVC to provide the required reactive power in the control range.

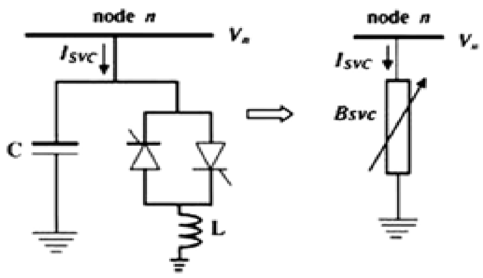

Figure-1: Static model of SVC

In practice, an SVC can be considered as a variable reactance whose reactance can be varied by varying the firing angle. The susceptance of SVC (B_{svc}) can be controlled to operate either inductive or capacitive mode within the limits of operation. From the Fig.1 we can write

$$I_{SVC} = jB_{SVC} V_k \quad (5)$$

The reactive power injected by the SVC into bus *k* is given by

$$Q_{SVC} = V_k^2 B_{SVC} \quad (6)$$

Suitable control of this equivalent reactance allows voltage magnitude regulation at the SVC point of connection. In Eqn. (6) to modify the corresponding jacobian elements at SVC bus. 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.

2.2 Thyristor Controlled Series Capacitor (TCSC)

The power flow control with the TCSC is to decrease or increase the series impedance of the lines, by adding a capacitive or inductive reactance. The rating of the TCSC depends on transmission line where it is located. Fig.2 shows a model of the transmission line with one TCSC connected between bus-i and bus-j.

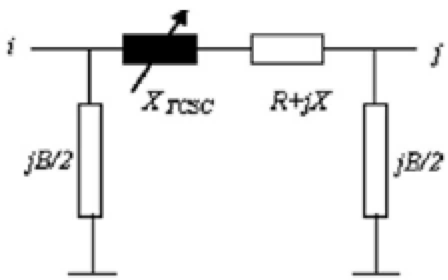

Figure-2: Equivalent circuit of TCSC

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The reactance of the line with TCSC is given by

$$x_{ij} = x_{line} + x_{TCSC} \quad (7)$$

$$x_{TCSC} = \gamma_{TCSC} * x_{line} \quad (8)$$

Where, X_{line} is the reactance of the transmission line and γ_{TCSC} is the compensation factor of TCSC. The level of applied compensation of the TCSC usually varies between 20% inductive and 80% capacitive (Bhattacharyya). The real and reactive power flow from bus-i to bus-j and bus-j to bus-i in the line given by Eqn (1) to (4) with modified g_{ij} and b_{ij} as given by

$$g_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_{TCSC})^2}, \; b_{ij} = \frac{-(x_{ij} - x_{TCSC})}{r_{ij}^2 + (x_{ij} - x_{TCSC})^2}$$

2.3 Unified Power Flow Controller (UPFC)

The UPFC is able to control all parameters such as voltage magnitude, impedance and phase angle affecting power flow in the transmission line simultaneously (Bhattacharyya). UPFC consists of two switching converters operated from a common DC link as shown in Fig.3. The working range of the UPFC angle is between -180° and -+180°. The UPFC may act as an SVC, a TCSC or a phase shift controller. UPFC can be modeled as a combination of series and shunt element i.e., TCSC, SVC respectively. The decoupled model of UPFC can be easily implement in conventional power flow studies as shown in Fig 4.

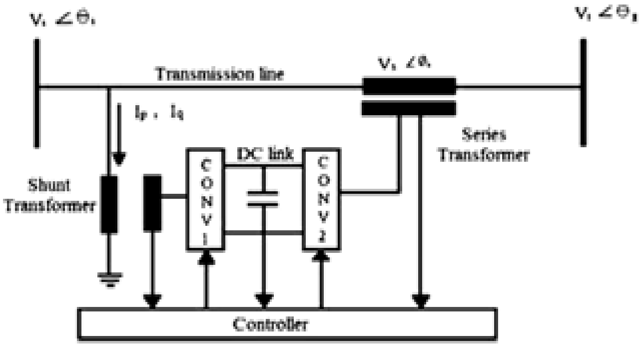

Figure-3: Static model of UPFC

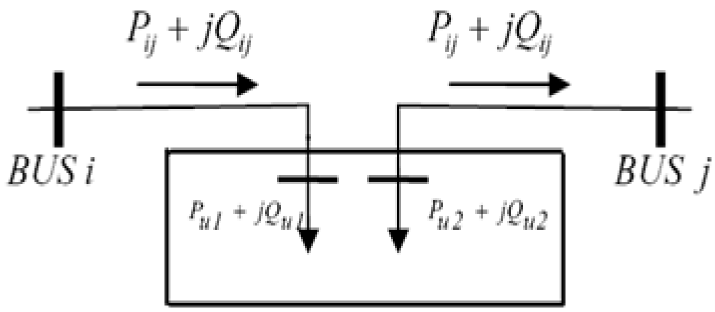

Figure-4: Decoupled model for UPFC

In load flow study, the model of UPFC can be obtained with represented by four variables such as $P_{u1}, Q_{u1}, P_{u2}, Q_{u2}$ and shown in Fig 4. The real power flow from bus- i to bus- j is given by

$$P_{ij} = P_{u1} \quad (9)$$

Although UPFC can control the power flow but, it cannot generate the real power. Therefore, we have:

$$P_{u1} + P_{u2} = 0 \quad (10)$$

The reactive power output of UPFC (Q_{u1} and Q_{u2}) can be set to an arbitrary value depending on the rating of UPFC to maintain bus voltage. In the proposed method the decision for the placement of multiple FACTS devices in a line or at the remote end of a line is made on the basis of power flow in each line. TCSCs are to modify reactance of some selected lines, SVCs control the reactive injection at weak buses and UPFC is connected at some specified buses to control Voltage, phase angle associated with these buses and impedances of the lines nearby to the buses connected with UPFC.

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3. AVAILABLE TRANSFER CAPABILITY (ATC) EVALUATION

There are different sensitivity factors available in the literature to calculate ATC for a given system (Xiao). The calculation of ATC using power transfer distribution factor (PTDF) is easy, simple and less time-consuming. Basically, these factors give the relationship between the amount of transaction and the actual power flow in a line. In this study, AC load flow study based PTDF is used to identify the system parameters for a change in MW transaction under normal and contingency conditions. Considered a bilateral transaction t_k between a seller bus 'm' and buyer bus 'n', the transmission line '*l*' carries the part of the transacted power and is connected between buses i and j. Let us considered, the change in real power transactions between the above seller and buyer say by Δt_k MW and due to this, the change in real power flow in a transmission line connected between buses i and j is ΔP. From this, the AC power transfer distribution factors (ACPTDF) can be defined as

$$ACPTDF_{ij,mn} = \frac{\Delta P}{\Delta t_k} \qquad (11)$$

The above factors have been proposed and are evaluated using base case load flow results using Newton-Raphson-Jacobian elements [J_T]. The mathematical representation of the system performance equation can be given as

$$\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V}\\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}\end{bmatrix}^{-1} \begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = [J_T]^{-1}\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} \qquad (12)$$

The power change in a transaction causes the change of active power flow in line i- j. These changes can be mathematically represented as

$$\frac{\partial P_{ij}}{\partial \delta_m} = \begin{Bmatrix} -V_i V_j Y_{ij}\sin(\delta_i - \delta_j - \theta_{ij}) & for\ m = i\\ V_i V_j Y_{ij}\sin(\delta_i - \delta_j - \theta_{ij}) & for\ m = j\\ 0 & for\ m \neq i, j \end{Bmatrix} \qquad (13)$$

$$\frac{\partial P_{ij}}{\partial V_m} = \begin{Bmatrix} 2V_i V_j Y_{ij}\cos(\theta_{ij}) + V_j Y_{ij}cos(\delta_i - \delta_j - \theta_{ij}) & for\ m = i\\ V_j Y_{ij}\cos(\delta_i - \delta_j - \theta_{ij}) & for\ m = j\\ 0 & for\ m \neq i, j \end{Bmatrix} \qquad (14)$$

In bi-lateral transaction, due to change in Δt_k MW, the following two mismatch vectors are changed in Eq. (12) and these values are non-zero elements.

$$\Delta P_i = \Delta t_k \ ;\ \Delta P_j = -\Delta t_k \qquad (15)$$

Based on these mismatch vectors and change in power transactions are considered to calculate the new voltage magnitudes and angles at all buses. The change in power flows in all transmission lines are calculated using new voltage profiles. The ACPTDF in each line for a given transaction are evaluating using Eqn (11) and ATC of a transaction between buses 'm' and 'n' can be calculated as given by

$$ATC_{mn} = \min(T_{ij,\ mn}),\ ij \in N_L \qquad (16)$$

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

$$\begin{Bmatrix} \frac{(P_{ij}^{max} - P_{ij}^{0})}{PTDF_{ij,mn}}; & PTDF_{ij,mn} > 0\\ \frac{(-P_{ij}^{max} - P_{ij}^{0})}{PTDF_{ij,mn}}; & PTDF_{ij,mn} < 0\\ \infty; & PTDF_{ij,mn} = 0 \end{Bmatrix} \qquad (17)$$

where P_{ij}^{max} , P_{ij}^{0} are maximum power flow limit in MW and base case power flow of a line between bus *i* and *j*.

4. PROBLEM FORMULATION

The objective is to maximize the ATC when a transaction is taking place between a seller bus (m) and buyer bus (n). The objective function to be maximized is given by

$$J = Max\ (ATC_{mn}) \tag{18}$$

It is subjected to the following equality, in-equality, and practical constraints.

$$P_{Gi} - P_{Di} - \sum_{j=1}^{nb} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{19}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{nb} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \tag{20}$$

where P_{Gi}, Q_{Gi} are the real and reactive power generations at ith bus, P_{Di}, Q_{Di} are the real and reactive power demands at ith bus, $Y_{ij}\ \theta_{ij}$ are the bus admittance magnitude and its angle between ith and jth buses, δ_i, δ_j are voltage angles of bus i and bus j respectively $nb,\ n_g$ is the total number of buses and generators.

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \quad for\ i = 1,2 \ldots.. n_g \tag{21}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \quad for\ i = 1,2 \ldots.. n_g \tag{22}$$

$$V_b^{min} \le V_b \le V_b^{max} \quad for\ i = 1,2 \ldots.. n_b \tag{23}$$

The constraints on the FACTS devices

$$-100\ MVAr \le Q_{SVC} \le 100\ MVAr \tag{24}$$

$$-0.8x_{line} \le x_{TCSC} \le 0.2x_{line}\ \ p.u. \tag{25}$$

The Eqn (24) and (25) are considered as constraints for placing UPFC. The installation cost of TCSC, SVC and UPFC are taken from (Manikandan).

$$C_{SVC} = 0.0003S^2 - 0.3051S + 127.38\ US\$/KVAr \tag{26}$$

$$C_{TCSC} = 0.0015S^2 - 0.713S + 153.75US\$/KVAr \tag{27}$$

$$C_{UPFC} = 0.0003S^2 - 0.2691S + 188.22US\$/KVAr \tag{28}$$

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

$$S = Q_1 - Q_2 \tag{29}$$

Where Q_1 and Q_2 represent the reactive power flow in the line before and after installing FACTS device in MVAr.

5. OPTIMAL PLACEMENT OF FACTS DEVICES

In general, enhancement of ATC is obtained by placing multiple FACTS devices in the best location. Initially, all possible device installation locations are identified in a given system. By the experience, the following two heuristic rules are formulated to minimize the computation burden and to simplify the problem complexity in identifying the best installation location: (i). FACTS device is not installed in a line where tap changing transformers are installed. (ii) FACTS device is not installed in a line between buses where generators and shunt compensators are installed. Later, FACTS device is placed in all possible locations and the main objective of ATC is maximized while satisfying system constraints and device limits. This process is repeated in all possible locations. Finally, the location which has maximized ATC is considered to be the best location to install FACTS device. The basic steps involved in enhancing ATC values with FACTS devices using GA, PSO were discussed in (Nireekshana) and FPA is discusses in (Yang).

Step1: Read the system input data.

Step2: Run a base case load flow.

Step 3: Consider wheeling transactions (t_k)

Step 4: Compute AC power transfer distribution factors using the Eqn. (11).

Step 5: Take transactions as variables, line flow, real and reactive power limits of generators as constraints and compute the feasible wheeling transactions determine the ATC as per Eqn. (16).

Step 6: Find the limiting element in the system buses, i.e., that carry power close to the thermal limit.

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Step 7: Place multiple FACTS devices in the limiting element.

Step 8: Run GA, PSO, and FPA algorithm separately to obtain the settings of FACTS devices. Step 9: Calculate ATC after incorporating FACTS devices.

Step 10: Is any other transaction has to be carried then consider the next transaction and go to step 3, otherwise stop the procedure.

6. SIMULATION RESULTS AND DISCUSSIONS

To demonstrate the effectiveness of the proposed methodology, IEEE-30 bus test systems are considered. In OPF problem, ATC is considered as objectives, and this problem is solved while satisfying system constraints. The ATC has been determined using AC power transfer distribution factors based on the line flow limit under normal and line outage condition. A multiple FACTS devices are placed at the optimal locations using GA, PSO, and FPA, and comparative analysis of the system performance with and without multiple FACTS devices is made. The method run for each increment of the transaction over its base value until any of the line flows or the bus voltages hit the limiting value. IEEE-30 bus system consists of six generators and forty-one lines are considered and shown in Fig 5. For this system, the total active power demand is 283.4MW and there are six generators connected at buses 1, 2, 5, 8, 11, 13, and two shunt compensators connected at buses 10 and 24 and four tap changing transformers connected between buses 6–9, 6–10, 4–12 and 27–28. The system data are in a per-unit system and taken from (Manikandan) and the base MVA value is taken to be 100 MVA. Here, the transactions with generators connected to buses 2, 5, 8, 11 and 13 are treated as seller buses and the load buses are treated as buyer buses.

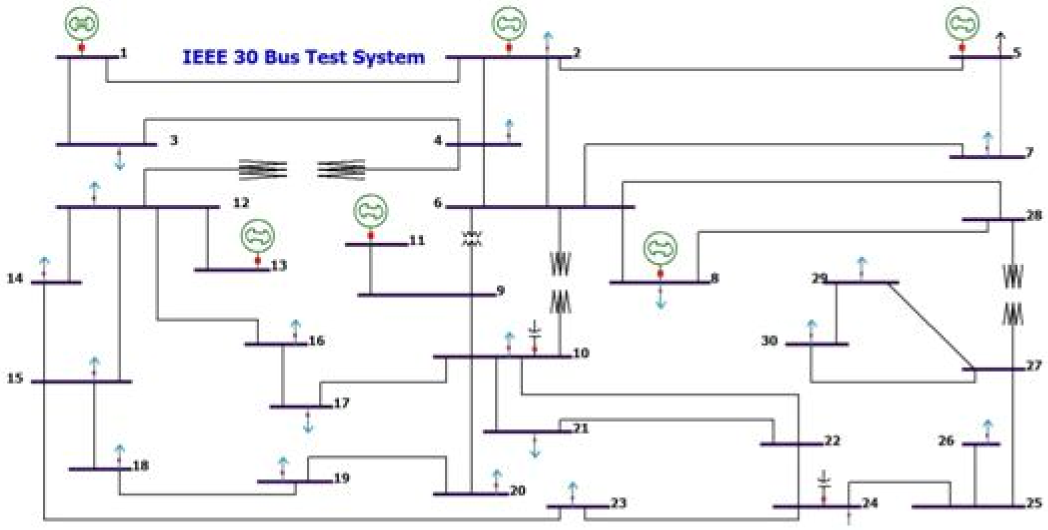

Figure-5: Single line diagram of the IEEE 30-bus system

In this study enhancement of ATC is obtained with optimal location and size of multiple FACTS devices such as SVC-UPFC, TCSC-UPFC, and SVC-TCSC-UPFC by applying GA, PSO and FPA separately. Installation cost of these FACTS devices has also been calculated for each transaction with reference to ATC value. The analysis is made for normal as well as contingency. Table 1 shows optimal location, type and setting of multiple FACTS devices using GA, PSO, and FPA for the bilateral transaction between a seller bus-11 in the source area and buyer bus-27 in sink area with the objective of maximizing the ATC. It can be seen from Table I, the FPA technique was able to find solutions close to the optimum and performed slightly better than GA and PSO. The results also show that multiple FACTS device such as SVC-TCSC-UPFC devices could enhance ATC much higher than other combination of SVC-UPFC and TCSC-UPFC devices. The ATC is increased from 41.293MW to 47.69 MW and 48.29 MW using GA and PSO respectively, while FPA technique could search better value which is 48.95 MW for the same location. Comparing these techniques, it can be observed from the Table 1 and 2 that FPA technique always outperformed the GA and PSO in terms of values of objective function and speed of convergence.

Hence the further analysis is performed with proposed FPA technique. In this study, five transactions between a seller bus in the 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 Eqn (18) are considered. A different combination of multiple FACTS is installed in the test system to study the effectiveness of the devices in enhancing ATC for different bilateral transactions under the normal and contingency operating conditions. The variation of ATC values for maximization of ATC with

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multiple FACTS devices under the normal operating condition is shown in Fig.6. For a contingency case, the branch line outage between buses 9 and 10 is considered. The effects of these FACTS devices during the contingency case on ATC enhancement are best is shown in Fig.7. From the Table 1 and Fig 6 and 7, it is identified that the ATC value is enhanced using multiple FACTS controllers. Out of which, the maximum ATC value is obtained with SVC-TCSC-UPFC devices when compared to remaining multiple FACTS controllers. Furthermore, the percentage of ATC increment in contingency case is completely higher compared to the normal condition. This shows that at the case of line breakdown, multiple FACTS devices can be effectively used to increase the transfer capabilities of the available lines. However, it is shown that at contingency case, SVC-TCSC-UPFC devices are the best choice of FACTS type for ATC enhancement and it is connected to the lines closer to the bus where violation occur. The comparative studies of active and reactive losses of the test system with multiple FACTS devices for a bilateral transaction between buses 11-27 are also tabulated in Table 1. It can be observed that the active and reactive power losses are reduced with use multiple SVC-TCSC-UPFC devices but the installation cost of this device is more.

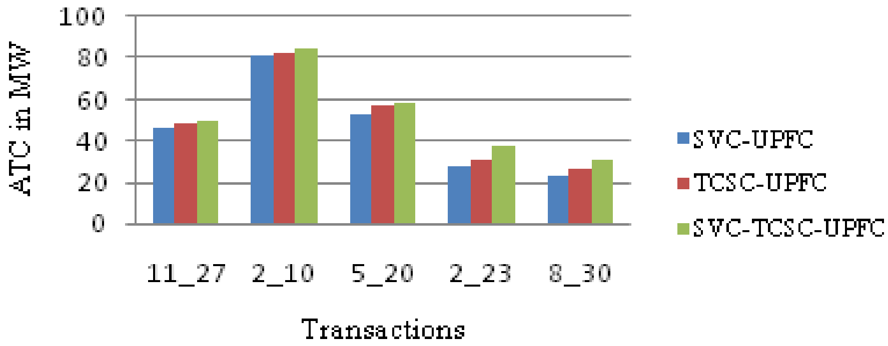

Figure-6: ATC enhancement for IEEE-30 bus system with multiple FACTS devices using FPA technique under normal operating conditions

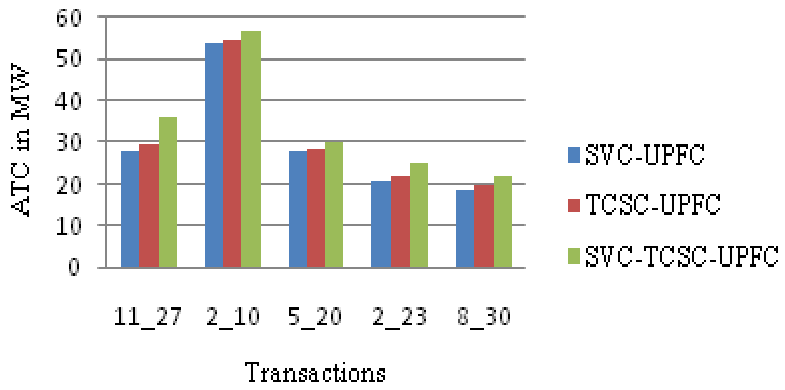

Figure-7: ATC enhancement for IEEE-30 bus system with multiple FACTS devices using FPA technique under contingency operating conditions

Table-1: Results for IEEE-30 bus system under normal operating conditions for bilateral transaction (11-27)

ATC without FACTS (MW)	Allocation Technique	Control parameters of multiple FACTS devices with enhancement of ATC					% decrease in power loss	
		Facts type	Location	Size	Installation cost (x10^8 US $)	ATC (MW)	Active power loss	Reactive power loss
41.293	GA	SVC UPFC	Bus-28 Line 22-24 & bus 24	7.2 MVAr -8.96 % X_{line} & 6.54 MVAr	0.395	45.14	11.94	12.48
		TCSC UPFC	Line 6-28 Line 22-24 & bus 24	-10.2 % X_{line} - 12.4 % X_{line} & 10.57 MVAr	1.512	48.62	14.86	11.41

		SVC TCSC UPFC	Bus-27 Line 6-28 Line 29-30 & bus 30	42.44 MVAr -15.15 % X_{line} - 18.64 % X_{line} & 60.32MVAr	2.684	46.54	15.54	16.24
41.293	PSO	SVC UPFC	Bus-28 Line 22-24 & bus 22	5.7 MVAr -7.08 % X_{line} & 6.9 MVAr	0.324	48.36	12.12	13.32
		TCSC UPFC	Line 6-28 Line 22-24 & bus 24	-15.1% X_{line} - 8.5 % X_{line} & 10.02 MVAr	1.467	48.11	15.18	12.58
		SVC TCSC UPFC	Bus-27 Line 6-28 Line 29-30 & bus 30	32.6 MVAr -10.2 % X_{line} - 22.7 % X_{line} & 63.7 MVAr	2.534	49.32	16.22	16.72
41.293	FPA	SVC UPFC	Bus-28 Line 22-24 & bus 24	5.2 MVAr -9.15% X_{line} & 6.56 MVAr	0.296	47.69	13.36	14.38
		TCSC UPFC	Line 6-28 Line 22-24 & bus 22	-10.1% X_{line} - 6.3 % X_{line} & 12.18 MVAr	1.234	49.24	15.21	14.34
		SVC TCSC UPFC	Bus-27 Line 6-28 Line 29-30 & bus 30	34.57 MVAr -13.09 % X_{line} - 19.48 % X_{line} & 53.93 MVAr	2.298	49.96	16.53	19.44

7. CONCLUSION

This paper introduces a novel method using FPA technique to find the optimal allocation of multiple FACTS devices for maximizes the ATC. Simulations were performed on IEEE-30 bus system test system. The results show the effectiveness of the new approach in simultaneously optimized the multiple FACTS devices location, rated values, installation cost and FACTS types. From the results obtained, it can be concluded that multiple SVC-TCSC-UPFC devices significantly enhances ATC, reduces total losses and improved the stability of the system under normal and contingency conditions when compared to remaining FACTS controllers. The proposed FPA technique generally outperformed the GA and PSO techniques that were compared in terms of speed of optimization and accuracy of the results obtained.

8. ACKNOWLEDGEMENT

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