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ALLEVIATION OF LINE OVERLOADS UNDER CONTINGENCY BY OPTMAL UTILISATION OF FACTS DEVICES USING EVOLUTIONARY COMPUTATION TECHNIQUES

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ABSTRACT

This paper proposes the evolutionary computational techniques for determining the most suitable locations and settings for installing the Flexible AC Transmission (FACTS) devices, Thyristor Controlled Series Capacitors (TCSC) and Unified Power Flow Controllers (UPFC), to eliminate line overloads under single contingency in a power system. The mostly affected lines of the system during single line outage are ranked using an index called Contingency Severity Index. To find the best locations among the ranked lines to install the FACTS devices, and to determine the settings of those devices, an optimization problem is formulated and solved using two evolutionary computation techniques, real coded Genetic Algorithm (RGA) and Particle Swarm Optimization (PSO). The reactance model for TCSC and the decoupled model for UPFC are considered for this work. Simulated Binary Crossover (SBX) and Non-uniform polynomial mutation are employed to improve the performance of the Genetic Algorithm used. Simulations are performed on IEEE 6-bus, 30-bus and 118-bus test systems. The results are compared in terms of improved system security before and after placing the FACTS devices and the performance of both techniques are analyzed.

Keywords: contingency, flexible AC transmission (FACTS), thyristor controlled series capacitor (TCSC), unified power flow controller (UPFC), real coded genetic algorithm (RGA), particle swarm optimization (PSO).

1. INTRODUCTION

Power systems are commonly planned and operated based on N-1 security criterion, which implies that the system should remain secure under all important first contingencies. Designing the system to meet this criterion is somewhat conservative and costly. In present day power system, there will be an increase in number of situations where power flow equations have either no real solution or solution with violating operating limits such as voltage limit (insecure case), particularly, in contingency analysis and planning applications. Contingency screening and ranking is one of the components of on-line system security assessment. Various methods for contingency screening and ranking have been reported in literatures [1-3].

FACTS devices are solid state devices that have the capability of control over various electrical parameters in transmission networks. These devices, by controlling the power flows in the network, can help to reduce the flows in heavily loaded lines resulting in an increased loadability, low system loss, improved stability of the network, and reduced cost of production [4-6].

TCSC is one such device which offers smooth and flexible control of line impedance. UPFC is a versatile controller that can be used to control the power flow in the transmission systems by controlling the impedance, voltage magnitude and phase angle. Most of the researchers have focused the utilization of these devices on various issues such as loadability enhancement, determination of available transfer capability, etc. [7, 8]. However, these can be used to enhance the power system security with much faster response compared to the traditional control devices [9].

In this paper, utilization of these devices during single contingency is investigated. In order to evaluate the suitability of a given line for placing the FACTS device, contingency severity index is calculated for each line. This index is used to rank the lines that are mostly affected during all the possible single contingencies. Once the rank list is obtained, an optimization problem is formulated to find out the best locations among the ranked lines to install the devices and to determine the best settings of the devices. The objective used in this problem is to eliminate or reduce the line overloads thereby increasing the security margin.

Population based co-operative and competitive stochastic search algorithms are employed in recent years in the research area of computational intelligence. Some well established search algorithms such as Genetic Algorithm [10] and Particle Swarm Optimization [11] have been successfully implemented to solve the complex problems. In this work, Real Coded Genetic Algorithm (RGA) and Particle Swarm Optimization (PSO) have been applied to solve the problem. Simulated Binary Crossover and Polynomial mutation are employed to improve the performance of the Genetic Algorithm used. Illustrations using the IEEE 6-bus, 30-bus and 118-bus test systems exhibit the effectiveness of both techniques.

2. PROBLEM FORMULATION

2.1. Contingency ranking

The purpose of contingency ranking is to list the lines which are more sensitive to the largest number of contingencies. This portion describes the calculation of the contingency severity index [12].

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Contingency Severity Index (CSI) for line "j" is defined as the sum of the sensitivities of line "j" to all the considered single contingencies (m), and is expressed as

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

p_i is the line outage probability based on the historical data about the faults occurring along that particular line in a specified duration of time. Here, Pi is taken as 0.02. u_{ij} is 1 or 0 depending upon whether or not the j[th] line is overloaded due to outage of i[th] line. W_{ij} is the normalized excess power flow with respect to the base case flow through line "j" during the outage of line "i" and is given by:

$$W_{ij} = \frac{P_{ij,cont}}{P_{j,Base}} - 1 \tag{2}$$

$P_{ij,\,cont}$ -Power flow through line "j" during contingency "i"

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

Lines are then ranked by their corresponding index values. In general, larger the index value a line has, the more sensitive it will be.

2.2. Allocation of FACTS devices

Previous works on this topic investigate the generation rescheduling and load shedding as the primary corrective strategies for alleviating overloads on transmission lines [13]. In the newly emerging deregulated operation, the design of system control devices and their associated performance will have to be based on economic incentives. The rescheduling of generation and load shedding may not be acceptable by both power providers and customers, due to their significant effect on the existing power transaction contracts. In addition, they may be harmful for system security due to the discontinuous action of load shedding and slow adjustment of generation rescheduling.

An alternative solution can be devised through the use of FACTS technology. Proper use of TCSCs and UPFCs can reduce or eliminate the unwanted loop flows, and hence increase the system security margin.

For a large-scale power system, more than one device may have to be installed in order to achieve the desired performance. Once the number of devices is decided, the optimal locations where the devices have to be installed and the optimal settings of those devices are found by the algorithms, in such a way that the number of overloads are eliminated or reduced and the security margin is maximized.

2.3. Optimal locations of devices

In previous works reported, the lines were chosen as per rank order and devices are placed in those locations.

In this work, all lines having the CSI values are considered, and the best locations to install the devices are determined by the proposed algorithms. This approach yields improved results in enhancing the security margin.

2.4. Modeling of devices

In this work, TCSC is modeled as a variable reactance as shown in Figure-1 [10, 14]. The reactance value can vary from $-0.5X_L$ to $+0.5X_L$, where X_L is the reactance of the line in which TCSC is connected.

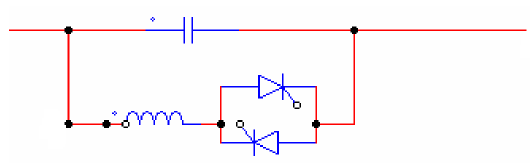

Figure-1. The reactance model of TCSC.

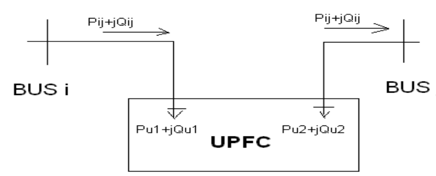

Figure-2. The decoupled model of UPFC.

For UPFC, the decoupled model is used as shown in Figure-2 [15, 16]. This model is composed of 2 separate load buses since UPFC can control the power flow over the transmission line and bus voltages where it is installed. An UPFC has 4 variables P_{u1}, Q_{u1}, P_{u2}, and Q_{u2}. With the losses of the UPFC assumed to be neglected, the active power flow P_{ij} that goes from bus i to bus j can be expressed by Equation (3). An UPFC can control the power flow but cannot generate the real power flow. So the condition of Equation (4) should be satisfied.

$$P_{ij} = P_{u1} \tag{3}$$

$$P_{u1} + P_{u2} = 0 \tag{4}$$

Each reactive power output of the UPFC, Q_{u1} *and* Q_{u2} can be set to an arbitrary value within the capacity of UPFC to maintain the bus voltages. Therefore if multiple UPFCs are installed in the power system, the control variables of the k-th UPFC are represented as follows:

$$UPFC_{k\text{-th}} = [P^u_{k1} \;\; Q^u_{k1} \;\; P^u_{k2} \;\; Q^u_{k2}] \tag{5}$$

$$P^u_{k1} + P^u_{k2} = 0 \tag{6}$$

Where,

P^u_{k1} = 1[st] bus active power of the k-th UPFC
Q^u_{k1} = 1[st] bus reactive power of the k-th UPFC
P^u_{k2} = 2[nd] bus active power of the k-th UPFC
Q^u_{k2} = 2[nd] bus reactive power of the k-th UPFC

2.5 Optimal setting of devices

To determine the best possible settings of the devices, the optimization problem is formulated and is given by

$$Obj = \text{Minimise } (U_n + F_t) \quad (7)$$

Where,

U_n = total number of overloads in all the lines after the all possible single contingencies
F_t = function representing severity of overloading.

$$F_t = \sum_{c=1}^{m}\sum_{k=1}^{n} a_k \left[\frac{P_k}{P_k^{\max}}\right]^4 \quad (8)$$

where
m = Number of single contingency considered
n = Number of lines
a_k = weight factor=1.
P_k = real power transfer on line k.
P_k^{max} = maximum real power transfer on line k.

The following are the constraints associated with the formulated problem.

2.5.1. TCSC constraint

$$-0.5X_L < X_{TCSC} < 0.5X_L \quad (9)$$

X_L - original line reactance in per unit
X_{TCSC} - reactance offered by TCSC

2.5.2. UPFC constraint

The constraints associated with the decoupled model of UPFC are as follows:

$$-100 \text{ MW} \le P_{u1} \le 100 \text{ MW} \quad (10)$$

$$P_{u2} = -P_{u1} \quad (11)$$

$$-100 \text{ MVAR} \le Q_{u1} \le 100 \text{ MVAR} \quad (12)$$

$$-100 \text{ MVAR} \le Q_{u2} \le 100 \text{ MVAR} \quad (13)$$

Where
P_{u1}, P_{u2} are the real power injected into the system
Q_{u1}, Qu2 are the reactive power injected into the system

2.5.3. Voltage stability constraints

The bus voltage V_b must lie within the following limits and V_S represents the voltage violation.

$$Vs = \begin{cases} 0 & \text{if } 0.9 < V_b < 1.1 \\ 0.9 - V_b & \text{if } V_b < 0.9 \\ V_b - 1.1 & \text{if } V_b > 1.1 \end{cases} \quad (14)$$

2.5.4. Power balance constraints

The equality constraints are the power balance constraints which are monitored by the load flow solution.

$$\sum P_G = \sum P_D + P_L \quad (15)$$

Where

$\sum P_G$ = Total power generation
$\sum P_D$ = Total power demand
P_L = Losses in the network

$$P_i = \Sigma |E_i| |E_k| [G_{ik}\cos(\theta_i-\theta_k)+B_{ik}\sin(\theta_i-\theta_k)] \quad (16)$$

$$Q_i = \Sigma |E_i| |E_k| [G_{ik}\sin(\theta_i-\theta_k)-B_{ik}\cos(\theta_i-\theta_k)] \quad (17)$$

Where
P_i Real power injected at bus i.
Q_i Reactive power injected at bus i.
θ_i, θ_k 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.

2.5.5. Fitness function

The fitness function used in RGA and PSO is as follows:

$$Fitness = F_t + U_n + \lambda . V_S \quad (18)$$

Where, λ is the penalty factor.

3. ALGORITHMS AND IMPLEMENTATIONS

3.1. Real coded Genetic Algorithm

Genetic algorithm is a kind of stochastic search technique based on the mechanism of natural Selection and survival of the fittest [5] and [7]. Further, it combines the function evaluation with the randomized and/or well-structured exchange of information among the solutions to arrive at a global optimum. More importantly, GA appears attractive because of its superior robust behaviour in nonlinear environments over the other optimization techniques. The architecture of the GA implementation can be segregated into the following three constituent phases namely: initial population generation, fitness evaluation and genetic operations.

It has been widely confirmed that real-number encoding performs better than binary or gray encoding for constrained optimization. Owing to the adaptive capability, SBX crossover and polynomial mutation operators are employed. Tournament selection is used as selection mechanism in order to avoid premature convergence.

3.1.1. Simulated binary crossover

In SBX crossover, 2 offspring solutions are created from 2 parents as follows:

$$\beta_{qi} = \begin{cases} (2u_i)^{\frac{1}{\eta c+1}}, u_i \le 0.5 \\ \left(\frac{1}{2(1-u_i)}\right)^{\frac{1}{\eta c+1}}, otherwise \end{cases} \quad (19)$$

Then compute the offspring $x_i^{(1,t+1)}$ and $x_i^{(2,t+1)}$

$$x_i^{(1,t+1)} = 0.5\left[(1+\beta_{qi})x_i^{(1,t)} + (1-\beta_{qi})x_i^{(2,t)}\right] \quad (20)$$
$$x_i^{(2,t+1)} = 0.5\left[(1-\beta_{qi})x_i^{(1,t)} + (1+\beta_{qi})x_i^{(2,t)}\right]$$

3.1.2. Non-uniform polynomial mutation

Newly Generated Offspring Undergoes Polynomial Mutation Operation. Similar To Sbx Operator, The Probability Distribution Can Also Be A Polynomial Function, Instead Of Normal Distribution. The new offspring is determined as follows:

$$y_i^{(1,t+1)} = x_i^{(1,t+1)} + (x_i^U - x_i^L)\bar{\delta}_i \quad (21)$$

where the parameter $\bar{\delta}_i$ is calculated from the polynomial probability distribution.

$$p(\delta) = 0.5(\eta_m + 1)(1 - |\delta|)^{\eta_m} \quad (22)$$

$$\bar{\delta}_i = \begin{cases} (2r_i)^{\frac{1}{\eta m+1}} - 1, & \text{if } r_i < 0.5 \\ 1 - [2(1 - r_i)]^{\frac{1}{\eta_m - 1}}, & \text{if } r_i \ge 0.5 \end{cases} \quad (23)$$

where η_m is the mutation index.

3.1.3. Implementation of RGA

The implementation of RGA to the device allocation problem is performed in the following steps.

Step-1: The bus data, line data, and number of FACTS devices are given as inputs.

Step-2: The initial population of individuals are created in normalized form so as to satisfy the FACTS device constraint.

Step-3: For each individual in the population, the fitness function is evaluated in denormalized form after simulating all possible single contingencies by using AC Load flow.

Step-4: By applying tournament selection, Simulated Binary Crossover (SBX) and Polynomial mutation, new offspring population is created for next generation.

Step-5: If maximum number of function evaluations are reached, then go to next step, else go to step 3.

Step-6: Print the best locations and corresponding settings.

3.1.4. Parameter tuning for RGA

Population size =100
Crossover probability, Pc=0.8
Mutation probability, Pm = 1/number of variables
Crossover index, ηc =5
Mutation index, η_m =20.

3.2. Particle swarm optimization

PSO is a population based and self adaptive search optimization technique which is initialized with a group of random particles and searches for optima by updating generations. In every iteration, each particle is updated by following “2 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 Equations (24) and (25) [18]:

$$V_i^{k+1} = W \times V_i^k + C_1 \times rand_1 \times (P_{besti} - S_i^k) + C_2 \times rand_2 \times (G_{best} - S_i^k) \quad (24)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \quad (25)$$

Where
V_i^{k+1} = Velocity of i^th individual at (k + 1)^th iteration
V_i^k = Velocity of i^th individual at k^th iteration
W = Inertia weight
C_1, C_2 = Acceleration coefficients
$rand_1$, $rand2$ = Random numbers selected between 0 and 1
P_{best} = Best position of the i^th individual
G_{best} = Best position among the individuals (group best)
S_i^{k+1} = Position of i^th individual at (k + 1)^th iteration
S_i^k = Position of i^th individual at k^th iteration.

The inertia weight ‘W’ is modified using Eq. (26) to enable quick convergence.

$$W = W_{max} - \frac{(W_{max} - W_{min})}{iter_{max}} \times iter \quad (26)$$

W_{max} = Initial value of inertia weight
W_{min} = Final value of inertia weight
$Iter$ = Current iteration number
$iter_{max}$ = Maximum iteration number

3.2.1. Implementation of PSO

The implementation of PSO to the device allocation problem is performed in the following steps [18].

Step-1: The bus data, line data, and number of FACTS devices are given as inputs.

Step-2: The initial population of individuals are created in normalized form so as to satisfy the FACTS device constraints.

ARPN Journal of Engineering and Applied Sciences

Step-3: For each individual in the population, the fitness function is evaluated in denormalized form after simulating all possible single contingencies by using AC Load flow.

Step-4: The velocity is updated by using Eq. (24) and new population is created by using Eq. (25)

Step-5: If maximum number of function evaluations are reached, then go to next step, else go to step 3.

Step-6: Print the best locations and corresponding settings.

3.2.2. Parameter tuning for PSO

Population size=30
Acceleration coefficients C1 and C2=1
Wmax=0.9 and Wmin = 0.4

4. RESULTS AND DISCUSSIONS

Programming codes for RGA and PSO were developed using MATLAB 7.10 on a PC with a CORE i3 processor, 2.4 GHz and 3 GB RAM. Many trials with independent population initializations have been made to acquire useful conclusion of the performance of the algorithms. In this work, ten independent trials were conducted. The maximum number of function evaluations was set at 10, 000 to ensure the effectiveness. The algorithms are implemented in IEEE 6-bus, IEEE 30-bus and IEEE 118-bus test systems.

4.1. Contingency ranking

Table-1 shows the list of ranked lines after all the single contingencies are simulated in IEEE -6 bus system. The severity index value indicates how a particular line is affected for all the single contingencies. More it is affected, higher is the severity index. 4 lines namely 1-2, 1-4, 2-4, and 1-5 possess the index values. Remaining 7 lines are having zero index value. As a result, these 4 lines are considered for the placement of FACTS devices. Once the rank list is obtained, the optimal locations to install the devices and the settings of device are obtained using the proposed algorithms.

Table-1. Contingency ranking for IEEE 6-bus system.

Line	Rank	No. of overloads	Severity index
1-2	1	2	0.0367
1-4	2	3	0.0256
2-4	3	1	0.0213
1-5	4	2	0.0171

Table-2 shows the list of ranked lines for IEEE 30-bus system after all the single contingencies are simulated. There are 41 possible contingencies, leaving 3 lines (25-26, 9-11, 12-13) connected to isolated buses, only 38 single contingencies are considered. The severity index is calculated for all the 41 lines considering 38 contingencies and the lines are ranked. Table-3 shows the list of ranked lines for IEEE 118-bus system after all the single contingencies are simulated.

Table-2. Contingency ranking for IEEE 30-bus system.

Line	Rank	No. of overloads	Severity index
6-28	1	1	0.1299
8-28	2	1	0.1217
15-23	3	2	0.0401
17-18	4	1	0.0295
27-29	5	1	0.0245
23-24	6	1	0.0210
27-30	7	1	0.0185
22-24	8	1	0.0176
21-22	9	2	0.0092
6-8	10	2	0.0066

Table-3. Contingency ranking for IEEE 118-bus system.

Line	Rank	No of overloads	Severity index
70-75	1	8	11.6038
35-36	2	7	8.8376
90-91	3	7	5.1835
13-15	4	6	3.9923
114-115	5	7	3.4272
34-43	6	5	2.7091
95-96	7	5	2.0043
24-72	8	6	1.8066
19-34	9	6	1.5632
65-66	10	12	1.4891
14-15	11	6	1.2237
32-113	12	8	1.1060
12-16	13	5	1.0056
65-68	14	5	0.9130

4.2. Optimal location and settings of TCSC

Firstly, the TCSC is considered as the device available for the placement. The line location and the reactance value of TCSC are set as the solution parameters to the algorithms. The results obtained for different test systems are discussed below.

4.2.1 IEEE 6-bus system

Table-4 compares the results of 2 techniques in terms of number of overloading (U_n), severity of overloading (F_t) and fitness values, by placing the TCSCs

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in the locations with their optimal settings in IEEE 6-bus system. The number of overloading U_n is 8, before any TCSC is placed. As the number of devices increases, U_n and F_t and thereby Fitness value decreases. When 4 devices are installed, RGA gives the reduced number of overloading from 8 to 4, whereas PSO gives 5. Also, the fitness value is reduced to 33.038 in RGA, whereas it is 34.580 in PSO. Figure-3 and Figure-4 depict the fitness convergence curve for 1 TCSC and 2 TCSCs respectively. For every device increment, it is observed that RGA exhibits better performance than PSO.

4.2.2. IEEE 30-bus system

Table-5 compares the results of 2 techniques in terms of number of overloading (U_n), severity of overloading (F_t) and fitness values ,by placing the TCSCs in the locations with their optimal settings in IEEE 30- bus system. It is assumed that the maximum number of TCSCs is 7, and the results are given for every 2 device increment. When all 7 devices are installed, RGA gives the reduced number of overloading from 13 to 11, whereas PSO gives 12. Also, the fitness value is reduced to 119.11 in RGA, whereas it is 122.42 in PSO. It is observed that the fitness values yielded by RGA are better than PSO for all the cases.

4.2.3. IEEE 118-bus system

Table-6 shows only the comparison of 2 techniques in terms of fitness values yielded by them for IEEE 118-bus system. The settings are not presented due to page limitation. It is assumed that the maximum number of TCSCs is 13, and the results are given for every 2 device increment. When all 13 devices are installed, RGA gives the reduced number of overloading from 795 to 187, whereas PSO gives 217. Also, the fitness value is reduced to 1065.2 in RGA, whereas it is 1173.5 in PSO. It is observed that RGA performs better than the PSO for all the cases.

4.3. Optimal location and settings of UPFC

Now, the UPFC is considered as the device available for the placement. The line location and the settings of UPFC are set as the solution parameters to the algorithms. The results obtained for different test systems are given below

4.3.1. IEEE 6-bus system

The results of 2 techniques are compared in Table-7 in terms of number of overloading (U_n), severity of overloading (F_t) and fitness values, by placing the UPFCs

Table-4. Optimal settings of TCSC and severity of overloading before and after placing TCSC for IEEE 6-bus system.

No of devices	PSO					RGA				
	Severity of overloading			Optimal setting		Severity of overloading			Optimal setting	
	U_n	F_t	Fitness	line	X_{TCSC} (p.u)	U_n	F_t	Fitness	line	X_{TCSC} (p.u)
0	8	32.665	-	-	-	8	32.665	-	-	-
1	7	32.002	39.002	1-4	-0.0698	6	31.368	37.368	1-2	0.1482
2	6	31.520	37.520	1-4 1-5	-0.0529 0.1398	5	31.467	36.467	2-4 1-4	0.0704 -0.0559
3	6	30.463	36.463	1-2 1-4 1-5	0.1108 0.0263 0.1504	5	30.257	35.257	1-2 2-4 1-5	0.1266 0.0720 0.1018
4	5	29.580	34.580	1-2 1-4 2-4 1-5	0.1387 0.0193 0.0601 0.1496	4	29.038	33.038	1-2 1-4 2-4 1-5	0.1500 0.0134 0.0728 0.1262

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Table-5. Optimal settings of TCSC and severity of overloading before and after placing TCSC for IEEE 30-bus system.

No. of devices	PSO					RGA				
	Severity of overloading			Optimal setting		Severity of overloading			Optimal setting	
	U_n	F_t	Fitness	line	X_{TCSC} (p.u)	U_n	F_t	Fitness	line	X_{TCSC} (p.u)
0	13	125.62	-	-	-	13	125.62	-	-	-
1	13	118.50	131.50	8-28	0.0882	13	116.28	129.28	8-28	-0.1010
3	13	112.75	125.75	8-28 15-23 6-28	0.1851 -0.2490 -0.0327	12	110.45	122.45	8-28 21-22 6-8	-0.1010 0.0118 0.1043
5	12	111.59	123.59	23-24 27-29 6-28 22-24 27-30	0.1201 -0.2996 0.0520 -0.1652 -0.0421	12	109.23	121.23	6-28 6-8 8-28 23-24 22-24	-0.0299 0.0118 -0.1021 0.0279 0.0882
7	12	110.42	122.42	6-28 8-28 27-30 21-22 27-29 17-18 15-23	-0.1091 -0.0299 -0.0563 0.0999 -0.0792 0.3012 -0.0422	11	108.11	119.11	15-23 27-29 6-28 21-22 8-28 27-30 17-18	-0.0149 -0.3240 -0.0299 0.0118 -0.1032 0.0287 0.1092

in the locations with their optimal settings in IEEE 6-bus system. The number of overloading U_n is 8, before any TCSC is placed. As the number of devices increases, U_n and F_t and thereby Fitness value decreases. When 2 devices are installed, RGA gives the reduced number of overloading from 8 to 2, whereas PSO gives 3. Also, the fitness value is reduced to 15.303 in RGA, whereas it is 18.983 in PSO. For every device increment, it is observed that RGA exhibits better performance than PSO.

4.3.2. IEEE 30-bus system

Table-8 shows the results when the UPFCs are placed in the optimal locations with settings obtained from RGA and PSO in IEEE 30-bus system. The number of overloading and fitness value decrease as the number of UPFCs is increased. When 2 UPFCs are installed, RGA gives the reduced number of overloading from 13 to 5, whereas PSO gives 7. The fitness value is reduced to 77.73 in RGA, whereas it is 91.78 in PSO. It is observed that RGA exhibits better performance than PSO for all the cases.

4.3.3. IEEE 118-bus system

Table-9 shows the results when the UPFCs are placed in the optimal locations with settings obtained from RGA and PSO in IEEE 118-bus system. The fitness value

Table-6. Severity of overloading before and after placing TCSC for IEEE 118-bus system.

No. of devices	PSO			RGA		
	U_n	F_t	Fitness	U_n	F_t	Fitness
0	795	5237.5	-	795	5237.5	-
1	753	2213.6	2966.6	729	2055.6	2784.6
3	698	2098.9	2796.9	665	1997.9	2662.9
5	619	1928.2	2547.2	581	1865.9	2446.9
7	513	1693.2	2206.2	479	1609.5	2088.5
9	392	1459.9	1851.9	366	1390.6	1756.6
11	309	1179.8	1488.8	281	1099.0	1380.0
13	217	956.5	1173.5	187	878.2	1065.2

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ARPN Journal of Engineering and Applied Sciences

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Table-7. Optimal settings of UPFC and severity of overloading before and after placing UPFC for IEEE 6-bus system.

No. of devices	PSO						RGA					
	Severity of overloading			Optimal setting			Severity of overloading			Optimal setting		
	U_n	F_t	Fitness	line	UPFC setting		U_n	F_t	Fitness	line	UPFC setting	
0	8	32.665	-	-	-	-	8	32.665	-	-	-	-
1	5	25.895	30.895	1-2	Pu1=-49.87 Qu1=24.73	Pu2=49.87 Qu2=-4.73	4	22.515	26.515	1-2	Pu1=-41.61 Qu1=20.53	Pu2=41.61 Qu2=-20.53
2	3	15.983	18.983	1-2	Pu1=-59.50 Qu1=-40.00	Pu2=59.50 Qu2=40.00	2	13.303	15.303	1-2	Pu1=-70.35 Qu1= -27.1	Pu2=70.35 Qu2= 27.1
				1-4	Pu1=60.33 Qu1=8.89	Pu2=-60.33 Qu2=-8.89				2-4	Pu1=56.14 Qu1=2.47	Pu2=-56.14 Qu2=-2.47

Table-8. Optimal settings of UPFC and severity of overloading before and after placing UPFC for IEEE 30-bus system.

No. of devices	PSO						RGA					
	Severity of overloading			Optimal setting			Severity of overloading			Optimal setting		
	U_n	F_t	Fitness	line	UPFC setting		U_n	F_t	Fitness	line	UPFC setting	
0	13	125.62	-	-	-	-	13	125.62	-	-	-	-
1	11	117.65	128.65	15-23	Pu1=-52.78 Qu1=34.98	Pu2=52.78 Qu2=-34.98	11	100.02	111.02	8-28	Pu1=-16.14 Qu1=13.51	Pu2=16.14 Qu2=-13.51
2	7	84.78	91.78	15-23	Pu1=-43.86 Qu1=28.66	Pu2=43.86 Qu2=-28.66	5	72.73	77.73	8-28	Pu1=-16.14 Qu1=13.51	Pu2=16.14 Qu2=-13.51
				8-28	Pu1=-20.00 Qu1=-11.98	Pu2=-20.00 Qu2=-11.98				6-28	Pu1=78.14 Qu1=-53.77	Pu2=-78.14 Qu2=53.77

Table-9. Severity of overloading before and after placing UPFC for IEEE 118-bus system.

devices	PSO			Real coded GA		
	U_n	F_t	Fitness	U_n	F_t	Fitness
0	795	5237.5	-	795	5237.5	-
1	653	1190.7	1843.7	602	1106.4	1708.4
3	488	961.6	1449.6	455	873.9	1328.9
5	309	845.2	1154.2	274	764.9	1038.9
7	174	711.2	885.27	140	655.8	795.8
9	56	602.7	658.7	35	513.1	548.1

decreases thereby the security level is enhanced, as the number of UPFCs is increased. When 9 UPFCs are installed, RGA gives the reduced number of overloading from 795 to 35, whereas PSO gives 56. RGA gives the least fitness value as 548.1, whereas PSO gives 658.7. It is observed that RGA exhibits better performance than PSO for all the cases.

5. CONCLUSIONS

This paper proposes evolutionary computational approach for determining the most suitable locations and settings for installing TCSC and UPFC to eliminate line overloads under single contingency in a power system. Using Contingency Severity Index, the mostly affected lines during single contingency are ranked. The optimization problem is formulated and solved to find out optimal locations among the ranked lines and settings of the devices to be placed using RGA and PSO algorithms. The usage of Simulated Binary Crossover (SBX) and Non-uniform Polynomial Mutation improves the performance of RGA. Simulations are performed on IEEE 6-bus, 30-bus and 118-bus test systems. The observations made from the obtained results are following:

a) As the number of FACTS devices increases, the number of overloads and severity of overloading are reduced.
b) Beyond certain number of devices, the severity of overloading is not reduced appreciably.
c) For the same number of devices, UPFC results in increased security margin than TCSC in all the test systems.

ARPN Journal of Engineering and Applied Sciences

d) The settings of devices given by RGA result in enhanced security margin than the settings given by PSO in all the test systems.
e) The computation time is less for PSO than RGA in all the test systems.

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