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A novel method for optimum fault current limiter placement using particle swarm optimization algorithm

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SUMMARY

Connection of distributed generation to the grid and the expansion of transmission system in order to meet the growing for electricity are causing the extent and complexity of the network structure. The occurrence of fault in such networks leads to flow large short circuit currents through the system, which may exceed the rating of existing circuit breakers and can damage system equipment. The utilization of fault current limiters (FCLs) in power systems can be an effective method to limit fault currents. FCLs can offer many benefits, but these benefits depend on the number, installation location, and impedance of FCL. In this paper, determining the number, location, and impedance of FCLs in network is modeled as a new optimization problem when objective functions are reliability, power loss, and economical use of FCLs. Also, a combination of discrete and continuous particle swarm optimization algorithm is employed to solve problem. Modified RBTS 2 bus test system is considered to evaluate the effectiveness and feasibility of the proposed method. Obtained results show the importance of finding optimum number, location, and impedance of FCLs in minimization of the proposed objective functions. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: distributed generation (DG); fault current limiter (FCL); placement and particle swarm optimization (PSO)

1. INTRODUCTION

Today, the increase in energy demand, rise in natural gas and oil prices, the rapid growth of privatization, and the emergence of new technologies have caused developments in the electrical industry and serious attention to the distributed generation technology. Connection of distributed generation (DG) to the grid is causing the extent and complexity of the network structure [1]. With the installation of DG in the network, the magnitude and direction of currents flowing of feeders and short circuit current levels in different points of the network will be changed. Because one of the important parameters in the selection of equipment installed in the network such as the circuit breaker (CB), transformers, current transformers, and fuse is short circuit current passing through them, so with the installation of DG in the network, short circuit current levels increase and in some cases may exceed allowable level of equipment on the network particularly CB and even can damage equipment. In some parts of the network, the increase in short circuit current is so severe that is larger than interrupt capacity of available CBs in market [2]. Using fault current limiters (FCLs) in power systems can be an effective way to limit fault currents and can greatly relieve the aforementioned problems. FCLs are elements that are placed in series with the network equipment to reduce the level of short circuit current during a fault. Under normal operating conditions, FCLs have very low impedance, so voltage drop on the network is very low [3,4]. Also FCLs are capable of maintaining of power system in acceptable level of reliability and stability. FCLs can have other benefits such as increasing the energy transition capacity and reducing of voltage sag during a fault occurred. Although FCLs can have many benefits, these benefits are

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dependent on the number, location, and impedance of FCL. Thus, from point of view of design and operation of the power system, it is necessary to find a method that can help determine optimum number and optimum location for the installation of the FCL [5–9].

Fault current limiter placement with different purposes is a nonlinear optimization problem, and it cannot be solved with conventional mathematical techniques. Computational intelligence techniques based on guided stochastic search is useful to solve such problems. In References [10,11], hierarchical genetic algorithm (GA) combined with a micro GA was used to find the optimum locations of FCL. Reference [5] used a search space reduction technique and GA to find the optimum number and locations for FCL placement. Reference [6] also proposed indices of reliability improvement and fault current reduction for determining the location of FCL. In this paper, particle swarm optimization (PSO) algorithm is proposed to simultaneously determine the number, location, and impedance size of FCLs. The proposed PSO algorithm is composed of two different types:

- Discrete PSO (DPSO) algorithm, which is used to denote state of FCL install or uninstall on the lines.
- Continuous PSO (CPSO) algorithm, which is used to determine the impedance of the FCL.

Also, in this paper, an objective function is considered in FCL placement problem for the first time, which is composed of three parts: (i) improving reliability; (ii) minimizing the real power loss; and (iii) economical use of FCLs. Finally, the proposed algorithm is applied on modified RBTS 2 bus test system, and obtained results show the effectiveness of algorithm.

2. PROBLEM FORMULATION

The problem of FCL optimal placement is a nonlinear optimization problem, and different objectives can be pursued by implementing it. In this study, objective function including reliability enhancement, minimization of the real power loss, and the economical use of FCL is defined to solve the optimization problem. Objective function is explained as follows:

2.1. Improvement of reliability

2.1.1. Impact of fault current limiter on device reliability. Installation of FCL in the distribution network can affect on the network reliability. Commonly, series connection of a new device with the system causes system reliability to be deteriorating [12]. FCL, in contrast, reduces the frequency of the excessive fault current, thereby often improving the failure rate of devices [13,14]. But this improvement depends on the location of FCL installation. Various reasons may cause a fault to fail in a protective device. Some of the reasons include degraded operation, worn, arcing, and fault current. Because of the characteristics of FCL, which can reduce fault currents in a network, this paper is focused on fault current among various reasons.

As mentioned, failure rate of devices is changed by installing FCL, which its value is obtained from the following equation [6]:

$$\lambda_{0,k,f} = \lambda_{0,k,f}{}^{faultcurrent} + \lambda_{0,k,f}{}^{degradedoperation} + \lambda_{0,k,f}{}^{worn} + \lambda_{0,k,f}{}^{arcing} + \dots \quad (1)$$

$$\lambda_{l,k,f} = \lambda_{0,k,f} + \lambda_{0,k,f}{}^{faultcurrent}\eta_{l,k,f} \quad (2)$$

$\lambda_{l,k,f}$ is the failure rate for failure event f at k^{th} load after installing of FCL in the l^{th} line.

$\lambda_{0,k,f}$ is the failure rate that is only caused by fault current for failure event f at k^{th} load when FCL does not exist in a network ($l=0$). And $\eta_{l,k,f}$ is the fault current reduction efficiency of failure rate for failure event f at k^{th} load when FCL is installed in the l^{th} line.

2.1.2. Estimation of distribution reliability. In this paper, a distribution reliability index, namely, Weighted Load Reliability Index (WLRI) is used to estimate the distribution reliability [6]. The proposed index is composed of traditional reliability indices (System Average Interruption Duration

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Index, System Average Interruption Frequency Index, and Average Service Unavailability Index) and is presented in (3) and (4).

$$WLRI_{l,k} = \sum_{m=1}^{3} w_m R(m,l,k) \tag{3}$$

$$R(m,l,k) = \begin{cases} \dfrac{\sum_{f\in\forall failureevents} \lambda_{l,k,f} N_k}{\sum_{k=1}^{K} N_k} & (m=1) \\ \dfrac{\sum_{f\in\forall failureevents} r_{l,k,f}\ \lambda_{l,k,f} N_k}{8760\sum_{k=1}^{K} N_k} & (m=2) \\ \dfrac{\sum_{f\in\forall failureevents} r_{l,k,f}\ \lambda_{l,k,f} N_k}{\sum_{k=1}^{K} N_k} & (m=3) \end{cases} \tag{4}$$

where w_m is the normalization factor for the value of m^{th} reliability indices, and $r_{l,k,f}$ and N_k are repair time and the number of customers, respectively.

2.2. *Power loss minimization*

Fault current limiter placement can be performed with the purpose of minimizing real power loss [15]. The total real power loss is calculated as follows:

$$P_{loss} = \sum_{i=1}^{N_{br}} R_i \times |I_i|^2 \tag{5}$$

where R_i and I_i are the resistance and actual current of the i^{th} branch, respectively. N_{br} is the number of the branches.

2.3. *Economical use of fault current limiter*

For the economical use of FCL, it is necessary to use a minimum number of FCLs and/or the smallest FCL circuit parameters [11]. This objective can be formulated as follows:

$$f(X) = c_2 \frac{\sum_{i=1}^{N_{FCL}} Z_{i,FCL} - Z_{FCL}^{expected}}{Z_{FCL}^{expected}} + c_3 \frac{N_{FCL} - N_{FCL}^{expected}}{N_{FCL}^{expected}} \tag{6}$$

where $Z_{i,FCL}$ and N_{FCL} are the impedance of the i^{th} FCL and the number of fault current limiter inserted in the system, respectively. $Z_{FCL}^{expected}$ and $N_{FCL}^{expected}$ are the expected impedance of FCLs and the expected number of FCLs inserted in the system, respectively.

2.3.1. Objective function. The problem of FCL optimal placement is a multi-objective optimization. In this paper, the multi-objective weighting approach is used to formulate the problem.

For the purpose of optimization, the main objective function, which composed of three objectives mentioned earlier, can be formulated as follows:

$$OF = c_1 \frac{RS(X)}{RS(X=O)} + c_2 \frac{\sum_{i=1}^{N_{FCL}} Z_{i,FCL} - Z_{FCL}^{expected}}{Z_{FCL}^{expected}} + c_3 \frac{N_{FCL} - N_{FCL}^{expected}}{N_{FCL}^{expected}} + c_4 \frac{P_{loss}(X)}{P_{loss}(X=O)} \tag{7}$$

$$RS(X) = \sum_{k=1}^{K} w_k . WLRI(X,k) \tag{8}$$

$$w_k = \frac{CIC\ of\ kth\ load\ point}{average\ CIC\ of\ all\ types\ of\ customers} \tag{9}$$

$$P_{loss}(X) = \sum_{i=1}^{N_{br}} R_i \times |I_i|^2 \tag{10}$$

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$$X = [X_1, X_2], \qquad X_1 = [ls_1, ls_2, \ldots, ls_n], \;\; X_2 = [Z_{1,FCL}, Z_{2,FCL}, \ldots, Z_{n,FCL}] \tag{11}$$

Subject to

$$Z_{i,FCL}{}^{min} \le Z_{i,FCL} \le Z_{i,FCL}{}^{max} \qquad i = 1 \ldots N_{FCL} \tag{12}$$

$$I_j^{sc} \le I_j^{sc,max} \qquad j = 1 \ldots N_B \tag{13}$$

where index *RS* is used to determine the effect of installation location of FCL on distribution reliability.

w_k is determined by considering customer interruption cost of each customer [16] as a weighting factor by the significance of k^{th} load.

X is the vector of control variables, which is a 2*n*-dimensional vector. ls_i is the state of the i^{th} candidate line and can take only two values 0 or 1, for which 0 and 1 correspond to FCL uninstallation and installation states on the line, respectively. $Z_{i,FCL}$ and N_{FCL} are the impedance of the i^{th} FCL and the number of fault current limiter inserted in the system, respectively. $Z_{i,FCL}$ and N_{FCL} are obtained from the vector X.

c_1, c_2, c_3, and c_4 are weighting factors for trading off between *RS*, $N_{FCL,}$ and the summation of circuit parameter of FCLs. N_B is the total number of system busses. I_j^{sc} is the short circuit current for bus *j*.

3. PARTICLE SWARM OPTIMIZATION ALGORITHM

The idea of PSO algorithm was introduced by Kennedy and Eberhart in 1995 for the first time. PSO is the computation algorithm inspired by nature and is based on iteration. The inspiration for this algorithm was the social behavior of animals such as the mass movement of birds and fish. PSO started with an initial random population matrix like many other optimization methods. Each member of the population is called a particle. Indeed, the PSO algorithm is composed of a certain number of particles that are initialized randomly. For each particle, both values of position and velocity are defined, which are modeled with a position vector and a velocity vector, respectively. These particles iteratively move around in *n*-dimensional search space to search the new options by calculating objective function as an assessment criterion. A memory unit is allocated to save the best fit parameters of each particle (*Pbesti*, *i* = 1, 2,3, . . .) as well as a single most fit particle (*Gbest*) among all the particles in the group. With the experience gained from this memory, particles will decide how to move in next iteration. In each iteration, all particles move around in *n*-dimensional search space until the optimum solution is found. If X_i and V_i represent the position and velocity vectors of each particle, respectively, then updating the position and velocity of particles is performed using

$$V_i^{(t+1)} = \omega . V_i^{(t)} + k_1 . rand_1(o) . \left(Pbest_i\text{-}X_i^{(t)}\right) + k_2 . rand_2(o) . \left(Gbest\text{-}X_i^{(t)}\right) \tag{14}$$

$$X_i^{(t+1)} = X_i^{(t)} + V_i^{(t+1)} \tag{15}$$

In the aforementioned equations, *i* and *t* denote the number of particle and the number of iteration of the algorithm, respectively. $rand_1(0)$ and $rand_2(0)$ are random independent numbers distributed between zero and one uniformly. Constants k_1 and k_2 are known as learning factors, and they are used to increase or decrease the impact of *Gbest* and *Pbest*. The parameter ω is also used to improve the performance of the algorithm [17–19].

In this paper, we have divided the vector of control variables into two parts X_1 and X_2 to solve the optimization problem. Vector X_1 consists of control variables ls_i, and because it can take only two values 0 or 1, it is a discrete optimization problem with binary optimization variables. Then, DPSO should be used to solve it. Vector X_2 consists of impedance of FCLs corresponding to vector X_1 and can take each value. CPSO should be used to solve it.

Updating the position of particles in DPSO algorithm is not the same as CPSO algorithm but is obtained by using the following equation:

$$X_i^t = \begin{cases} 1, & rand(.) \le S(V_i^t) \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

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$$S(V_i^t) = \frac{1}{1 + \exp(-V_i^t)} \tag{17}$$

Flowchart of proposed algorithm is shown in Figure 1.

4. SIMULATION AND RESULT

In this section, the PSO algorithm is employed to solve the FCL placement problem; the value of PSO's coefficients are $\omega = 0.7$, $k_1 = 2$, and $k_2 = 2$, and also, the convergence criteria of the PSO algorithm is the number of iteration and is considered 200. Modified RBTS 2 bus test system [20] is issued to show the effectiveness of the proposed approach. This system is consists of a radial network from feeder 3 and a mesh network where feeders 1 and 2 are connected to each other. The single line diagram of this system is shown in Figure 2. In this network, protective devices include CB, line switch, and fuse. All the feasible locations for installing FCL are considered except for the lines nearby customers.

Customer, device reliability, and system data are shown in Tables I and II, respectively. Other data used in this simulation can be found in [6].

It is assumed that failure rates of CB, line switch, and 154/22.9 kV transformer only caused by fault current are equal to 0.0018, 0.002, and 0.00525, respectively. In the PSO-based FCLs optimization, in order to evaluate objective function, a balanced three-phase fault is considered that leads to analyze fault current for each device. On the basis of resulted fault currents, the device failure rate would be calculated. Then, WLRI and RS are calculated by (3) and (4) considering weighting factor by customer interruption cost of customers. Finally, the objective function is evaluated using the values of RS, X, $P_{loss}(X)$, and constraints.

The amount of WLRI for all loads before installing FCL in the distribution network is 0.6822. Also, before installing FCL in the network, system power loss is 0.9185 pu.

For testing the effectiveness of PSO in the optimal placement of FCL problem, seven cases with different values of c_1, c_2, c_3, and c_4 are tested. The variations of control parameter values related to these cases are listed in Table III. By applying the PSO to the test system of Figure 2, the output results are obtained. Location and impedance size of FCLs obtained by the PSO for seven cases are given in Table IV. In all cases, impedances of FCLs are considered to be continuous and in the range (i.e., 0.05 to 1 pu). The resulting WLRIs for all loads, after applying the PSO algorithm, are given in Table V.

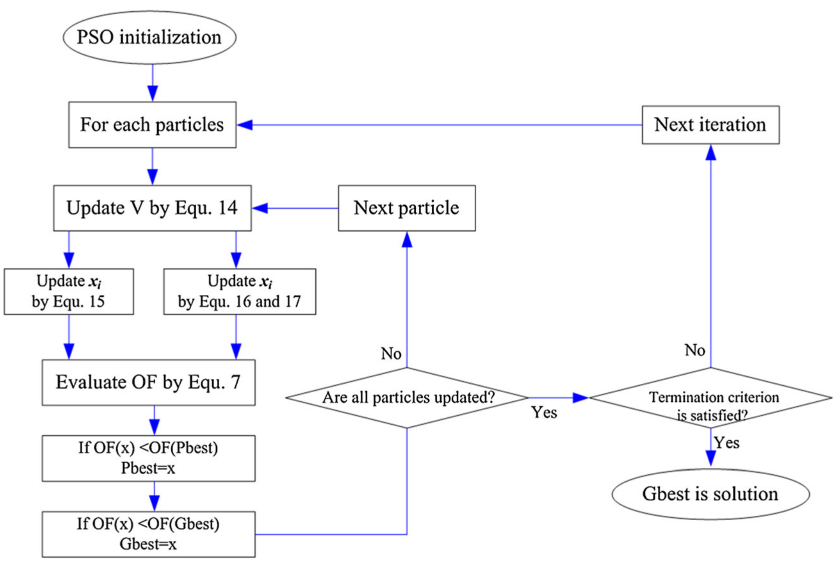

Figure 1. Flowchart of the proposed continuous particle swarm optimization–discrete particle swarm optimization.

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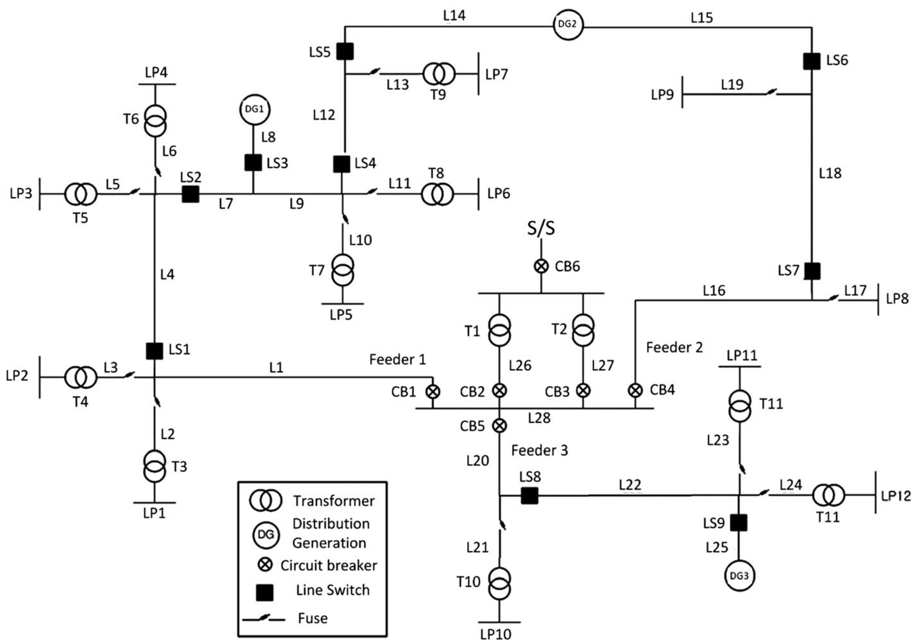

Figure 2. Case I: modified RBTS 2 bus.

Table I. Customer data.

k	Load	Type	Number of customers	w_k
1	LP1	Residential	210	0.5
2	LP2	Residential	210	0.5
3	LP3	residential	210	0.6
4	LP4	Commercial	10	1.5
5	LP5	Commercial	10	1.2
6	LP6	Commercial	10	1.0
7	LP7	Commercial	10	1.5
8	LP8	Large user	1	1.6
9	LP9	Large user	1	1.7
10	LP10	residential	250	0.7
11	LP11	Residential	200	0.7
12	LP12	Residential	240	0.8

Table II. Reliability and system data.

Device	Failure rate	Repair time	Switching time
154/22.90 kV	0.015 f/yr	15	—
22.9/0.23 kV	0.015 f/yr	10	—
22.9 kV bus	0.001 f/yr	2	—
22.9 kV line	0.065 f/km yr	5	—
Circuit breaker	0.006 f/yr	4	1
Line switch	0.010 f/yr	3	0.5

In Table IV, the proper case must be selected on the basis of the network operator priority. However, in this paper, to check which case is suitable compared with the others, the WLRI for faults at the load point is checked, and small values are selected as a suitable case. The small values of WLRI mean to improve the system reliability. As seen from Table IV, in cases 1 and 2, because of considering a zero

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Table III. Parameter variation.

Case no.	c_1	c_2	c_3	c_4
1	0.00	0.33	0.33	0.33
2	0.00	0.50	0.50	0.00
3	0.33	0.33	0.33	0.00
4	0.25	0.25	0.25	0.25
5	1.00	0.00	0.00	0.00
6	0.00	0.00	0.00	1.00
7	0.50	0.00	0.00	0.50

Table IV. Particle swarm optimization outputs (location and impedance of fault current limiter and loss power).

Case no.	Location of FCL	Z_{FCL} (pu)	P_{loss} (pu)	Z_{FCL} (pu) (total)
1	4, 14, 25	0.680, 0.630, 0.800	0.7391	2.1100
2	1, 14, 25	0.4679, 0.5475, 0.6935	0.7801	1.7089
3	1, 14, 25, 28	0.9792, 0.7124, 0.3337, 0.3099	0.8729	2.3352
4	1, 14, 20, 25	0.5224, 0.9604, 1.0000, 0.3346	0.6688	2.8174
5	1, 4, 7, 9, 12, 14, 16, 20, 22, 25, 26, 27, 28	1.0000, 1.0000, 1.0000, 1.0000, 0.0429, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000	0.0667	2.8174
6	1, 4, 7, 8, 9, 12, 14, 16, 18, 20, 22, 25, 26, 27, 28	1.0000, 1.0000, 1.0000, 1.0000, 0.0107, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000	0.0343	14.0107
7	1, 4, 7, 8, 9, 12, 14, 16, 18, 20, 22, 25, 26, 27, 28	1.0000, 1.0000, 1.0000, 1.0000, 0.0107, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000, 1.0000	0.0343	14.0107

FCL, fault current limiter.

Table V. Particle swarm optimization outputs (the amount of weighted load reliability (WLRI) for all loads).

	WLRI						
Load no.	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
1	0.6835	0.6501	0.6343	0.6478	0.6292	0.6313	0.6313
2	0.6839	0.6502	0.6344	0.6479	0.6293	0.6315	0.6315
3	0.6460	0.6522	0.6361	0.6497	0.6245	0.6264	0.6264
4	0.6459	0.6520	0.6359	0.6495	0.6244	0.6263	0.6263
5	0.6501	0.6549	0.6456	0.6498	0.6154	0.6276	0.6276
6	0.6499	0.6547	0.6454	0.6496	0.6153	0.6275	0.6275
7	0.6498	0.6544	0.6456	0.6493	0.6153	0.6206	0.6206
8	0.6808	0.6804	0.6672	0.6807	0.6265	0.6328	0.6328
9	0.6803	0.6803	0.6676	0.6811	0.6262	0.6218	0.6218
10	0.6894	0.6885	0.6730	0.6490	0.6420	0.6465	0.6465
11	0.6908	0.6899	0.6740	0.6505	0.6315	0.6348	0.6348
12	0.6994	0.6979	0.6782	0.6530	0.6344	0.6380	0.6380
Average	0.6708	0.6671	0.6531	0.6548	0.6262	0.6304	0.6304

weight for reliability index ($c_1 = 0$), almost all WLRIs have great values. In cases 2 and 3, c_4 is assumed to be zero. So the system power loss has slight decrease than when FCL does not exist in a network ($X = 0$). In cases 5, 6, and 7, despite the small values of WLRIs and $P_{loss}(X)$, the number and

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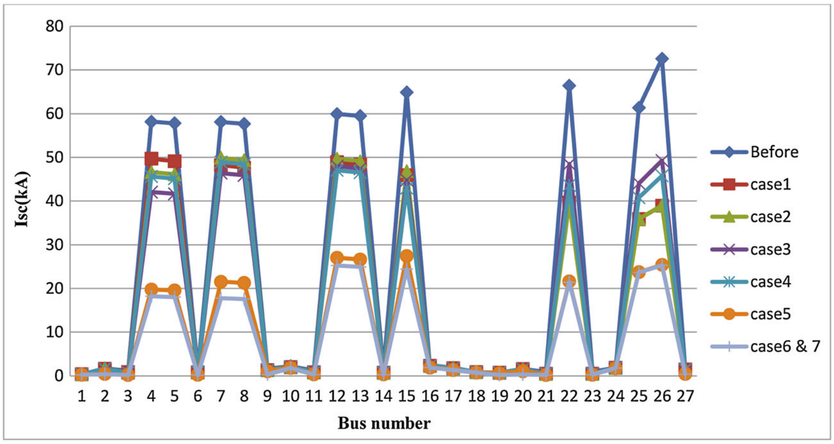

Figure 3. Short circuit currents before installation of the fault current limiters and for all seven cases.

impedance of FCLs have large values, which are not useful from economical point of view because of not considering corresponding weighting factor (c_2, $c_3 = 0$). In cases 5, 6, and 7, the results of PSO are not only economical but also protective devices that cannot operate properly because fault current level is much lower than the pick-up current of the existing protective devices. However, protective operation and coordination is out of scope of this paper. In the case 4, all weighting factors are assumed to be 0.25. As seen from the Table V, the WLRI values of case 4 are smaller than 0.6822, which mean to improve the system reliability.

In cases 3 and 4, WLRI values are smaller when not using FCL (i.e., 0.6822) because of considering corresponding suitable weighting factor. The results, which are shown in Table V, show that the average WLRI value of case 3 is smaller than case 4, but the system power loss is larger than case 4. Therefore, cases 3 and 4 are selected as suitable cases.

Also, to trust the obtained results in Tables IV and V, the resulting fault currents at all busses are shown in Figure 3.

5. CONCLUSION

In this paper, PSO algorithm is proposed to simultaneously determine the number, location, and impedance size of FCLs. In this paper, PSO algorithm is used in two different types: DPSO and CPSO. In order to implement the location and impedance of FCLs on the optimization problem, we have divided the vector of control variables into discrete and continuous parts. The proposed algorithm is applied on modified RBTS 2 bus test system with objective function including reliability enhancement, minimization of the real power loss, and the economical use of FCL. The simulation results demonstrate the impact of objective functions on the FCL placement problem.

6. LIST OF SYMBOLS AND ABBREVIATIONS

FCL	fault current limiter
DG	distributed generation
PSO	particle swarm optimization
GA	genetic algorithm
CB	circuit breaker
WLRI	weighted load reliability index
w	weighting factor
λ	failure rate

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r	repair time
N	number of customers
P_{loss}	total real power loss
R_i	resistance of the *ith* branch
I_i	actual current of the *ith* branch
N_{br}	number of the branches
$Z_{i,FCL}$	impedance of the ith FCL
$Z_{FCL}^{expected}$	expected impedance
$N_{FCL}^{expected}$	expected number of FCLs inserted in the system
CIC	customer interruption cost
N_{FCL}	number of fault current limiter inserted in the system

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