HYBRID DIFFERENTIAL EVOLUTION ALGORITHM BASED POWER SYSTEM SECURITY ANALYSIS USING FACTS

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Abstract—*This paper presents a novel stochastic hybrid differential evolutionary algorithm technique to find the optimal location of Flexible Alternating Current Transmission System (FACTS) devices with minimum cost of installation and to improve power system security. Differential Evolution algorithm (DE) is a simple evolutionary search algorithm and shows better performance but greedy in space searching. Particle Swarm Optimization (PSO) converges quickly and but stuck in local optima. In this paper hybrid differential evolutionary algorithm (DEPSO) is introduced to eliminate the problems of DE and PSO and solve the power system security problem with greater accuracy. The proposed algorithm minimizes the security index, loss and the installation cost of FACTS devices in the transmission network. Security index indicates the overload level of the transmission lines. Three types of FACTS devices, Static Var Compensator (SVC), Thyristor Controlled Series Compensator (TCSC) and Unified Power Flow Controller (UPFC) are considered and the proposed algorithm is verified by standard IEEE 14 bus network.*

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

1. Introduction

In the present situation, most of the power systems in the developing countries with large interconnected networks share the generation reserves to increase the reliability of the power system. However, with large interconnected networks there are increased complexities like fluctuations in reliability of power supply, which results in system instability, difficult to control the power flows, bus voltages and security problems that results large number blackouts in various parts of the world. The above consequences may be due to the weak interconnection of the power system, systematical errors in planning and operation, overload of the network [1].

To beat these problems and to supply the preferred power flow and bus voltages along the transmission line with better system security and reliability, FACTS devices becomes an alternative[2].

FACTS provides[3][4] the facility to increase the controllability and to improve the transmission system operation in terms of power flow, stability limits with advanced control technologies in the existing power systems. FACTS devices can be characterized into three types, such as series compensators, shunt 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 connected FACTS controller and is a Static Var generator or absorber whose output is adjusted to exchange inductive or capacitive current to maintain the bus voltage. Thyristor Controlled Series Compensator (TCSC) is a series type FACTS controller to improve the line flow by compensating the inductive reactance of the transmission line. The UPFC is a combined series – shunt type FACTS device 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], is applied for solving different optimization problems. For congestion management in the 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 reported [12]. To minimise generator fuel cost with multi-type FACTS a hybrid Tabu search and simulated annealing was reported [13]. Minimization of loss and for optimal location of TCSC, DE approach is reported [14]. A hybrid GA is used to solve OPF in a power system using FACTS was reported [15].

The organization of the paper is as follows and these sections explain about Section II power system security, section III FACTS modelling, and section IV problem formulation, section V overview of DE and its implementation, section VI overview of PSO and its implementation, section VII proposed DEPSO algorithm, section VIII results and discussion, section IX conclusion.

In this paper by applying DE,PSO,DEPSO techniques, the optimal location of the FACTS devices to get the minimum installation cost of FACTS devices, minimum loss and to enhance the power system security by minimizing the security index(SI), without violating the power system constraints. Here the TCSC is modelled as a variable reactance inserted in the transmission line and the SVC has been modelled as the reactive source added at the bus. UPFC is modelled as combination of TCSC in the line and SVC at a bus connected to the same bus. These algorithms are verified by standard IEEE 14 bus networks. It is observed that power system security is increased by minimizing system loss and security index. Security index is related line power flow and bus voltage. So by minimizing the security index we can improve the security [16].

2. Power System Security

Power system security is the ability to maintain the power flow of electricity from the generators to the consumers, under sudden disturbed conditions such as electric short circuits or unanticipated loss of system elements. The measures of power system security are amounts, duration and frequency of customer outages [17]. To maintain power system security is one of the major challenges facing 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 real power circulated evenly in relation to the line power flow capacity 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 near to the desired value. Minimization of both, JP and Jv. 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. As a result the index J can be used to indicate the severity of each contingency and security level of the operating system.

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

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

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: is the security index which means the even distribution of the total active flow

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

$V_{ref,i}$: Nominal voltage

3. Flexible Alternating Current Transmission Systems (Facts) Modeling

FACTS are highly engineered power electronics based devices. These controllers were introduced depending on the type of power system problems [2].In this paper three types of FACTS devices are used to improve security of power system. 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.

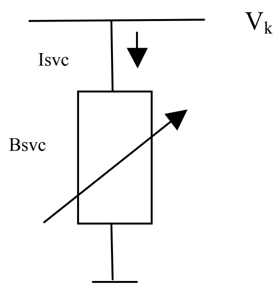

Fig.1: SVC Equivalent [20] variable Susceptance model

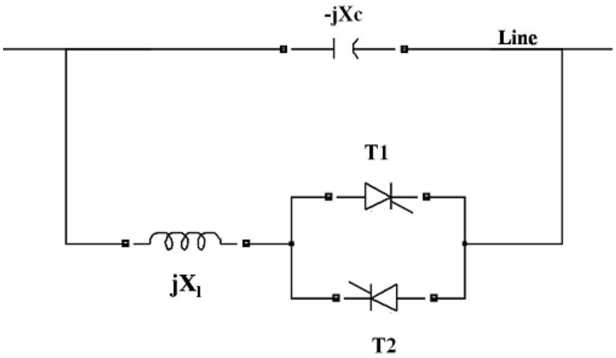

Fig. 2: Model of TCSC

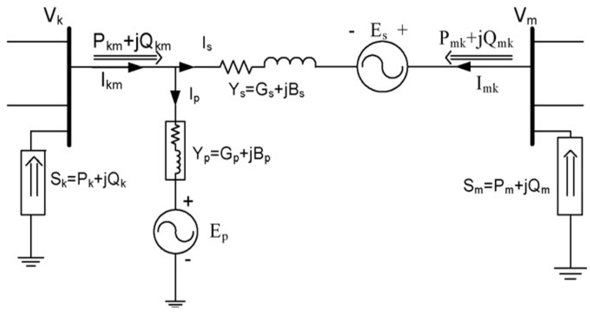

Fig. 3: Model of UPFC

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

E_p, E_s are voltage source converters 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 nodes k and m.

SVC is a shunt connected device and can be used for both capacitive and inductive compensation. In this paper the SVC is modeled as an ideal reactive power injection at bus i.

$$\Delta Q_i = Q_{svc} \tag{3}$$

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

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

So the power flow [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. UPFC control parameters 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.

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

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.

$$S = |Q_2| - |Q_1| \tag{9}$$

Where Q_2 is the reactive power flow in the transmission line after installing FACTS device in MVAR and the reactive power Q1 is before installing FACTS device. And The JP, JV 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.

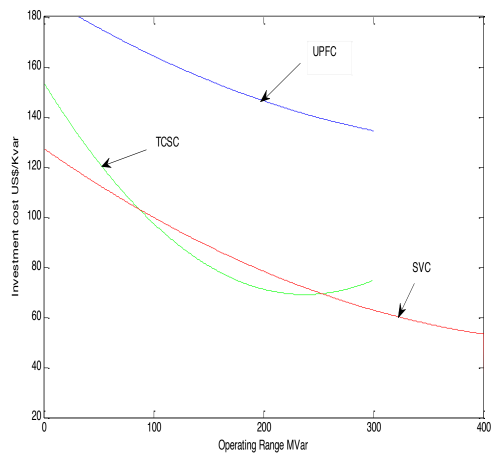

Fig.4 Cost function of FACTS Devices

The objective function is optimized with the following constraints.

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

Where P_{ij} is the line power flow between the busses 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 devices constraints:

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

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

(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

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

P_i is real power calculated for PQ bus,P_j 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,P_i^{net} is the specified real power at PV bus, V is the voltage magnitudes at different busses, θ is the phase angles of voltages at different busses.

5. Over view of DE and its implementation

DE was first proposed by Storn and price at Berkely in the year 1994-1996. It is stochastic population based search algorithm [18]. It is similar to the population based algorithms like GA but the main difference between DE and GA are the GA relay on crossover, while the evolutionary algorithms use mutation as primary search mechanism. In each generation NP population vectors have been generated. The first member of population is "individual 1" is set as the target vector. To generate noisy random vector three individuals are selected randomly from the population size. The weighted difference between the two individuals is added to the third randomly chosen vector to generate noisy random vector. The obtained noisy random vector does a cross over with the target vector to generate trail vector. The fitness functions of the two vectors are compared and the vector corresponding to the best fitness is taken as "individual 1" for the next generation.

$$X_{ij} = \left[x_{1,i,G,} x_{2,i,G,} \ldots\ldots x_{D,i,G}\right] \quad (13)$$

For i=1, 2…………, NP

Where G is the generation number and D is the dimension of the problem.

$$V_i = X_{r1,G} + F \times \left(X_{r2,G} - X_{r3,G}\right) \quad (14)$$

Where V_i is the noisy random vector. F is the weighting factor chosen as 0.8, which has a direct effect on convergence rate.

The three vectors $X_{r1,G}$,$X_{r2,G}$ and $X_{r3,G}$ are selected randomly.

Then to get the trail vector the crossing operation is used and the trail vector u_i is given by

$$u_{j,G+1} = \begin{cases} v_{j,i,G+1} & \text{If } rand_{j,i} \le CR \\ x_{j,i,G+1} & \text{If } rand_{j,i} > CR \end{cases} \quad (15)$$

Where the $rand_{j,i}$ is a randomly generated number between (0,1).CR is called as crossing factor, which is a user defined number between (0,1).

The fitness functions of the target vector $x_{i,G+1}$ and trail vector $u_{i,G+1}$ are compared and the vector corresponding to the best fitness taken for the next generation.

$$x_{i,G+1} = \begin{cases} u_{i,G+1} \text{ if } & f\left(u_{i,G+1}\right) \le f\left(x_{i,G}\right) \\ x_{i,G} & otherwise \end{cases} \quad (16)$$

The mutation, crossover and selection will be continued until the convergence criterion is satisfied.

5.1. Initialization

The initial population of particles is generated randomly between the given constraint range. The variable corresponding to the FACTS device is 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 and the location and the power system bus data is updated according to its SVC setting and the location. For UPFC combination of both. 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.

6. Over view of PSO and its implementation

PSO is population based optimization technique [8], it simulates birds flocking, which optimizes a certain objective function. 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 Xi, current velocities Vi, the individual intelligence Pbest and the group intelligence Gbest [5].

The equations shown below are used to compute the positions and velocities.

$$V_i^{j+1} = W \times V_i^j + C_1 \times rand_1 \times \left(Pbest_i - X_i^j\right) + + C_2 \times rand_2 \times \left(Gbest - X_i^j\right) \quad (17)$$

$$X_i^{j+1} = X_i^j + V_i^{j+1} \quad (18)$$

Where V_i^{j+1} is the velocity of the i^{th} particle in $(j+1)^{th}$ iteration.C1 and C2 are the learning factors and 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 below equation (19).

$$W = W_{\max} - \left(\frac{W_{\max} - W_{\min}}{iter_{\max}}\right) \times iter \quad (19)$$

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.

The pseudo code of the procedure:

For each particle
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

7. Proposed DEPSO Algorithm

In the hybrid differential evolution, which introduces one-to-one competition will provide faster convergence speed towards optimum. It uses less number of populations in the evolutionary process to get the global solution [22], [23].

To eliminate the problems in DE and PSO and to get the advantages of both the DEPSO algorithm is developed. The procedure is as follows.

- Initially generate a set of random values of population (NP).This initial set of population is considered as parent vector.
- Calculate the fitness value $F_1(i)$ using equation 5 for each of the particle in the parent vector; For i=1,2,3……….NP
- Now perform the operations like mutation, cross over and selection .The resultant vector is the Target vector.
- Calculate the fitness value $F_2(i)$ using equation 5 for each particle in the target vector.
- Obtain the overall best particle Gbest up to this iteration and Pbest is the set of best particles at that iteration.
- Evaluate each particle velocity in the parent vector using these Pbest and Gbest values.
- Now update the positions of each particle in the parent vector using these velocities using PSO.
- By using these values evaluate the fitness value $F_3(i)$ using equation 5 .
- By comparing the fitness values $F_1(i)$, $F_2(i)$ and $F_3(i)$; now select the best particles either from parent vector or target vector or PSO vector.
- Now these selected set of particles become parent vector for next iteration and repeat the steps for fixed number of iterations.

8. 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 best fit of FACTS is shown in fig.5

8.1. IEEE 14 bus Test system

The line data and bus data are taken from [24] and contain 20 lines. The setting of FACTS device, optimal installation cost ,minimum loss, best security indices are obtained by using the DE,PSO,DEPSO 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 located 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 line powers and bus voltages nearer to the limits then automatically J_p, J_v will be reduced. The performance of the proposed hybrid differential evolution technique is compared with DE and PSO.The parameters of DE, PSO are shown in table 1, 2 respectively and combination of both for DEPSO.

Table 1: DE parameters

NP	D	F	CR	Iterations
50	2	1.2	0.5	100

Table 2: PSO parameters

C_1,C_2	1.5
W_{max}	0.9
W_{min}	0.4
No.of swarm beings	50
No.of iterations	100

For all these artificial intelligence techniques the parameters used are:
Population size: 50
Error tolerance: 0.01
Constraints used to generate the population:

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

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

Table 3, 4, 5 shows the optimal locations, sizes of the devices using DE, PSO, DEPSO algorithms.

Table 3: FACTS allocation and the size of the device with DE

	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	-	-	228	2-3		-
SVC	80	13	-	-	-	-
UPFC	-	-	-	-	223	3-4

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	9	-	-	-	-
UPFC	-	-	-	-	210	6-12

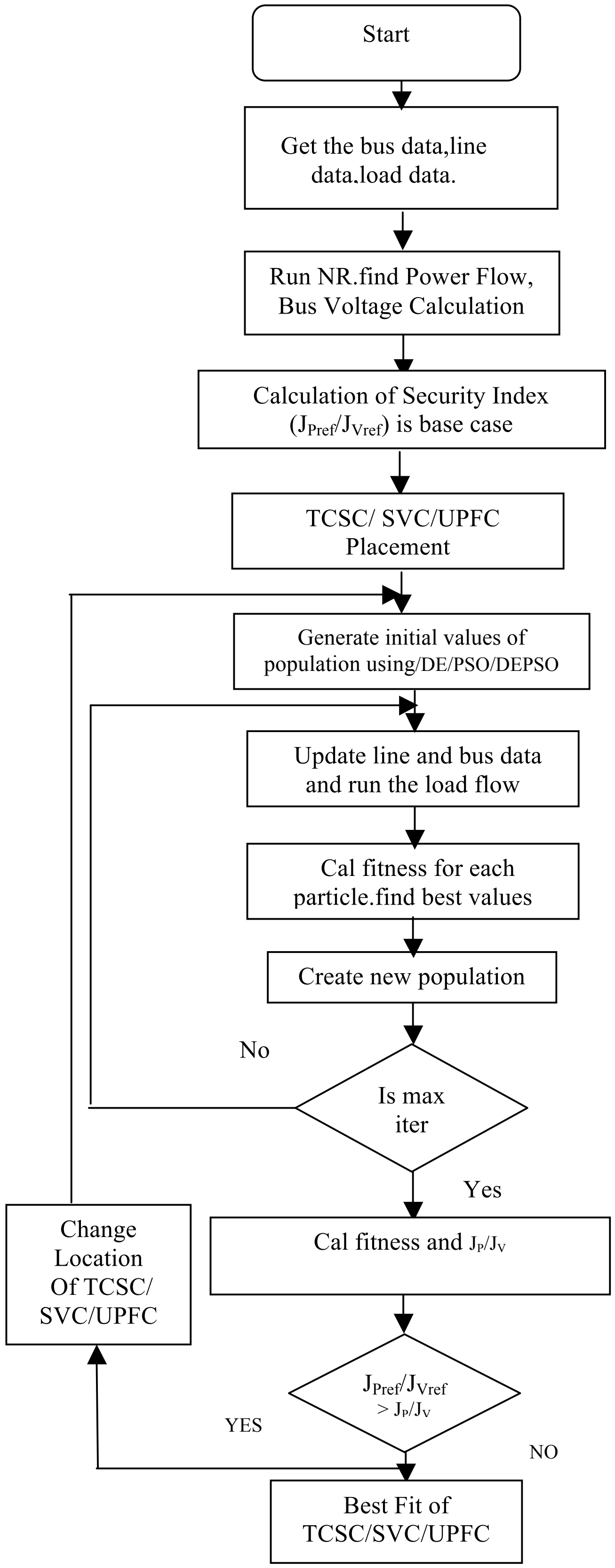

Fig.5. Flow chart representation of Best fit of TCSC/SVC/UPFC

Table 5. FACTS allocation and the size of the device with DEPSO

Device Type	SVC Size (MVA)	SVC Location Bus no:	TCSC Size (MVA)	TCSC Location Bus no- Bus no	UPFC Size (MVA)	UPFC Location Bus no- Bus no:
TCSC	-	-	224	6-11	-	-
SVC	90	4	-	-	-	-
UPFC	-	-	-	-	164	2-5

Table 6: Security Indices and installation costs using DE

Device	Jp	Jv	Cost$	Losses(MW)
Without FACTS	10	4.0	-	13.6
TCSC	9.9	3.7	1935000	12.2
SVC	9.1	3.4	1225700	12.3
UPFC	8.5	2.8	1861382	12.0

By observing the table 6 the security indices are improved in case of TCSC the values improved from 10 ,4.0 to 9.9 and 3.7,in case of SVC the values improved from 10 ,4.0 to 9.1and 3.4, in case of UPFC the values improved from 10 ,4.0 to 8.5 and 2.8. Among these devices the security index using UPFC is less. The losses without connecting FACTS is 13.6 MW and these are reduced significantly by using the FACTS devices.

Table 7: 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

By observing the table 7 the security indices are improved in case of TCSC the values improved form 10, 4.0 to 8.5 and 3.9, in case of SVC the values improved form 10, 4.0 to 7.9 and 3.3, in case of UPFC the values improved form 10, 4.0 to 7.5 and 3.1. Among these devices the security index using UPFC is less. The losses without connecting FACTS is 13.6 MW and these are reduced significantly by using the FACTS devices.

Table 8: Security Indices and installation costs using DEPSO

Device	Jp	Jv	Cost$	Losses(MW)
Without FACTS	10	4.0	-	13.6
TCSC	7.9	3.9	1444476	12.21
SVC	7.6	3.4	1089289	12.10
UPFC	7.4	2.9	1796304	11.50

By observing the table 8 the security indices are improved in case of TCSC the values improved form 10, 4.0 to 7.9 and 3.9, in case of SVC the values improved form 10, 4.0 to 7.6 and 3.4, in case of UPFC the values improved form 10, 4.0 to 7.4 and 2.9. Among these devices the security index using UPFC is less. By observing these tables the values obtained by DEPSO are more accurate than the other methods. By observing the tables 6, 7, 8 the security indices are reducing with reference to base case security index and losses also reduced with reference to base case.

The graphs shown in Fig.6, 7, 8 are fitness variation in every iteration using DE, PSO and DEPSO. It is clear that the convergence is accurate using DEPSO.

The losses without connecting FACTS is 13.6 MW and these are reduced significantly by using the FACTS devices so by using these evolutionary optimization techniques the optimal location and setting of the Flexible Alternating Current Transmission System devices is obtained and the cost of installation ,system losses, security indices are minimized.

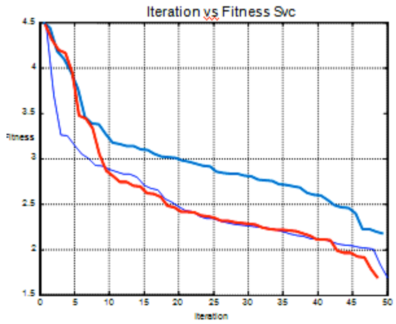

Fig.6 Fitness variation in every iteration using SVC

DEPSO
DE
PSO

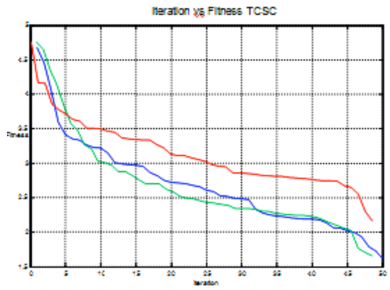

Fig.7 Fitness variation in every iteration using TCSC

DE
PSO
DE PSO

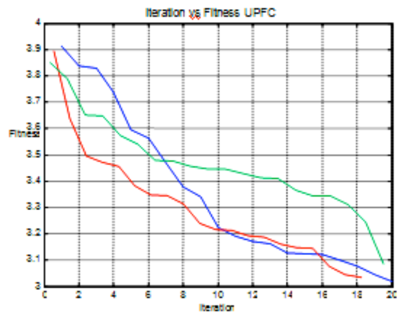

Fig.8 Fitness variation in every iteration using UPFC

DEPSO
PSO
DE

9. Conclusion

In this paper a novel optimization algorithm called hybrid differential evolution algorithm (DEPSO) has been proposed to achieve a better result and to eliminate the problems of DE and PSO to solve the power system security problem with a greater accuracy**.** The efficacy of the proposed algorithm is tested on IEEE 14-bus system. The test results of proposed algorithm are compared with the well-known heuristic search methods DE, PSO. From the test results, it is observed that, the proposed algorithm converges to best solution compared to differential evolution (DE), Particle Swarm Optimization (PSO) techniques. By using DE, PSO, DEPSO algorithms the security indices reduced compared to the base case security indices. Among these algorithms there is better improvement of system security by using the proposed (DEPSO) algorithm. Thus, the proposed hybrid differential evolution algorithm is more effective for the security analysis.

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