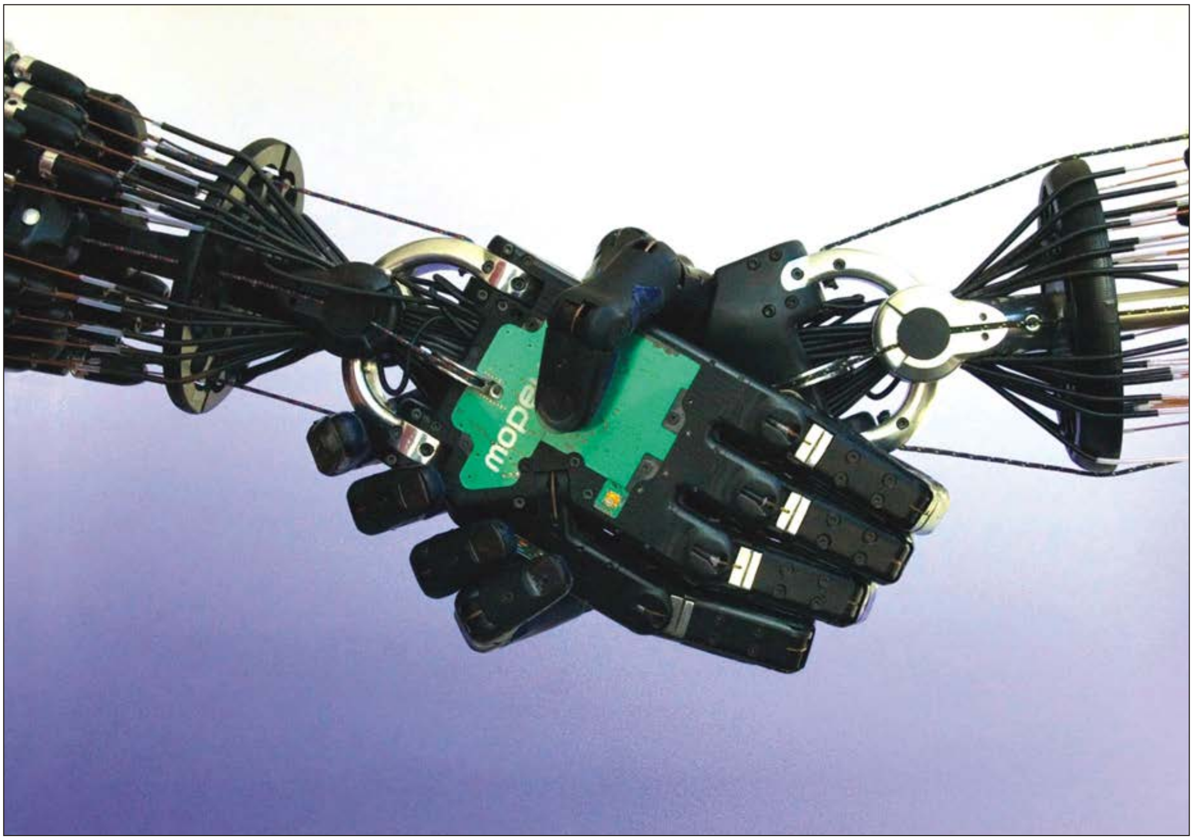

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Particle Swarm Optimization Applications to Static Security Enhancement Using Multi Type Facts Devices*

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Abstract: This study 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 double contingencies. 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.

Key words: Contingency severity index, particle swarm optimization, performance index, static security assessment

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 (Paserba *et al*., 1995; Gerbex *et al*., 2001).

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 (Ejebe and Wollenberg, 1979; Mikolinnas and Wollenberg, 1981; Lauby *et al*., 1983; Chen and Bose, 1989).

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. (Hingorani and Gyugyi, 1999).

FACTS devices control the power flow in the network, reduces the flow in the heavily loaded lines thereby resulting in increase load ability, improved security and stability of the network (Krishna and Padiyar, 2005; Kazemi and Sohrforouzani, 2006).

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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 (Huang and Zhu, 2001).

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 (Visakha and Jenkins, 2004).

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 (Gerbex *et al*., 2001) and Evolutionary Programming (Venkatesh *et al*., 2003) are successfully implemented to solve the complex problems. The PSO algorithm was introduced by Kennedy and Eberhart (1995) and Shi and Eberhart (1999) and further modifications in PSO algorithm were carried out in (Ratnaweera *et al*., 2004). PSO is applied for solving various optimization problems in electrical engineering (Yoshida *et al*., 1999; Saravanan *et al*., 2007).

TCSC is used for static security enhancement in order to eliminate or reduce line overloads (Yunqiang and Abur, 2002). In this study, only single contingencies were considered due to complexity of the problem.

This study depicts the use of multi-type devices, combination of TCSC and UPFC during double contingencies are 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 (Yunqiang and Abur, 2002). 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 double 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. 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.

PROBLEM FORMULATION

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 double 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×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 double contingencies.

The Ratio Matrix W

This is an (m×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:

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

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×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:

$$P_{m\times 1} = [p_1 p_2 \ldots p_m]^T \tag{2}$$

Where:

p_i = Probability of occurrence for contingency i and is taken as 0.02
m = No. of contingencies

Thus the CSI for branch j is defined as the sum of the sensitivities of branch j to all the considered double contingency and is expressed as:

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

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

CSI values are calculated for every branch using Eq. 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.

Optimal Settings of FACTS Devices

In this study 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 double contingencies, the optimization problem will have to be solved using PSO technique.

The objective function for this work is:

obj = minimize {SOL and IC}

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

Where:

m = No. of double contingency considered
n = No. 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:

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

$$C_{UPFC} = 0.0003S^2 - 0.2691S + 188.22 \text{ (US\$/KVAR)} \tag{6}$$

Where:
S = Operating range of UPFC in MVAR
S = $|Q_2\text{-}Q_1|$
Q_1 = MVAR flow through the branch before placing FACTS device
Q_2 = MVAR flow through the branch after placing FACTS device

The objective function is solved with the following constraints:-

Voltage Stability Constraints

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

$$VS = \begin{cases} 0 & \text{if } 0.9 < Vb < 1.1 \\ 0.9 - Vb & \text{if } Vb < 0.9 \\ Vb - 1.1 & \text{if } Vb > 1.1 \end{cases} \tag{7}$$

Vb- voltage at bus b

FACTS Devices Constraints

The FACTS device limit is given by:

$$\begin{aligned} &-0.5X_L < X_{TCSC} < 0.5X_L \\ &-200\text{MVAR} \le Q_{SVC} \le 200\text{MVAR} \end{aligned} \tag{8}$$

Where:
X_L = Original line reactance in p.u
X_{TCSC} = Reactance added to the line where UPFC is placed in p.u
Qsvc = Reactive power injected at SVC placed bus in MVAR

Power Balance Constraints

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

$$\sum P_G = \sum P_D + P_L \tag{9}$$

Where:
ΣP_G = Total power generation
ΣP_D = Total power demand
P_L = Losses in the transmission network

$$P_i = \sum |E_i|\,|E_k|\,[G_{ik}\cos(\theta_i - \theta_k) + B_{ik}\sin(\theta_i - \theta_k)] \tag{10}$$

$$Q_i = \sum |E_i|\,|E_k|\,[G_{ik}\sin(\theta_i - \theta_k) + B_{ik}\cos(\theta_i - \theta_k)] \tag{11}$$

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_i, B_{ik} = Elements of Y- bus matrix

OVER VIEW 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:

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

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

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

Where:

V_i^k = Velocity of agent i at k^{th} 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 k^{th} iteration
S_i^{k+1} = Current position of agent i at $(k+1)^{th}$ iteration
$itermax$ = 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 Eq. 12 and the position is modified by using Eq. 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 Eq. 8

Step 3: For each individual in the population, the fitness function given by (15) is evaluated in denormalized form after simulating all possible double contingencies by using AC Load flow

Step 4: The velocity is updated by using (12) and new position 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

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 3 GHz, 256 MB RAM, 40 GB Hard drive using MATLAB 7.0 version.

IEEE 6-Bus, Eleven Branch System

The bus data and line data of the six bus test system are taken from (Allen and Wollenberg, 2003). This system is analyzed for double contingencies.

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 which are given in Table 1.

Table 1 shows that, branch number 3-6 is chosen as the best location to place the first available multi type FACTS devices for double contingencies. Depending on the available budget, the placement of other FACTS devices can proceed where branch 2-3 will be the second choice, branch 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 technique.

Table 2 Shows that the severity index (SOL) and the number of overloads are reduced from 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, three number of FACTS devices is considerable for optimal system security enhancement for double contingencies. The optimal settings, line number and the type of device are obtained by solving optimization algorithms using PSO which is shown in Table 3.

Table 1: Ranking of Branches

Rank	Branch	CSI
1	3-6	0.8720
2	2-3	0.6931
3	1-2	0.4866
4	1-5	0.4100
5	2-6	0.3597
6	2-5	0.3280
7	2-4	0.3064
8	1-4	0.2736

*: Remaining branches having less CSI value

Table 2: Overloading of branches before and after placing multi type FACTS devices

No. of devices	SOL	No. of overloads	FACTS device cost (US$)	Fitness function
0	447.39	188	0	0
1	382.71	187	2.9306e+006	6.1280e+009
2	342.36	179	7.9347e+007	0.5856e+010
3	318.20	175	9.5265e+006	5.5502e+009
4	258.53	182	2.8480e+007	5.6950e+009
5	505.40	198	3.3205e+007	6.2356e+009

Table 3: Optimal settings of multi type facts devices

		Type of devices			
No. of devices	Branch No.	TCSC	UPFC	Reactance X_{TCSC}	Reactive power Qsvc (MVAR)
1	2-6	1	0	0.1598	0
2	2-6	0	2	0.5010	-85.7757
	2-4			0.2716	-101.0229
3	1-5	1	2	0.0299	-36.004
	2-6			0.0017	20.9624
	1-4			0.3816	0
4	3-6	0	4	-0.4314	-122.032
	1-5			0.8079	-146.1893
	2-4			-0.2068	-40.6733
	1-4			1.2442	-120.0641
5	3-6	0	5	-0.4858	109.7632
	2-3			-0.3566	-118.6482
	1-5			0.5246	-51.9278
	2-5			0.6621	-135.2774
	2-4			0.7756	-131.2918

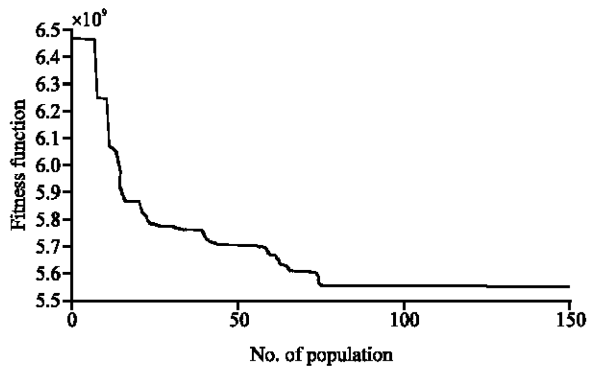

Fig. 1: Fitness convergence curve for IEEE 6bus system-double contingency

Figure 1 represents the fitness convergences curve for IEEE 6 bus system for double contingencies. Number of population taken in x-axis and Fitness function taken in y-axis. PSO parameters used in this study are:

- No. of population = 30
- Max Generation = 150
- $C_1 = C_2 = 2$

IEEE 30-Bus, Forty One Branch Systems

The IEEE 30 bus system consists of 41 branches. Line data, bus data are taken from (Pai, 1979). This system is also analyzed for double contingencies.

Double Contingency

Considering two branches 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 study. These contingencies are ranked based on CSI values which are given in Table 4.

After raking 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 is given in Table 5 and 6.

Table 4: Ranking of branches

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

Table 5: Overloading of branches-before and after placing multi type FACTS devices

No. of devices	SOL	No. of overloads	FACTS devices cost (US$)	Fitness function
0	546.2114	105	0	0
1	540.9482	91	4.6391e+007	7.5111e+009
2	524.9482	84	3.6900e+007	7.4852e+009
3	519.8329	78	2.3750e+007	7.4673e+009
4	528.5074	91	2.1813e+007	7.3991e+009
5	529.0064	100	2.5188e+007	7.7408e+009

Table 6: Optimal settings of multi type facts devices

		Type of devices			
No. of devices	Branch No.	TCSC	UPFC	Reactance X_{TCSC}	Reactive power Qsvc (MVAR)
1	2-6	0	1	-0.6992	26.0844
2	23-24	1	1	-1.2200	-15.381
	2-6			-0.6392	0.00
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	0.00
5	25-27	1	4	-0.3319	0.00
	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. 2: Fitness convergence curve for IEEE 30 bus system-double contingency

Figure 2 represents 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
- $C_1 = C_2 = 2$

CONCLUSION

This study 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 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 double contingencies. In 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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