

Optimal Location of Multi Type Facts Devices for Multiple Contingencies Using Particle Swarm Optimization

S. Sutha, and N. Kamaraj

Abstract—In deregulated operating regime power system security is an issue that needs due thoughtfulness from researchers in the horizon of unbundling of generation and transmission. Electric power systems are exposed to various contingencies. Network contingencies often contribute to overloading of branches, violation of voltages and also leading to problems of security/stability. To maintain the security of the systems, it is desirable to estimate the effect of contingencies and pertinent control measurement can be taken on to improve the system security. This paper presents the application of particle swarm optimization algorithm to find the optimal location of multi type FACTS devices in a power system in order to eliminate or alleviate the line over loads. The optimizations are performed on the parameters, namely the location of the devices, their types, their settings and installation cost of FACTS devices for single and multiple contingencies. TCSC, SVC and UPFC are considered and modeled for steady state analysis. The selection of UPFC and TCSC suitable location uses the criteria on the basis of improved system security. The effectiveness of the proposed method is tested for IEEE 6 bus and IEEE 30 bus test systems.

Keywords—Contingency Severity Index, Particle Swarm Optimization, Performance Index, Static Security Assessment.

I. INTRODUCTION

POWER system security, congestion management, power quality and power regulations are major concepts that draw the attention of power researchers in deregulated surroundings. Security assessment is an issue of utmost grandness under 'open market access system' to render authentic and procure electricity to its customers under all conditions. In a day to day operation it may be beyond the operator scope to take preventive control during emergencies. However, the operator can use various control devices and FACTS devices to restore the system to normal conditions [1], [2].

Contingency screening and ranking is one of the components of on-line system security assessment. The target of contingency ranking and screening is to rapidly and

precisely grade the decisive contingencies from a large list of plausible contingencies and rank them according to their severity for further rigorous analysis. Various PI-based methods for contingency screening and ranking have been reported in literature [3]-[6].

FACTS devices are solid state converters that have the capability of control of various electrical parameters in transmission networks. FACTS devices include Thyristor Controlled Series Compensator (TCSC), Static Var Compensator (SVC), Unified Power Flow Controller (UPFC) and Static Compensator (STATCOM) etc. [7]

FACTS devices control the power flow in the network, reduces the flow in the heavily loaded lines there by resulting in an increase loadability, improved security and stability of the network are reported in [8], [9].

Thyristor Controlled Series Compensator (TCSC) is one such device which offers smooth and flexible control for security enhancement with much faster response compared to the traditional control devices [10].

Unified Power Flow Controller (UPFC) is capable of providing active, reactive and voltage magnitude control under normal and network contingencies conditions without violating the operating limits [11].

Population based co-operative and competitive stochastic search algorithms are very popular in the recent years in the research area of computational intelligence. Some well established search algorithms such as GA [12] and Evolutionary Programming [13] are successfully implemented to solve the complex problems. The PSO algorithm was introduced by Kennedy and Eberhart [14],[15] and further modifications in PSO algorithm were carried out in [16]. PSO is applied for solving various optimization problems in electrical engineering [17], [18].

In this paper, utilization of the multi type devices, combination of TCSC and UPFC during single and double contingencies is investigated. UPFC is modeled as a combination of a TCSC in series with a line and SVC connected across the corresponding buses between which the line is connected. Contingency severity index values are calculated for every branch using [19]. This index is used to decide on the best location for the multi type devices. Once located, the type and optimal settings of FACTS devices with respect to single and multiple contingencies can be obtained by optimization. The objectives used in this problem are eliminating or alleviating the line overloads and minimizing the installation cost of the multi type FACTS devices.

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Computer simulations are done for IEEE 6 bus, IEEE 30 bus test systems. From the test results it is observed that the number of over loads and installation cost are reduced after placing certain number of FACTS devices. Further increase of FACTS devices, shows no improvement in reduction of overloading or cost of installation.

II. PROBLEM FORMULATION

A. Optimal Placement of FACTS Devices

The essential idea of the proposed multi type FACTS devices, UPFC and TCSC placement approaches is to determine a branch which is most sensitive for the large list of single and multiple contingencies. This section will describe the definition and calculation of the contingency severity index CSI and the optimal placement procedure for the UPFC and TCSC.

The participation matrix U: This is an (m x n) binary matrix, whose entries are "1" or "0" depending upon whether or not the corresponding branch is overloaded, where n is the total number of branches of interest, and m is the total number of single and multiple contingencies.

The ratio matrix W: This is an (m x n) matrix of normalized excess (overload) branch flows. It's (i, j)th element, w_{ij} is the normalized excess power flow (with respect to the base case flow) through branch "j" during contingency "i" and is given by :

$$W_{ij} = \frac{P_{ij,cont}}{P_{oj,Base}} - 1 \quad (1)$$

where,

$P_{ij,cont}$ - Power flow through branch "j" during Contingency "i"

$P_{oj,Base}$ - Base case power flow through branch "j".

The Contingency probability array P: This is an (m x 1) array of branch outage probabilities. The probability of branch outage is calculated based on the historical data about the faults occurring along that particular branch in a specified duration of time. It will have the following form:

$$P_{m \times 1} = [p_1 \ p_2 \ \dots \ p_m]^T \quad (2)$$

where

P_i - Probability of occurrence for contingency "i" and is taken as 0.02.

m - The number of contingencies

Thus the CSI for branch "j" is defined as the sum of the sensitivities of branch "j" to all the considered single and multiple contingency, and is expressed as

$$CSI_j = \sum_{i=1}^m p_i u_{ij} w_{ij} \quad (3)$$

where u_{ij} and w_{ij} are elements of matrices U and W respectively.

CSI values are calculated for every branch by using (3). Branches are then ranked according to their corresponding CSI values. A branch has high value of CSI will be more sensitive for security system margin. The branch with the largest CSI is considered as the best location for FACTS device.

B. Optimal Settings of FACTS Devices

In this paper UPFC is modeled as combination of a TCSC in series with the line and SVC connected across the corresponding buses between which the line is connected. After fixing the location, to determine the best possible settings of FACTS devices for all possible single and multiple contingencies, the optimization problem will have to be solved using PSO technique.

The objective function for this work is,

obj = minimize { SOL and IC }

$$SOL = \sum_{c=1}^m \sum_{k=1}^n a_k \left(\frac{P_k}{P_k^{max}} \right)^4 \quad (4)$$

where,

m - Number of single contingency considered

n - Number of lines

a_k - weight factor=1.

P_k - real power transfer on branch k.

P_k^{max} - maximum real power transfer on branch k.

IC - Installation cost of FACTS device

SOL - Represents the severity of overloading

Installation cost includes the sum of installation cost of all the devices and it can be calculated using the cost function given by,

$$C_{TCSC} = 0.0015S^2 - 0.71S + 153.75 \text{ (US$/KVAR)} \quad (5)$$

$$C_{UPFC} = 0.0003S^2 - 0.269S + 188.22 \text{ (US$/KVAR)} \quad (6)$$

where, S - Operating range of UPFC in MVAR

$$S = |Q_2 - Q_1|$$

Q_1 - MVAR flow through the branch before placing FACTS device.

Q_2 - MVAR flow through branch after placing FACTS device.

The objective function is solved with the following constraints:-

1. Voltage Stability Constraints

VS includes voltage stability constraints in the objective function and is given by,

$$VS = \begin{cases} 0 & \text{if } 0.9 < V_b < 1.1 \\ 0.9 - V_b & \text{if } V_b < 0.9 \\ V_b - 1.1 & \text{if } V_b > 1.1 \end{cases} \quad (7)$$

V_b - Voltage at bus b

2. FACTS Devices Constraints

The FACTS device limit is given by,

$$\begin{aligned} -0.5 X_L < X_{TCSC} < 0.5 X_L \\ -200 \text{ MVAR} \leq Q_{SVC} \leq 200 \text{ MVAR} \end{aligned} \quad (8)$$

where

- X_L - original line reactance in per unit
- X_{TCSC} - reactance added to the line where UPFC is placed in per unit
- Q_{SVC} - reactive power injected at SVC placed bus in MVAR

3. Power Balance Constraints

While solving the optimization problem, power balance equations are taken as equality constraints. The power balance equations are given by,

$$\sum P_G = \sum P_D + P_L \quad (9)$$

where

- $\sum P_G$ - Total power generation
- $\sum P_D$ - Total power demand
- P_L - Losses in the transmission network
- $P_i = \sum |E_i| |E_k| [G_{ik} \cos(\theta_i - \theta_k) + B_{ik} \sin(\theta_i - \theta_k)]$ (10)
- $Q_i = \sum |E_i| |E_k| [G_{ik} \sin(\theta_i - \theta_k) + B_{ik} \cos(\theta_i - \theta_k)]$ (11)

where

- P_i - Real power injected at bus i.
- Q_i - Reactive power injected at bus i.
- θ_i, θ_k - The phase angles at buses i and k respectively.
- E_i, E_k - Voltage magnitudes at bus i and k respectively.
- G_{ik}, B_{ik} - Elements of Y – bus matrix.

III. OVERVIEW OF PSO AND ITS IMPLEMENTATION FOR OPTIMAL LOCATION OF FACTS DEVICES

PSO is initialized with a group of random particles and the searches for optima by updating generations. In every iteration each particle is updated by following “two best” values. The first one is the best solution (fitness value) it has achieved so far. This value is called Pbest. Another best value that is

tracked by the particle swarm optimizer is the best value obtained so far by any particle in the population. This best value is the global best called Gbest. After finding the best values the particles update its velocity and position with the following equation:

$$V_i^{k+1} = W * V_i^k + C_1 * rand_1 * (P_{besti} - S_i^k) + C_2 * rand_2 * (G_{besti} - S_i^k) \quad (12)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \quad (13)$$

$$W = W_{\max} - \left(\frac{W_{\max} - W_{\min}}{iter_{\max}} \right) * iter \quad (14)$$

where

- V_i^k = Velocity of agent i at kth iteration
- V_i^{k+1} = Velocity of agent i at (k+1)th iteration
- W = The inertia weight
- $C_1 = C_2$ = Weighting Factor (0 to 4)
- S_i^k = Current position of agent i at kth iteration
- S_i^{k+1} = Current position of agent i at (k+1)th iteration
- $iter_{\max}$ = Maximum iteration number
- $iter$ = Current iteration number
- P_{besti} = P_{best} of agent i
- G_{besti} = G_{best} of the group
- W_{\max} = Initial value of inertia weight = 0.9
- W_{\min} = Final value of inertia weight = 0.2

The velocity of the particle is modified by using (12) and the position is modified by using (13). The inertia weight factor is modified according to (14) to enable quick convergence. Calculation of fitness function:

$$\text{Fitness function} = SOL + (\lambda_1 \times VS) + (\lambda_2 \times IC) \quad (15)$$

where

- λ_1 - Penalty factor
- λ_2 - Scaling factor

Algorithm:

- Step 1. The bus data, line data, and number of FACTS devices are given as inputs
- Step 2. The initial population of individuals is created in normalized form so as to satisfy the FACTS device's constraints given by (8)
- Step 3. For each individual in the population, the fitness function is evaluated by using (15) in denormalized form after simulating all possible single and multiple contingencies by using AC Load flow
- Step 4. The velocity is updated by using (12) and new population is created by using (13)

- Step 5. If maximum iteration number is reached, then go to next step else go to step 3
- Step 6. Print the best individual's settings.

IV. RESULTS AND DISCUSSION

The solutions for optimal location of FACTS devices to minimize the installation cost of FACTS devices and overloads for IEEE 6 bus, IEEE 30 bus test systems were obtained and discussed in this section. The simulation studies were carried out on Intel Pentium IV Processor computer with 3GHZ, 256MB RAM, 40GB Hard drive using MATLAB 7.0 version.

A. IEEE 6-Bus, Eleven Branch System

The bus data and line data of the six bus test system are taken from [20]. This system is analyzed for both single and double contingencies.

1. Single Contingency

The location of FACTS devices depend upon the CSI values which are calculated for 11 branches by considering all single contingencies. Then the branches are ranked according to their values of CSI which are given in Table I.

2. Double Contingency

Considering two branches outaged at a time for 11 branches, 55 double contingency combinations are available. Considering all the double contingency combinations, the 11 branches are ranked based on their CSI values are given in Table I.

TABLE I
RANKING OF BRANCHES FOR IEEE 6-BUS SYSTEM

1. SINGLE CONTINGENCY			2. DOUBLE CONTINGENCY		
Rank	Branch	CSI	Rank	Branch	CSI
1	1-2	0.0445	1	3-6	0.872
2	2-6	0.0383	2	2-3	0.6931
3	1-4	0.0329	3	1-2	0.4866
4	3-5	0.0286	4	1-5	0.4100
5	2-5	0.0279	5	2-6	0.3397
6	2-4	0.0252	6	2-5	0.3280
7	2-3	0.0205	7	2-4	0.3064
			8	1-4	0.2736

Table I shows that, branch number 1-2, 3-6 is chosen as the best location to place the first available multi type FACTS devices for single and double contingencies. Depending on the available budget, the placement of other FACTS devices can proceed where branch 2-6, 2-3 will be the second choice, branch 1-4, 1-2 are the third choice and so on. Once the location is determined, their type, their optimal settings and cost of installation can be obtained by solving the optimization problem using PSO. The Table II shows the overloading of branches when different numbers of FACTS devices are installed.

TABLE II
OVER LOADING OF BRANCHES- BEFORE AND AFTER PLACING MULTI TYPE FACTS DEVICES

I. SINGLE CONTINGENCY					
No. of devices	SOL	No. of overloads	Facts device cost (US\$)	Fitness function	Execution time (seconds)
0	1.260266	23	0	0	0.1410
1	1.078061	19	3.7821e+006	2.0515e+009	231.30
2	1.007011	18	1.2391e+007	1.9555e+009	230.90
3	96.4418	17	1.6353e+007	1.8822e+009	232.30
4	89.5330	15	1.5404e+007	1.7193e+009	232.79
5	93.4915	17	1.7964e+007	1.8334e+009	226.84

II. DOUBLE CONTINGENCY					
No. of devices	SOL	No. of overloads	FACTS device cost (US\$)	Fitness function	Execution time (seconds)
0	447.39	188	0	0	0.29700000
1	382.71	187	2.9306e+006	6.1280e+009	1.4043e+003
2	342.36	179	7.9347e+007	0.5856e+010	1.6802e+003
3	318.30	175	9.5265e+006	5.5502e+009	1.3614e+003
4	238.53	182	2.8480e+007	5.8930e+009	1.1499e+003
5	505.40	198	3.3205e+007	6.2356e+009	1.4159e+003

Table II shows that the severity index (SOL) and the number of overloads are reduced from 23 to 15 when four FACTS devices are placed for single contingencies and 188 to 175 when three FACTS devices are placed for double contingencies. Further increase of devices, shows no improvement in reduction of severity, overloading and cost of installation, rather they start increasing. Hence in this case, four and three number of FACTS devices is considerable for optimal system security for single and double contingencies. The optimal settings, line number and the type of device are obtained by solving optimization algorithms using PSO is given in Table III.

TABLE III
OPTIMAL SETTINGS MULTI TYPE FACTS DEVICES

I. SINGLE CONTINGENCY					
No. of devices	Branch Number	Type of device		Reactance X_{TCSC} Per Unit	Reactive Power Q_{SVC} (MVAR)
		TCSC	UPFC		
1	3-5	0	1	0.4978	-155.1191
2	3-5 2-4	0	2	0.5038 0.5134	-150.4248 -141.3419
3	2-6 3-5 2-4	1	2	0.1530 0.4374 1.1655	0 -119.3479 -146.2072
4	2-6 1-4 3-5 2-5	1	3	0.2900 -0.1623 1.0353 0.6689	-113.1021 -134.7928 -122.7183 0
5	1-2 2-6 1-4 2-3 3-5	0	5	-0.2451 0.1704 -0.1532 -0.6143 0.4014	-136.9343 -131.8085 -36.1739 -155.3881 -64.1792

II. DOUBLE CONTINGENCY

No. of devices	Branch Number	Type of device		Reactance X_{TCSC} Per Unit	Reactive Power Q_{SVC} (MVAR)
		TCSC	UPFC		
1	2-6	1	0	0.1598	0
2	2-6 2-4	0	2	0.5010 0.2716	-85.7757 -101.0229
3	1-5 2-6 1-4	1	2	0.0299 0.0017 0.3816	-36.004 20.9624 0
4	3-6 1-5 2-4 1-4	0	4	-0.4314 0.8079 -0.2068 1.2424	-122.032 -146.1893 -40.6733 -120.0641
5	3-6 2-3 1-5 2-5 2-4	0	5	-0.4858 -0.3566 0.5246 0.6621 0.7756	109.7632 -118.6482 -51.9278 -135.2774 -131.2981

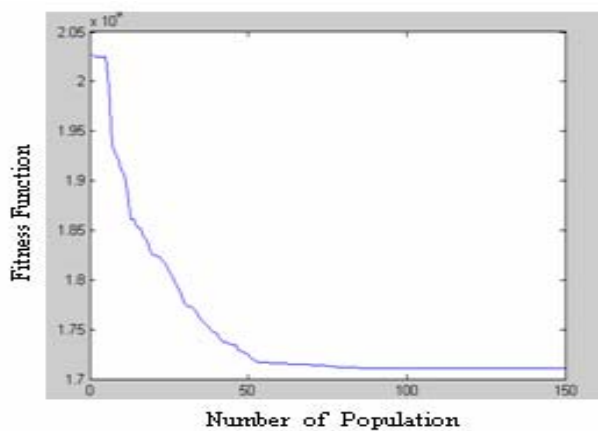


Fig. 1 Fitness convergence curve for IEEE 6Bus system-Single contingency

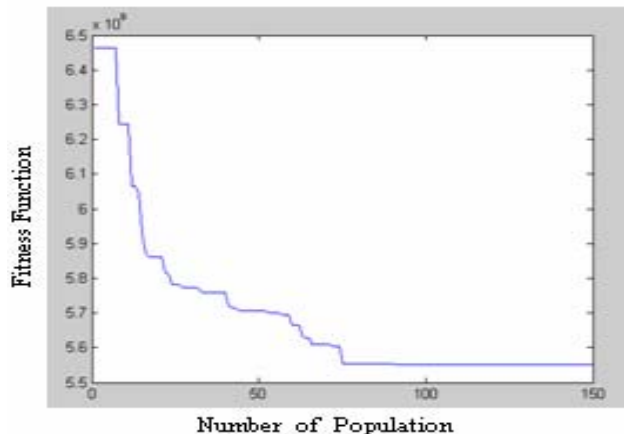


Fig. 2 Fitness convergence curve for IEEE 6Bus system-Double contingency

Fig. 1 and Fig. 2 represent the fitness convergence curve for IEEE 6 bus system for single and double contingencies. Number of population taken in X axis and Fitness function taken in Y axis. The simulation carried out with multiple runs to get the optimal results of multi-type FACTS devices. PSO parameters used in this work are:

- i) No. of population = 30
- ii) Max Generation = 150
- iii) $C_1 = C_2 = 2$

B. IEEE 30-Bus, Forty one Branch Systems

The IEEE 30 bus system consists of 41 branches. Line data, bus data are taken from [21]. This system is also analyzed for both single and double contingencies.

1. Single Contingency

There are 41 possible contingencies, leaving 3 branches(25-26,9-11,12-13) connected to isolated buses only 38 single contingencies are considered. The CSI index is calculated for all the 41 lines considering 38 contingencies and the branches are ranked and it is given in Table IV.

2. Double Contingency

Considering two branches are outaged at a time, for 41 branches, 820 double contingency combinations are available. Leaving the branches connected to isolated buses, the remaining double contingency combinations are considered in this work. These contingencies are ranked based on CSI values which are given in Table IV.

TABLE IV
RANKING OF BRANCHES FOR IEEE 30-BUS SYSTEM
1. SINGLE CONTINGENCY 2.DOUBLE CONTINGENCY

Rank	Branch	CSI
1	15-18	0.0511
2	25-27	0.0505
3	2-6	0.0460
4	22-24	0.0424
5	1-3	0.0389
6	3-4	0.0384
7	27-29	0.0245
8	1-2	0.0232
9	27-30	0.0185

Rank	Branch	CSI
1	25-27	0.8894
2	22-24	0.7306
3	16-17	0.4899
4	23-24	0.2464
5	2-6	0.2060
6	2-4	0.1935
7	15-23	0.1920
8	15-18	0.1631
9	14-15	0.1588
10	6-10	0.1400
11	4-12	0.1018
12	10-21	0.1048
13	12-15	0.0991
14	1-2	0.0883
15	10-17	0.0870
16	1-3	0.0814
17	3-4	0.0802
18	18-19	0.0699
19	6-28	0.0265
20	27-29	0.0262
21	9-10	0.0194
22	12-13	0.0161

After ranking of the branches the PSO algorithm is used to find out the location of the devices, their types, and settings to alleviate the line overloads and to improve the system security margin which are given in Table V and VI.

TABLE V
OVER LOADING OF BRANCHES - BEFORE AND AFTER PLACING MULTI TYPE
FACTS DEVICES

I. SINGLE CONTINGENCY					
No. of devices	SOL	No. of overloads	FACTS device Cost (US\$)	Fitness function	Execution time (seconds)
0	145.7700	16	0	0	0.17800
1	144.7901	15	1.8398e+007	1.8459e+009	14010.80
2	144.0800	14	2.1090e+007	1.7985e+009	14072.79
3	141.7725	13	1.9409e+007	1.8156e+009	13921.73
4	140.6269	13	9.9994e+006	1.7378e+009	14115.35
5	142.8015	14	2.7990e+007	1.8338e+009	14223.51

II. DOUBLE CONTINGENCY

No. of devices	SOL	No. of overloads	FACTS device Cost (US\$)	Fitness function	Execution time (seconds)
0	546.2114	105	0	0	0.488150
1	540.9482	91	4.6391e+007	7.5111e+009	14134.04
2	524.2522	84	3.8900e+007	7.4852e+009	14232.04
3	519.8329	78	2.3750e+007	7.4673e+009	14115.06
4	528.5074	91	2.1813e+007	7.3991e+009	14045.18
5	529.0064	100	2.5188e+007	7.7408e+009	14005.67

TABLE VI
OPTIMAL SETTINGS OF MULTI TYPE FACTS DEVICES

I. SINGLE CONTINGENCY					
No. of devices	Branch Number	Type of device		Reactance $X_{TCSC} (pu)$	Reactive Power $Q_{SVC} (MVAR)$
		TCSC	UPFC		
1	2-6	0	1	-0.4274	-54.3545
2	2-6	1	1	0.2319	0
	3-4			0.9366	0.3438
3	15-18	3	0	0.1788	0
	2-6			-0.2500	0
	22-24			-0.3223	0
4	15-18	2	2	0.2068	32.54
	2-6			0.3449	0
	3-4			-0.3170	0
	27-29			0.4538	-56.24
5	15-18	2	3	0.5488	0
	2-6			-0.2833	-43.9082
	22-24			-0.5839	-18.4190
	3-4			-0.2047	64.4621
	27-30			-0.1327	0

II. DOUBLE CONTINGENCY

No. of devices	Branch Number	Type of device		Reactance $X_{TCSC} (pu)$	Reactive Power $Q_{SVC} (MVAR)$
		TCSC	UPFC		
1	2-6	0	1	-0.6992	26.0844
2	23-24	1	1	-1.2200	-15.0381
	2-6			-0.6392	0
3	2-6	0	3	-0.7191	-25.3856
	14-15			-0.1352	-19.5650
	12-15			0.1472	-49.3143
4	22-24	1	3	-0.5680	-29.7246
	2-6			-0.7286	42.9757
	15-23			-0.4667	17.5657
	10-17			0.2946	0
5	25-27	1	4	-0.3319	0
	2-6			0.3539	-51.2918
	15-18			-0.0917	60.6020
	6-10			0.0219	-64.2678
	4-12			0.1328	24.2349

Fig. 3 and Fig. 4 represent the fitness convergence curve for IEEE 30 bus system for single and double contingencies. Number of population taken in X axis and Fitness function taken in Y axis. PSO parameters used in this work are:

- No. of population = 25
- Max Generation = 100
- $C_1 = C_2 = 2$

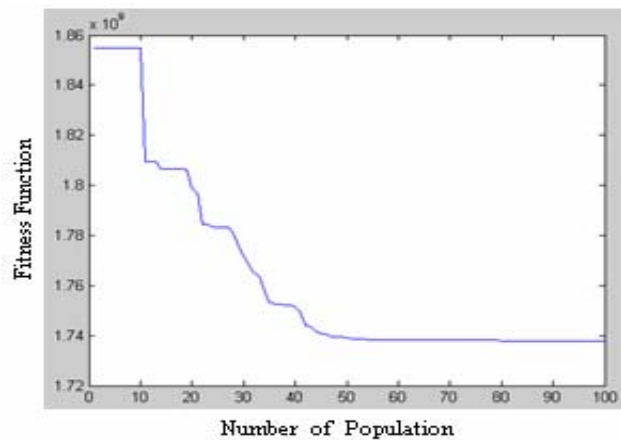


Fig. 3 Fitness convergence curve for IEEE 30Bus system-Single contingency

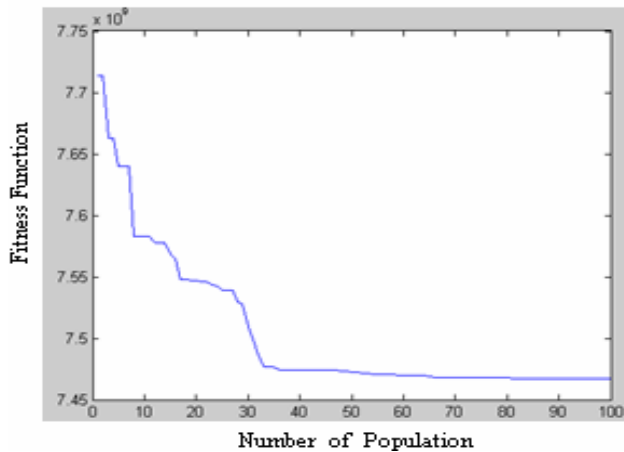


Fig. 4 Fitness convergence curve for IEEE 30Bus system-Double contingency

V. CONCLUSION

This paper presents a procedure to place multi type FACTS devices along the system branches based on the contingency severity index (CSI) values to alleviate system overloads and to improve the system security margin during single and double contingencies. TCSC and UPFC, the combination of TCSC and SVC were considered in this work. Simulations were performed on IEEE 6 and 30 bus systems. The location of multi type FACTS devices, the type of device to be placed, and their settings were taken as the optimization parameters for both single and double contingencies. In both single and double contingencies, it is observed that the system security margin cannot be improved further after placing certain optimal number of multi type FACTS devices. These settings can be effectively used on-line to enhance the system security margin without investing in additional transmission resources.

IEEE 6 bus, IEEE 30 bus test systems are used to evaluate the performance of this approaches. Numerical results confirm the effectiveness of the proposed procedures.

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