Adaptive Fuzzy Particle Swarm Optimization Coordination of FACTS Devices to Enhance the Power System Security

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Abstract—*In deregulated power environment the power system parameters such as transmission line power flows and the system bus voltages are operated closer to the nominal values to meet the system demand. But this condition is unsafe for the power system secure operation. In order to sustain the system security and to meet the system demand with existing transmission lines, the Flexible AC Transmission System (FACTS) devices are one of the alternatives. In this paper, the bus voltage deviation and the line power flow factor to the maximum limit are considered as security indexes, which are taken as objectives for security problem and those are compensated by optimally placing the FACTS devices. Here, the FACTS devices used are Thyristor Controlled Series Compensator (TCSC), Static VAR Compensator (SVC) and Unified Power Flow Controller (UPFC). In this paper the proposed algorithm introduces Adaptive Fuzzy Particle Swarm Optimization (AFPSO) for optimal setting of FACTS devices. Here the inertia weight w is dynamically adjusted by using the fuzzy "IF/THEN" rules to increase the search ability. Additionally, power system losses and installation costs of FACTS devices are also included in the objective function for economic operation of FACTS installations. The proposed AFPSO method has been tested on IEEE 14 bus test system for optimal setting of FACTS devices and the results are compared with the Particle Swarm Optimization (PSO).*

Key words—*FACTS, TCSC, SVC, UPFC, Security Index (SI), PSO and AFPSO.*

1. Introduction

In recent years power system demand has been increased substantially while the growth of power generation and transmission has been inadequate due to environmental limitations and resources. As a result some of the transmission lines are heavily loaded and the power system security becomes a limiting factor. To overcome this problem and to supply the preferred power flow and bus voltages along the transmission line with better system security, Flexible AC Transmission System (FACTS) devices are mainly used [1]. By appropriate organization of FACTS controllers in the power system, both the real and reactive power flow in the transmission lines can be controlled. FACTS controllers can provide facilities in increasing the power system transmission capability and line power flow control flexibility [3], [4].

FACTS controllers can be classified into three types, such as series compensators, shunt compensators and combined series-shunt compensators [2]. Modelling of these FACTS devices in the power flow studies were reported in [5]. The SVC [2], [7] is a shunt controlled type FACTS device and is a Static Var generator or absorber whose output is adjusted to exchange capacitive or inductive current to keep the bus voltage. Thyristor Controlled Series Compensator (TCSC) is a series type FACTS controller to improve the transmission line power flow by compensating the inductive reactance of the transmission line. The UPFC is a combined series–shunt type FACTS controller for providing active power, reactive power, and voltage control and regulates all the three variables simultaneously or combination of them without violating the operating limits [5].

Evolutionary algorithms and population based algorithms are popular in recent years. Some well established algorithms like PSO was introduced by John Kennedy and Eberhart [8], for solving different optimization problems. For congestion management in power system the Genetic algorithm-based fuzzy logic multi-objective approach is attempted [9].The best location of FACTS devices to reduce generation cost using real power flow performance is introduced [10]. For allocation of FACTS and to improve system security GA approach is reported in [11]. For allocation of SVC in power system DE approach is used [12]. To minimise generator fuel cost with multi-type FACTS devices, a hybrid Tabu search and simulated annealing was reported [13]. Minimization of loss and optimal location of TCSC is done using DE approach [14]. A hybrid GA is used to solve OPF in a power system using FACTS devices [15].

In this paper, the proposed algorithm is Adaptive Fuzzy Particle Swarm Optimization (AFPSO) which is used to solve the optimal setting of FACTS controllers. Here the inertia weight (w) has been tuned by fuzzy “IF/THEN” rules to overcome the problems in PSO algorithm. The detailed version of PSO and its application for proposed purpose are explained in section 5 and Proposed AFPSO method is explained in the section 6. Prior to that, the power system security assessment is formulated in section 2 and employed FACTS devices are modeled in section 3 and finally is conclusion.

2. Power System Security

Power system security is the ability to keep the power flow from the generators to the customers, under unexpected disturbed conditions such as electric short circuits or unexpected loss of system components. The different measure of power system security are amounts, duration and frequency of customer outages [17]. Maintaining the power system security is one of the most important challenges faced by transmission system operators today. Reliable and secure operation of power systems is the key to the success of deregulation. The Security index will be a small value when the total active power circulated evenly in relation to the line flow capability of each line in the power system [16] and the index will increase as the number of overload lines increases. Similarly, when the bus voltage value is near to the desired value. Minimization of security indices means the maximization of security margins. Therefore it can be said that if the security index [18], [19] increases, the system security margin will decrease. The index J can be used to indicate the severity of each contingency and security level of the operating system.

Security index for real power =

$$J_P = \sum_{i}^{n} \sum_{i,j=1}^{n} W_i \left(\frac{p_{ij}}{p_{ij}^{\max}} \right)^{2n} \quad (1)$$

$$\text{Security index} = J_V = \sum_{i} W_i \left| V_i - V_{ref,i} \right| \quad (2)$$

i, j: bus numbers W_i : weighing factor

p_{ij} : Real power flow in the line between bus i and j

$p_{ij}^{\max}$: Maximum real power flow in line between bus i and j

J_P : Security index which means the even distribution of the total active flow

J_V : Security index which means how much the bus voltage is nearer to the ref voltage

$V_{ref,i}$: Nominal voltage

3. Flexible Alternating Current Transmission Systems (FACTS) Modeling

FACTS devices are composed of static devices usually power electronics based devices. These controllers are introduced depending on the type of power system problems [2]. In this paper, three types of FACTS controllers are used to enhance the power system security. These are Static Var Compensator (SVC), Thyristor Controlled Series Compensator (TCSC) and Unified Power Flow Controller (UPFC) which are shown in Fig.1, Fig.2, Fig.3, respectively.

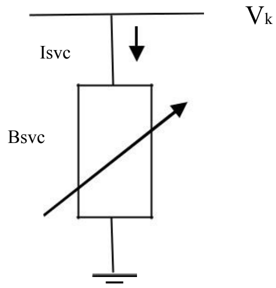

Fig.1: SVC Equivalent [20] variable Susceptance model

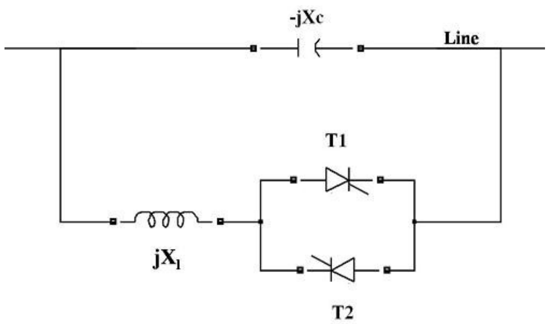

Fig. 2: Model of TCSC

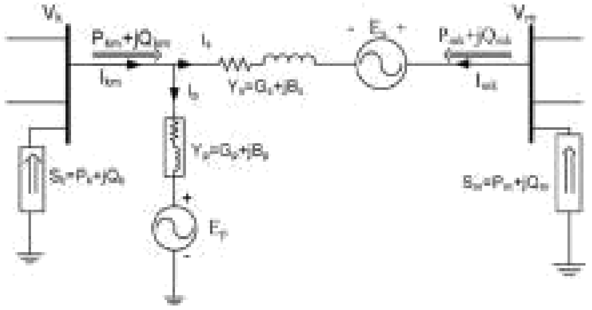

Fig. 3: Model of UPFC

In Fig. 3, the subscript p is used for parallel component and s is for series component.

E_p, E_s are voltage source converter voltages. Y_p is the admittance of parallel component and Y_s for series. P_{km}, Q_{km} are real and reactive power flows between node k and m.

SVC [1], [20] is a shunt connected type device which can be used to generate or absorb controllable reactive power by switching the capacitor and reactor banks "in" and "out" of the network. In this paper the SVC is modeled as an ideal reactive power injection at bus i.

$$\Delta Q_i = Q_{svc} \quad (3)$$

In case of TCSC the line power flow through the line i-j is named as P_{ij} .

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \quad (4)$$

So the power flow equation [18] in the line depends on the line reactance X_{ij}, the bus voltage magnitudes V_i and V_j and phase angle between sending end bus and receiving end bus δ_i and δ_j. SVC can control the bus voltage by changing reactive power at the connected bus. The TCSC can control the line power flow by changing the line reactance. The control parameters of UPFC are the bus voltage, line impedance and phase angle. By changing these parameters the power flow can be controlled.

4. Problem Formulation

The main objective of this paper is to minimize the cost of installation of FACTS devices, power system loss and security index. By combining all these fitness function or objective function (Obj fn) is formed.

$$Objfn = F = a_1 (J_p) + a_2 (J_v) + a_3 \text{(Total Investment Cost)} + a_4 (Losses) \quad (5)$$

Using the database of [2], the cost function of TCSC, SVC, and UPFC are shown in equations (6)-(8).

For TCSC

$C_{TCSC} = 0.0015S^2 - 0.713S + 153.75$ (US$/KVAR) (6)

For SVC

$C_{SVC} = 0.0003S^2 - 0.3051S + 127.38$ (US$/KVAR) (7)

For UPFC $C_{UPFC} = 0.0003S^2 - 0.2691S + 188.22$(US$/KVAR) (8) Where S is the operating range of the FACTS devices in MVAR.

$$S = |Q_2 - Q_1| \quad (9)$$

Where Q_2 is the reactive power flow in the transmission line after installing FACTS device in MVAR and the reactive power Q_1 is before installing FACTS device and The J_P, J_V are discussed in section II.

The coefficients a_1 to a_4 will be obtained by trial and error method. The used values are 0.2665, 0.5714, 0.1421 and 0.02.

The cost functions for the three FACTS devices are shown in Fig.4, which is obtained from the MATLAB simulation.

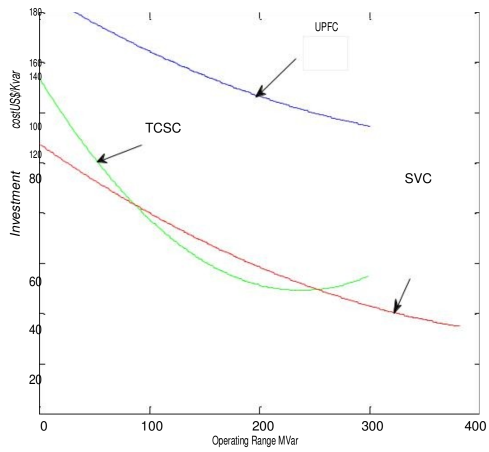

Fig.4 Cost function of FACTS Devices

The objective function is optimized with the following constraints.

Line thermal limits: $P_{ij} \le P_{ij}^{max}$

Where P_{ij} is the line power flow between the buses i and j.

P_{ij}^{max} is the line thermal rating.

Bus voltage limits: $0.9 \le V_b \le 1.1$, where V_b is the bus voltage

FACTS device constraints:

$$-0.7 X_L \le X_{TCSC} \le 0.2 X_L \quad (10)$$

$$-0.3\ p.u \le Q_{svc} \le 1\ p.u \quad (11)$$

The equations (10) and (11) for UPFC. Where X_{TCSC} is the reactance added in the line by providing TCSC. X_L is the transmission line where the TCSC is placed and Q_{SVC} is the injected reactive power at the bus by connecting SVC.

Power flow constraints: F (V, θ) =0

where

$$F(V,\theta) = \begin{Bmatrix} P_i(V,\theta) - P_i^{net} \\ Q_i(V,\theta) - Q_i^{net} \\ P_j(V,\theta) - P_j^{net} \end{Bmatrix} \quad \text{PQbus} \qquad (12)$$

Where P_i is the active power calculated for PQ bus, Pj is the real power calculated for PV bus, Q_i is the reactive power calculated for PQ bus, P_i^{net} is the specified real power for PQ bus, Q_i^{net} is the specified reactive power for PQ bus, Pj^{net} is the specified real power at PV bus, V is the voltage magnitudes at different busses, θ is the phase angle of voltages at different buses.

5. Over view of PSO and its implementation

PSO is population based optimization technique [8], it simulates the birds flocking. Initially a random population of particles are generated. Each individual particle is assigned with a velocity. For all particles, fitness or objective function values are evaluated. Unlike Genetic Algorithm (GA), PSO doesn't have crossover/mutation. Each particle knows its best value so far is called Pbest, in group is called Gbest among all Pbest. Each particle tries to change their position by considering its current positions X_i, current velocities V_i, the individual intelligence Pbest and the group intelligence Gbest [5]. This process is repeated until either maximum generations or convergence is reached.

The equations (13) & (14) are used to compute the velocities and positions.

$$V_i^{j+1} = W V_i^j + C_1 \, rand_1 \left(Pbest_i - X_i^j\right) + C_2 \, rand_2 \left(Gbest - X_i^j\right) \qquad (13)$$

$$X_i^{j+1} = X_i^j + V_i^{j+1} \qquad (14)$$

Where V_i^{j+1} is the velocity of the i^{th} particle in $(j+1)^{th}$ iteration. C_1 and C_2 are the learning factors and are taken between (0, 2.5). W is the inertia weight.rand1 and rand2 are the random numbers generated between (0, 1).$Pbest_i$ is the best position of the i^{th} individual. Gbest is the group best value. X_i^j is the position of i^{th} individual in j^{th} iteration.

The inertia weight W is changed by using the equation (15).

$$W = W_{max} - \frac{W_{max} - W_{min}}{iter_{max}} \, iter \qquad (15)$$

Where Wmax is the initial value of the inertia weight taken as 0.9, Wmin is the final value of the inertia weight taken as 0.4, $iter_{max}$ is the maximum number of iterations and iter is the current iteration. This algorithm can be implemented like the procedure explained in sub-section 5.1, 5.2.

5.1. Initialization

The initial population of particles is generated randomly between the given constraint range. The variables corresponding to the FACTS devices are their location and setting. For TCSC, SVC uses two variables (i.e. setting and location). UPFC is modeled as combination of shunt and series device, so uses 3 variables (series setting, shunt setting, location).

5.2. Fitness Function calculation

The fitness function is shown in equation (5), it consists of four terms. The first 2 terms corresponding to security indices, third term corresponds to FACTS investment cost, fourth term corresponds to power system loss. For each vector, the transmission line data is updated according to its TCSC setting, location and the power system bus data is updated according to its SVC setting, location. For UPFC, combination of both are used. Then the N-R load flow is performed to calculate the bus voltages, line flows. By using these values, fitness function is calculated. The procedure is repeated until the maximum number of iterations is reached.

The pseudo code of the PSO Procedure:

For each control variable:
Initialize particle
End
Do
For each particle calculate fitness value
If the fitness value is better than the best fitness value (pbest) in history set the current value as the new pbest
End
Choose the particle with the best fitness value of all the particles as the gbest
For each particle Calculate particle velocity according to velocity equation
Update particle position according to the position equation
End

While maximum iterations or minimum error criterion is not attained

6. Proposed Adaptive Fuzzy Particle Swarm Optimization (AFPSO)

The PSO algorithm has the problem to solve the optimal setting of FACTS devices because of the optimal setting of the inertia weight w. Sometimes the search will undergo to the local optima. To overcome this problem AFPSO [27] [28] is applied to tune the inertia weight w by using fuzzy "IF/THEN" rules. This method dynamically adjusts the inertia weight w. The inertia weight can control the exploration properties of the algorithm, with higher values providing a more global behaviour and lesser values providing a more local behaviour. In the AFPSO concept, the velocity and position of the particles are updated by using the equations which are same as in the case of PSO. The inertia weight (w) is dynamically adjusted by using the fuzzy "IF/THEN" rules as the iterations grow. To get the better inertia weight under fuzzy environment the inputs and outputs considered are the Normalized Fitness Values (NFV) and the present inertia weight (w). These are the two inputs, where as the correction of the inertia weight (Δw) is chosen as the output variable and these are expressed in fuzzy set notations. The input and output variables are depicted in Fig 5.

Fig.5 Fuzzy Inference system

For simplicity the fuzzy membership functions are chosen as the triangular membership functions and these input variables are represented in three linguistic values Small(S), Medium (M), Large (L).Where as the output variable is represented in three fuzzy sets of linguistic values Negative (NE), Zero (ZE), Positive (PE). These are shown in Figures 6 to 8. Next step is to form the fuzzy rules; The Mamdani type fuzzy rule base implication is used. For example IF (NFV is S) AND (G is M) THEN change in the inertia weight is NE. These rules are shown in the Table 1.

Normalize Fitness Value (NFV) is used to find the inertia weight for the correct choice of particle velocity, the limit chosen is in between 0 and 1.

$$NFV = \frac{F - F_{min}}{F_{max} - F_{min}} \quad (20)$$

For minimization problems, a small value of NFV indicates good solution. Fmin is a small value which is less than any acceptable feasible solution. Fmax is a large value which is obtained in the first iteration. F is the fitness function calculated from equation (5). The present inertia weight is chosen between 0.4 and 1. The change in inertia weight is chosen in between -0.1 and 0.1. Here each input is having three linguistic values so the possible rules are 3*3=9. As the number of rules increase the complexity of the problem increases. Finally the total output is defuzzified in to a crisp value by the use of the centroid method. The output Δw is coming from the fuzzy inference system (FIS), which is added to the inertia weight of present iteration to get the inertia weight for the next iteration. In this way as explained in this section the fuzzy logic system is described in three principle components. i) Fuzzification ii) Fuzzy rule base and reasoning iii) Defuzzification.

This fuzzy logic system architecture or fuzzy system structure is shown in Fig. 9.

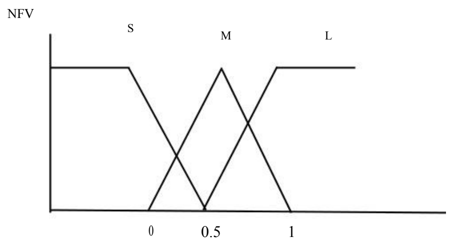

Fig.6 Membership function of NFV

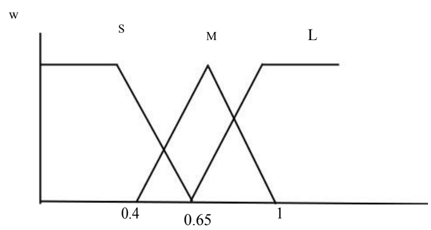

Fig.7 Membership function of w

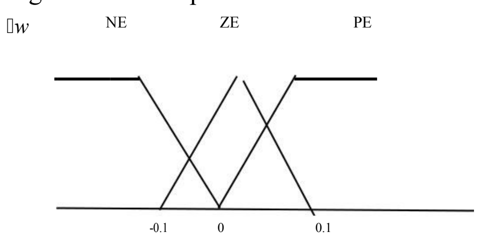

Fig.8 Membership function of Δw

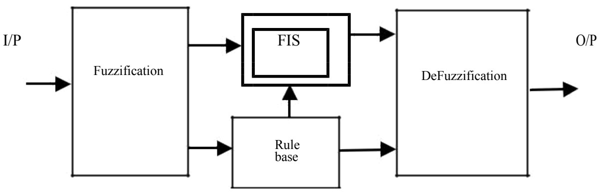

Fig.9 Fuzzy System structure

6.1 Application of AFPSO for enhancing the power system security

Step 1: Initialize the agents or parameters

In this step, the parameters include the location of FACTS devices, range of FACTS devices which are defined.

Step 2: Calculate the fitness value of each agent using the objective function equation (5) and update the Pbest and Gbest values.

Step 3: Update the inertia weight w by using the Fuzzy "IF/THEN" rules.

Step 4: Now update the velocity and position of each particle by using the equations (13), (14).

Step 5: Check the maximum number of iterations, if reached go to step 6 else go to step 2.

Step 6: The Gbest obtained in the last iteration, is the optimal value.

7. Results and Discussion

The solutions for minimization of power system loss, total investment cost of the FACTS devices, security indices were obtained. Here the IEEE 14 bus system is taken as test system for the case study. The simulation studies are carried out in the MATLAB environment. The flow chart for the best fit of FACTS devices using PSO and AFPSO are shown in Fig.10, 11.

7.1. IEEE 14 bus Test system

The bus data and line data are taken from [24] and contain 20 transmission lines. The setting of FACTS device, minimum loss and optimal installation cost, best security indices are obtained by using the PSO, AFPSO algorithms. It is observed that the FACTS devices improve the transmission line power flows, voltages nearer to its thermal and voltage ratings. The FACTS devices are positioned in order to reduce the loadings of reactive and active powers by forcing the power flows in other directions. This can be proved by reduction of security indices J_p, J_v. If the line powers and bus voltages are near to the limits then automatically J_p, J_v will be reduced. The performance of the proposed AFPSO technique is compared with PSO. The parameters of PSO are shown in Table 2. It is observed from the tables 4, 5, 6, 7 that the proposed AFPSO gives less power loss and installation cost by using FACTS controllers. And also the cost and performance index graphs are improved which are observed in figures 12 to 17. Therefore the parameters obtained from AFPSO are optimum compared to PSO technique. The inertia weight adjusts the search accuracy, which tends to fast convergence. In the PSO method the selection of w is inappropriate, which results the velocity of the particles decreases rapidly and particles will become immobile.

Table 1: Fuzzy rules for incremental inertia weight

Rule No.	NFV	w	Δw
1	S	S	ZE
2	S	M	NE
3	S	L	NE
4	M	S	PE
5	M	M	ZE
6	M	L	NE
7	L	S	PE
8	L	M	ZE
9	L	L	NE

Table 2: PSO parameters

Pop Size	50
Error tolerance:	0.01
C_1,C_2	1.5
W_{max}	0.9
W_{min}	0.4
No.of swarm beings	50
No.of iterations	100

The Constraints used to generate the population:

$$-0.7X_L \le X_{TCSC} \le 0.2X_L$$

$$0.3\,p.u \le Q_{svc} \le 1\,p.u$$

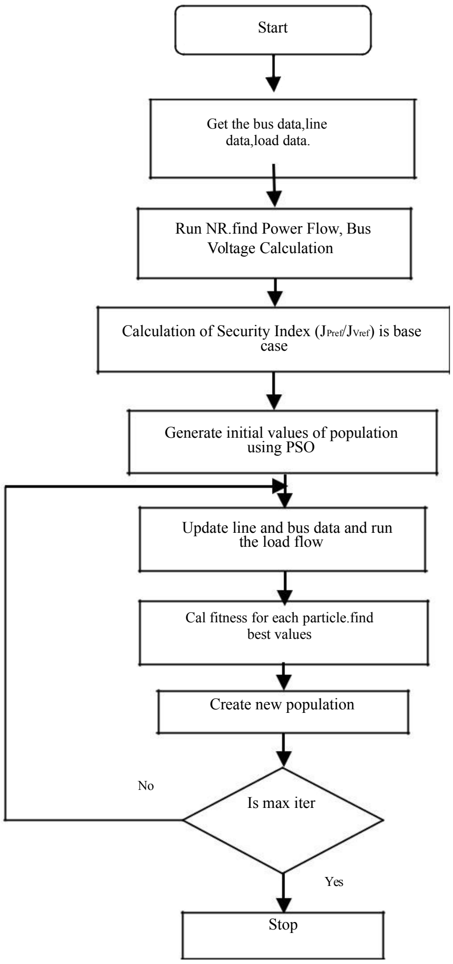

Fig.10 The flow chart representation of PSO

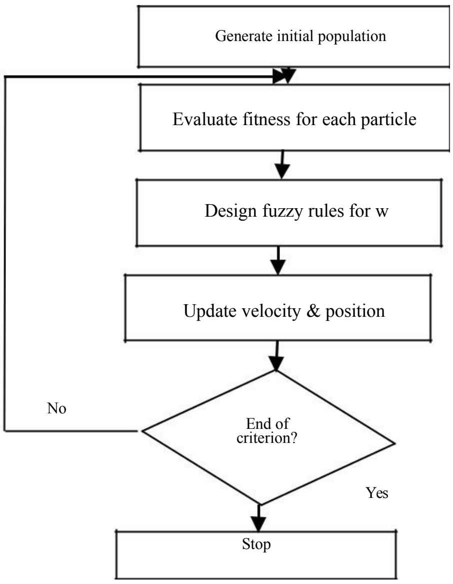

Fig.11 The flow chart of AFPSO

Table 4: FACTS allocation and the size of the device with PSO

	SVC		TCSC		UPFC	
Device Type	Size (MVA)	Location Bus no:	Size (MVA)	Location Bus no- Bus no	Size (MVA)	Location Bus no- Bus no:
TCSC	-	-	218	9-10	-	-
SVC	98	6	-	-	-	-
UPFC	-		-	-	210	6-12

Table 5: FACTS allocation and the size of the device with AFPSO

	SVC		TCSC		UPFC	
Device Type	Size (MVA)	Location Bus no:	Size (MVA)	Location Bus no- Bus no	Size (MVA)	Location Bus no- Bus no:
TCSC	-	-	206	4-6	-	-
SVC	95	9	-	-	-	-
UPFC	-	-	-	-	200	15-18

Table 6: Security Indices and installation costs using PSO

Device	Jp	Jv	Cost$	Losses(MW)
Without FACTS	10	4.0	-	13.6
TCSC	8.5	3.9	1426596	12.24
SVC	7.9	3.3	1225473	12.10
UPFC	7.5	3.1	1880456	11.8

Table 7: Security Indices and installation costs using AFPSO

Device	Jp	Jv	Cost$	Losses(MW)
Without FACTS	10	4.0	-	13.6
TCSC	8.1	3.5	1396596	11.94
SVC	7.5	3.1	1212473	11.80
UPFC	7.5	3.1	1799456	11.54

In the Graphs or Figures 12 to 17 the blue line indicates for PSO algorithm and red line indicates the AFPSO algorithm.

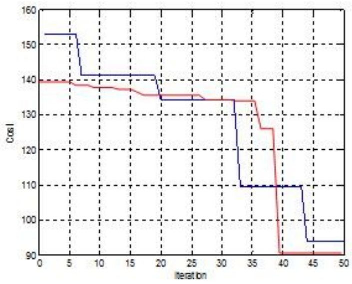

Fig. 12 Cost vs. iteration using SVC

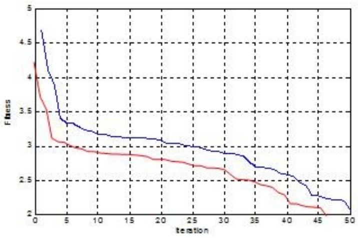

Fig. 13 Performance index evolution with SVC

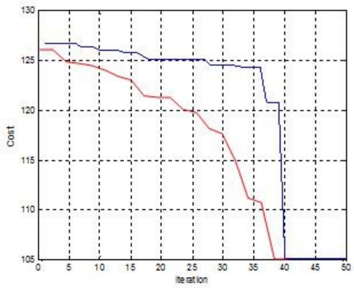

Fig. 14 Cost vs. iteration using TCSC

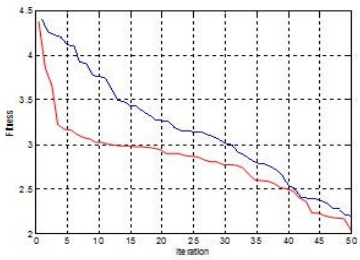

Fig. 15 Performance index evolution with TCSC

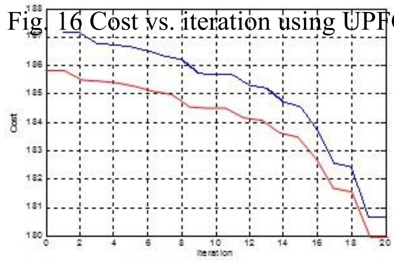

Fig. 16 Cost vs. iteration using UPFC

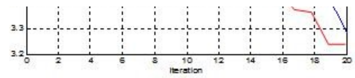

Fig. 17 Performance index evolution with UPFC

9. Conclusion

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