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Multi objective optimal allocation of fault current limiters in power system

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ABSTRACT

Transmission systems, connection of distributed generation to the grid are increased due to increase in power demands. This fact causes the increase in short circuit level of power networks. The occurrence of fault in such networks leads to large short circuit currents throughout the system, which may exceed the rating of existing circuit breakers and can damage system equipment. There are some approaches to reduce this fault current such as power network reinforcement and utilization of fault current limiter (FCLs) in power systems. Power system reinforcement is too difficult if not impractical. Therefore, the utilization of FCLs can provide an effective way to suppress fault currents. The effectiveness of FCL depends on the number of FCLs and their installation location. In this paper, a novel approach is presented to determine the optimal number and location of FCLs to improve the power network reliability and fault current reduction based on different conflicting objective functions. IEEE 39 BUS system and IEEE 57 BUS system are considered to evaluate the effectiveness and feasibility of the proposed method. The objective functions considered for the optimal allocation are reliability of power system, economic impact and short circuit current reduction. Unlike what has been previously done in literature, in this paper Pareto based optimization algorithms, namely non-dominated sorting algorithm, multiobjective particle swarm optimization and multiobjective evolutionary algorithm based on decomposition, are utilized to deal with this problem. The use of these methods made it possible to obtain the Pareto optimal front in which these objective functions are optimized simultaneously.

1. Introduction

Nowadays, with the increasing demand for electric energy, power systems have become greater and more complex, as a result fault current increases. By increasing the fault current, in some cases allowable level of equipment on the network particularly circuit breakers (CBs) may exceed the allowable level and even can damage equipments. Therefore, it is necessary to use CBs with higher breaking current. This, in turn imposes heavy costs on the system. If after identifying the fault, its current can clearly be limited by a method, a technically and economically significant saving is achieved. This is possible by fault current limiters (FCLs). FCLs are elements that are placed in series with the network equipment to reduce the level of short circuit current during a fault. This equipment normally reveals little resistance against the flow of the current; however, if short-circuit happens and in the initial moments after fault, their resistance suddenly increases which prevents more short circuit current [1,2]. Limiters do not cause voltage sag and power loss in the steady state conditions of the system [3]. In [4], authors examined transient stability due to use of FCLs in network with studying the rotor oscillation of generator after the occurrence of fault with large amplitude, e.g. short circuit. In [5], an application of a superconducting fault current limiter (SFCL) to enhance the power system transient stability is presented. In Ref. [6], power system security and stability enhancement is examined and particle swarm optimization (PSO) algorithm is used to optimize the system. In [7], two characteristics of FCL utilization, fault current limiting and voltage sag suppression in distribution network are examined. The effect of FCLs in distribution network in the presence of wind turbine generators is also investigated [8].The main focus of this paper is on fault current limitation effect of FCLs. In addition to the short circuit current limitation, studies have shown that the use of FCLs in power network allows the incensement in the transient stability of generators and consequently the global stability of the network [9,10]. Previous studies on FCL optimal allocation mainly focus on one objective function either fault reduction as in [11–13] or stability as in [9,13]. Hierarchical genetic algorithm (GA) combined with a

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micro GA was used to find the optimum locations of FCLs [14,15]. In [12], authors used a search space reduction technique and GA to find the optimum number and locations of FCLs. In Ref. [16], a two-stage placement approach is proposed, where Stage I benefits from the hierarchical fuzzy logic decision method and a variant of generic algorithm so-called Hashing-integrated. In order to sort feasible solutions, the hierarchical fuzzy logic decision method is used. The Hashing-integrated genetic algorithm determines an optimal FCL placement in the reduced search space. PSO is then employed in Stage II for optimizing the FCL parameters. The main focus of [17] is on the total operating time, which is the sum of the operating times of primary relays for each fault and minimax regret criterion is proposed for power system protection considering the uncertainty of the (distributed generation) DGs to determine SFCL placement. However, multiobjective approach and adaptive penalty factor are not considered in this research. In Ref. [18], an iterative mixed integer nonlinear optimization method is proposed to optimally locate and size FCLs in a power system. Another approach has examined the influence of fault type on the optimal allocation of SFCL in electrical power grid [10]. Eigenvalue analysis is also used to optimize resistive SFCL for multi-machine power system [19]. Multiobjective optimization algorithm is applied to solve different problems of power system such as reactive power and voltage control [20], power flow [21], and optimal power flow with FACTS devices [22]. In Ref. [23], sensitivity calculation of capacity constraints method is used to find out the optimal placement and value of the determined number of SFCLs. In Ref. [24], the effect of the presence of FCLs for maintaining over current relay coordination in power network with distributed generation is discussed.

In this paper, in order to optimally allocate the FCLs in a power system, three objectives functions are considered. The objective functions considered in FCL placement problem are: (a) improving reliability; (b) economical usage of FCLs and (c) minimizing the short circuit current. The benchmark problems considered are IEEE 39 Bus and IEEE 57 Bus. Unlike what can be seen in literature which combine different objective functions in a single objective function, in this study, the three objective functions are solved using Pareto based algorithms. The uses of such algorithms make it possible to simultaneously determine the number, location and the impedance values of FCLs. Moreover, existing methods in literature do not optimize the location and the value of FCLs; but rather choose some locations for the FCLs and then optimize their values. However, the proposed approach optimizes the location and the values of FCLs, simultaneously. The Pareto based optimization algorithms are multiobjective evolutionary algorithm based on decomposition (MOEA/D), multiobjective particle swarm optimization algorithm (MOPSO) and non dominated sorting genetic algorithm-II (NSGA-II). Since Swarm intelligence and evolutionary methods are two main classes of optimization methods used in multiobjective optimization approaches, MOPSO which is based on swarm intelligence and NSGA-II and MOEA/D which are evolutionary based methods are selected. Moreover, another contribution of the proposed approach in this study is the use of an adaptive penalty factor. The penalty factor used is relative to the violation of maximum short circuit allowed in the system. Furthermore, since the power system can tolerate some levels of short circuit current, another constraint is defined for the lower bound of the short circuit current which causes less FCLs to be used and reduces the costs considerably. In addition, another penalty term is considered for the violation of allowable interval of impedances. It is shown that the three multiobjective optimization algorithms are capable of obtaining an appropriate Pareto optimal front.

The rest of the paper is organized as follows: in Section 2, fault current calculation and the effect of adding a FCL on impedance matrix is described. In Section 3, the networks studied in this paper are introduced. In Section 4, the main problem considered in this paper, is formulated. In Section 5, multiobjectives optimization algorithms which are used in this paper are presented. Section 6 covers the simulation results. The concluding remarks are given in Section 7.

2. Fault current calculation and the effect of adding a FCL on Z_{BUS} impedance

Three phases symmetrical faults are used to specify the rating of CBs because it is the worst type of faults. For a balanced three-phase fault at bus i, the short-circuit current can be calculated as follows:

$$I_i^{sc} = \frac{E_i}{Z_{ii}} * I_b \tag{1}$$

where I_i^{sc} is the three-phase short circuit current at bus i and E_i is the voltage before the fault at bus i. Commonly, E_i can be set as 1.0 p.u. The parameter Z_{ii} is the diagonal impedance of the impedance matrix (Z_{bus}) and I_b is the base current [12]. When adding a line with impedance Z_b between buses j and k, each element of Z_{bus} can be modified as follows [12]:

$$Z_{xy}^{new} = Z_{xy}^{old} - \frac{(Z_{xj} - Z_{xk})(Z_{jy} - Z_{ky})}{Z_{jj} + Z_{kk} - 2Z_{jk} + Z_b} \tag{2}$$

where Z_{xy}^{new} and Z_{xy}^{old} are the modified and old elements of Z_{bus}, respectively. In addition, the effect of inserting the impedance Z_b series with the transmission line can be considered as a parallel impedance Z_p with the network which can be obtained as follows:

$$Z_p = (-Z_b)//(Z_b + Z_{FCL}) = -\frac{Z_b(Z_b + Z_{FCL})}{Z_{FCL}} \tag{3}$$

Fig. 1 represents the Thevenin equivalent by looking into the system from two existing buses when impedance Z_b is added between them. The modification to the diagonal entries of Z_{bus} after the FCL fired up at a branch between buses j and k is as follows:

$$\Delta Z_{ii} = -\frac{(Z_{jj} - Z_{ik})^2}{Z_{jj} + Z_{kk} - 2Z_{jk} + Z_p} \tag{4}$$

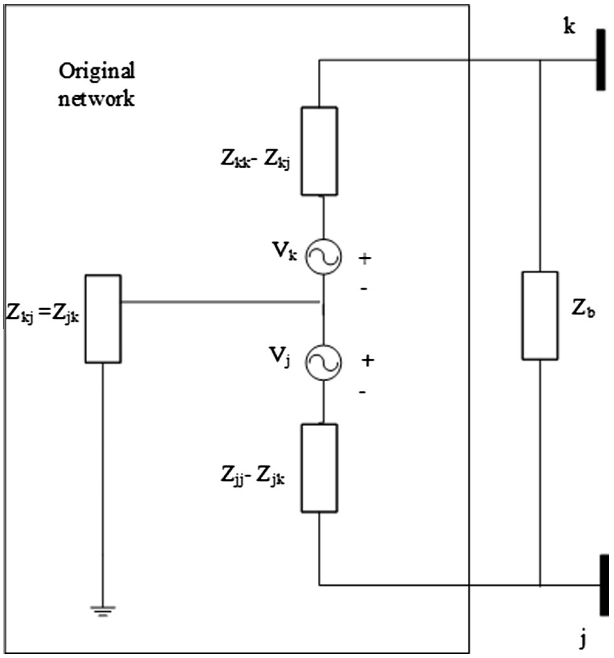

Fig. 1. Thevenin equivalent when line is added between k and j buses.

3. Introducing the studied networks

In this paper, there are two case studies that involve IEEE 10 generators 39 buses system and IEEE 57 buses system. The system descriptions are as follows. The IEEE 39 bus system has 10 generators, 29 load buses and 46 transmission lines. The single line diagram of the system is depicted in Fig. 2. The IEEE 57 Bus test case represents a portion of the American Electric Power System (in the Midwestern US) as it was in the early 1960's. This test case consists of 57 buses, 7 generators and 42 loads [25]. The single line diagram of the system is depicted in Fig. 3. According to IEC 62271 standard, the CB rating is 1250 A and short circuit breaking current assumed to be 21.5 kA and 25 kA for IEEE 39 bus system and IEEE 57 bus system, respectively.

4. Problem formulation

The problem of FCL optimal allocation is a nonlinear optimization problem, and may include several objective functions. In this study, objective functions considered are as reliability enhancement, the economical usage of FCLs and the short circuit current reduction. These objective functions are explained as follows:

4.1. Improvement of reliability

4.1.1. Influence of fault current limiter on system reliability

Installation of FCL in the power system can improve the network reliability. The addition of a new device in series with a system results in the weakening of the reliability of the system [26]. However, FCL lessens the failure rate of devices by decreasing the frequency of the excessive fault current [27,28]. The improvement made by the FCL depends on its installation location. There are various reasons which cause a fault to fail in a protective equipment such as degraded operation, worn, arcing, and fault current [29]. Since optimal allocation of FCLs results in fault current reduction and it does not influence other failure rate terms, the main concern of the current paper is fault current.

$$\lambda_{0,k,f} = \lambda_{0,k,f}^{faultcurrent} + \lambda_{0,k,f}^{degradedoperation} + \lambda_{0,k,f}^{worn} + \lambda_{0,k,f}^{arcing} + \cdots \tag{5}$$

$$\lambda_{l,k,f} = \lambda_{0,k,f} - \lambda_{0,k,f}^{faultcurrent} \eta_{l,k,f} \tag{6}$$

Eq. (5) describes some terms of system failure rate and (6) represents the failure rate for failure event f at kth load after installing FCL in the lth line. The parameter $\lambda_{0,k,f}^{faultcurrent}$ is the failure rate that is only caused by fault current for failure event f at kth load when FCL does not exist in a network ($l = 0$). The parameter $\eta_{l,k,f}$ is the fault current reduction efficiency of failure rate for failure event f at kth load when FCL is installed in the lth line [29].

4.1.2. Estimation of system reliability

There are various indices to evaluate system reliability such as system average interruption frequency index (SAIDI), average service unavailability index (ASUI) and average energy not supplied (AENS). But all characteristics of a system cannot be considered by one of these system reliability indices. Therefore, in this paper, weighted load reliability index (WLRI) which considers the effects of aforementioned indices is used to estimate the reliability of the system [29]. Note that the lower value of WLRI indicates greater value for system reliability. Eqs. (7) and (8) represent this index.

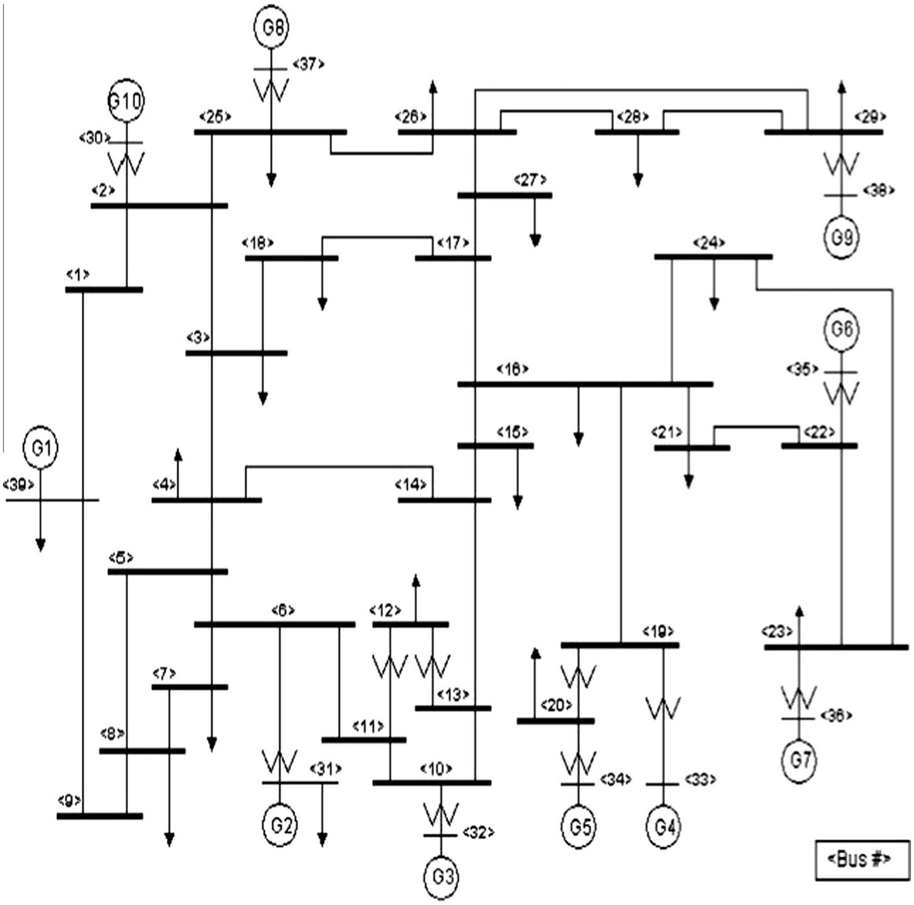

Fig. 2. Single line diagram of IEEE 39 buses system.

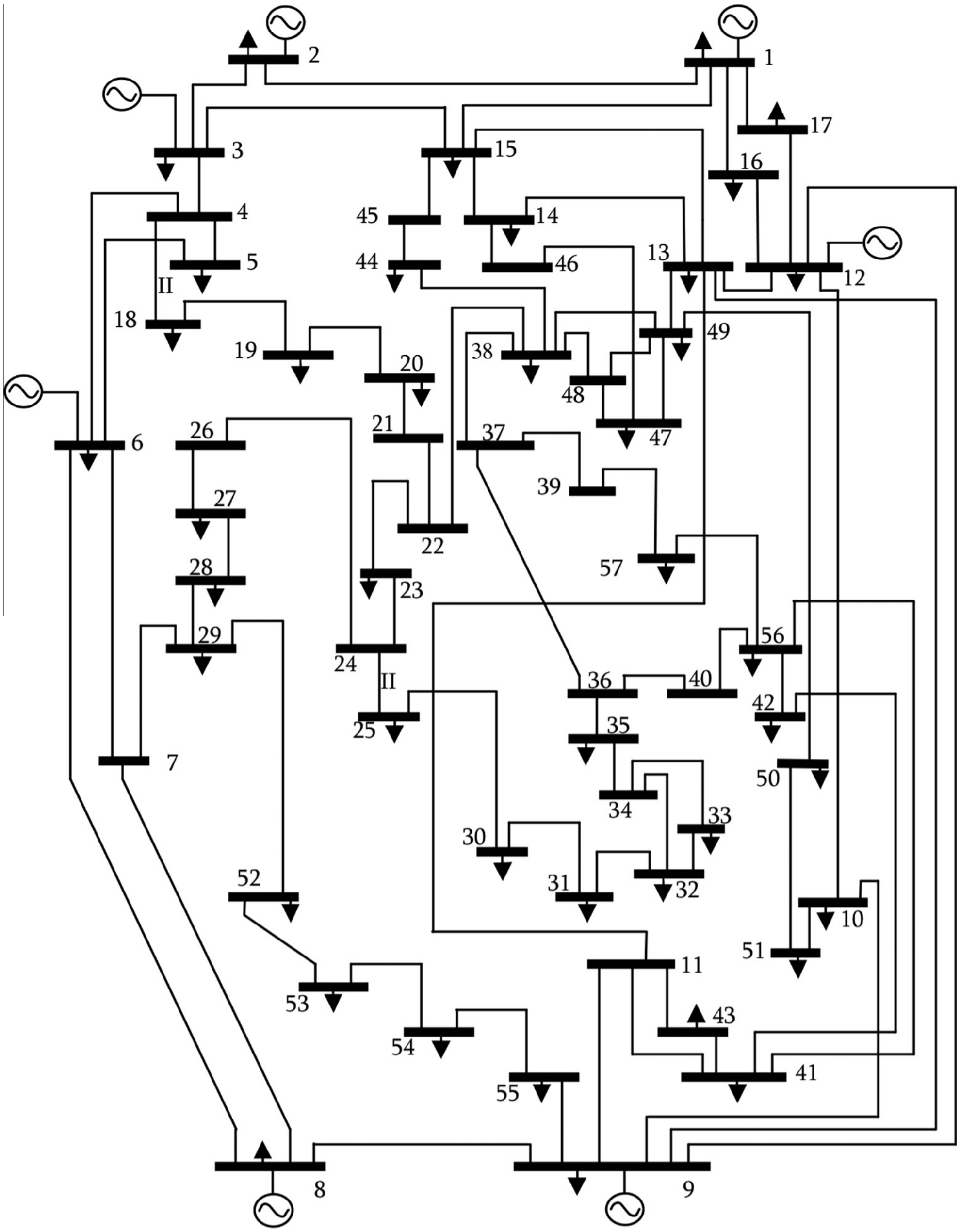

Fig. 3. Single line diagram of IEEE 57 buses system.

$$WLRI_{l,k}=\sum_{m=1}^{3}w_m R(m,l,k) \tag{7}$$

$$R(m,l,k)=\begin{cases}\dfrac{\sum_{f\in\forall failure\,events}\lambda_{l,k,f}N_k}{\sum_{k=1}^{k}N_k} & (m=1)\\ \dfrac{\sum_{f\in\forall failure\,events}r_{l,k,f}\lambda_{l,k,f}N_k}{8760\sum_{k=1}^{k}N_k} & (m=2)\\ \dfrac{\sum_{f\in\forall failure\,events}\lambda_{l,k,f}P_k}{\sum_{k=1}^{k}N_k} & (m=3)\end{cases} \tag{8}$$

In (7) and (8), w_m is the normalization factor for the value of m_{th} reliability index, and $N_k, r_{l,k,f}, P_k$ are the number of customers, the repair time, and the amount of electric demand power, respectively. The index *RS* determines the change of system reliability according to installation location of FCL.

This objective function is as follows:

$$f_1(x)=\frac{RS(x)}{RS(x=0)} \tag{9}$$

where

$$RS(x)=\sum_{k=1}^{K}w_k WLRI(x,k) \tag{10}$$

and

$$w_k=\frac{CIC\ of\ kth\ load\ point}{average\ CIC\ of\ all\ types\ of\ customers} \tag{11}$$

$$X=[X_1,X_2]\quad X_1=[sl_1,sl_2,\ldots,sl_n]\quad X_2=[z_{1,fcl},z_{2,fcl},\ldots,z_{n,fcl}] \tag{12}$$

where *RS* is an index that determines the effect of installation location of FCL on the system reliability. The weighting factor w_k indicates the significance of *k*th load and is determined by considering customer interruption cost of each customer [30]. The

$2n$-dimensional vector X represents the location and impedance of FCLs. The parameter sl_i is either one or zero whose value indicates the clear existence or absence of FCL in i_{th} line. The parameter $RS(X=0)$ is the index of system reliability when there are not any FCLs in the power system. The lower WLRI, the greater is the system reliability.

4.2. Economical aspects use of fault current limiter

Although FCL is used to minimize the short circuit current and improve the system reliability; it is necessary to use the minimum possible number of FCLs with the smallest possible FCL circuit parameters for economical purposes [13]. These objective functions can be formulated as follows:

$$f_2(x) = \frac{\sum_{i=1}^{N_{fcl}} Z_{i,fcl} - Z_{fcl}^{expected}}{Z_{fcl}^{expected}} + pf_z \tag{13}$$

$$f_3(x) = \frac{N_{fcl} - N_{fcl}^{expected}}{N_{fcl}^{expected}} \tag{14}$$

where $Z_{i,fcl}$ and N_{fcl} are the impedance of the i_{th} FCL and the number of fault current limiter used in the system, respectively. The parameters $Z_{fcl}^{expected}$ and $N_{fcl}^{expected}$ are the expected impedance of FCLs and the expected number of FCLs injected in the system, respectively. Expected impedance and expected number of FCLs consider to normalize their corresponding cost functions. These parameters are prediction of required FCLs number and impedances. Moreover, pf_z is the penalty factor which is defined as follows:

$$\begin{aligned} &if \quad Z_{i,fcl}^{min} \leqslant Z_{i,fcl} \leqslant Z_{i,fcl}^{max} \quad i = 1, \ldots N_{fcl} \\ &\qquad then \quad pf_z = 0 \\ &else \quad pf_z = max((Z_{i,fcl} - Z_{i,fcl}^{min}),\ (Z_{i,fcl}^{max} - Z_{i,fcl})) \end{aligned} \tag{15}$$

4.3. Fault current minimization

In most papers, main objective of FCL utilization is fault current minimization [10,12,31]. Despite the fact that the most power system faults are unsymmetrical, three phases symmetrical faults are used to specify the rating of CBs because it is the worst type of faults. This objective function can be formulated as follows:

$$I_i^{sc} = \frac{E_i}{Z_{ii}} * I_b + pf_I \tag{16}$$

where Z_{ii} represents the diagonal impedance of the impedance matrix (Z_{bus}) after inserting FCLs to the system. pf_I represents the penalty factor and is defined as follows:

$$\begin{aligned} &if \quad I_j^{sc} \leqslant I_j^{sc,max} \quad j = 1, \ldots, N_b \\ &\qquad pf_I = 0 \\ &else \quad pf_I = 500 * (|I_j^{sc} - I_j^{sc,max}|) \end{aligned} \tag{17}$$

In this paper, adaptive penalty factor is considered, so that, the amount of applied penalty to the cost function depends on the amount of violation of constrain rather than a constant value.

5. The heuristic multiobjective algorithms

In this paper, three multiobjective optimization algorithms are used to optimize objective functions. These algorithms are briefly described as follows:

5.1. Multiobjective evolutionary algorithm based on decomposition (MOEA/D)

MOEA/D is based on the decomposition of a multiobjective optimization problem into a number of scalar optimization subproblems. These subproblems are optimized at the same time. The subproblems with small distances between their aggregation coefficient vectors are said to be neighbor of each other. Each subproblem exchanges its information with its neighbors and is optimized using evolutionary optimization operators [32,33]. This algorithm has lower computational complexity at each generation when compared to NSGA-II [32,34,35]. The pseudocode for this algorithm is listed in Appendix A.

5.2. Multi objective particle swarm optimization algorithm (MOPSO)

MOPSO is designed based on PSO which tries to simulate the unpredictable social motion of natural species such as birds, fish and bees. This algorithm has been successfully applied to solve many engineering optimization problems because of its ease of implementation, speed of convergence and quality of solutions [34]. Basically, MOPSO is designed for problems involving continuous variables. In MOPSO, the personal best and global best solutions are selected from Pareto front [34]. The pseudocode for this algorithm is listed in Appendix B.

5.3. Non dominated sorting genetic algorithm-II (NSGA-II)

This algorithm uses the principal of non-dominated sorting. The older version of this algorithm needed some of the parameters to be selected by the user. However, K. Deb improved the algorithm to include less user defined parameters. The computational cost of this algorithm is also reduced [35,36]. The next generation in this algorithm is generated using the genetic operators. In this algorithm, the combination of parents and children population are sorted based on their Pareto front. The chromosomes of the last Pareto are selected based on their diversity. The solutions found by NSGA-II are better than two other contemporary multiobjective evolutionary algorithms: Pareto-archived evolution strategy (PAES) and strength-Pareto evolutionary algorithm (SPEA) in terms of finding more diverse set of solutions and in convergence to the Pareto optimal front [37]. The pseudocode for this algorithm is listed in Appendix C.

5.4. Optimization procedure

1. According to network data, the impedance matrix of the system Z_{bus} is created.
2. Three phase short circuit fault is applied to all buses.
3. In this research, three objective functions are considered: (1) System reliability improvement. (2) Economical aspect minimization that is considered as a function of the number of FCLs and impedances which are installed. (3) Short circuit current minimization. These objective functions are nonlinear and are functions of X. X is the vector of control variables, which is $2n$-dimensional vector which represents the location and impedance of FCLs and n is the number of the lines in the network.

$$X = [X_1, X_2] \quad X_1 = [sl_1, sl_2, \ldots, sl_n] \quad X_2 = [z_{1,fcl}, z_{2,fcl}, \ldots, z_{n,fcl}]$$

sl_i is either one or zero whose value indicates the existence or absence of FCL in i_{th} line.

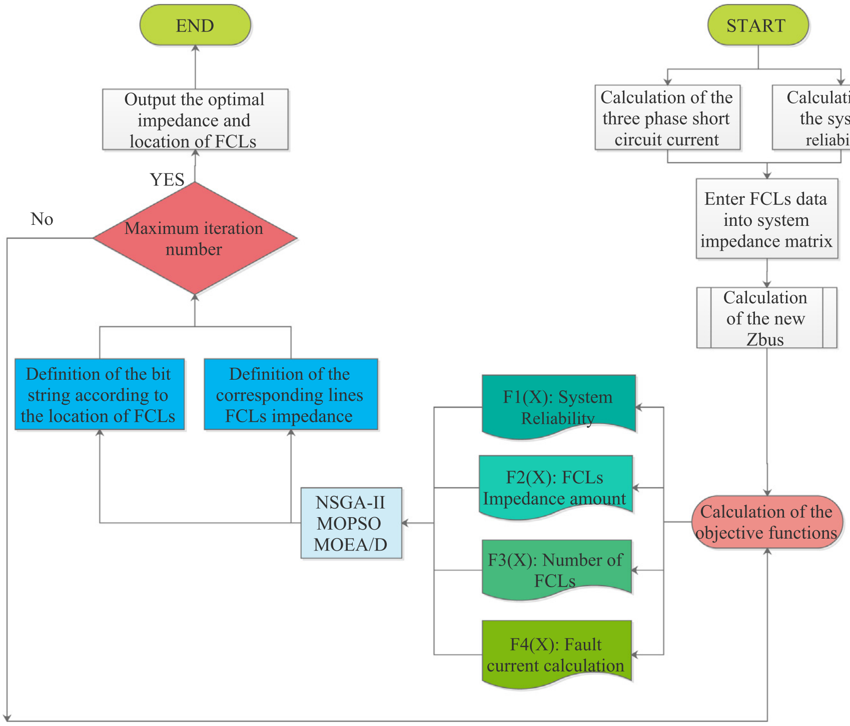

Fig. 4. General flowchart of the proposed optimum FCL allocation.

4. Aforementioned objective functions are functions of *X*. The optimization algorithms are implemented on these objective functions. A penalty term is used based on the safety margin of short circuit current. The proposed optimization procedure determines the location of FCLs and their corresponding values. General procedure flowchart is depicted in Fig. 4.

6. Simulation results

The multiobjective optimization problem discussed is applied to two different case studies found in literature, namely IEEE 39 Bus system and IEEE 57 Bus system.

6.1. IEEE 39 Bus SYSTEM

Fig. 2 illustrates the IEEE 39 Bus system. This system is previously described in Section 3. Before the injection of FCL to the network, system short circuit current was 32.277 p.u and weighted load reliability index (WLRI) was 0.527.

Figs. 5–7 represent the Pareto front obtained by MOEA/D algorithm, MOPSO and NSGA-II for IEEE 39 Bus system. Fig. 8 shows the Pareto front obtained from these three methods are depicted in one figure. The results obtained by MOEA/D algorithm dominate the results obtained by the other two methods. However, as can be seen from Fig. 8, the results obtained by NSGA-II are more diverse. A solution is called nondominated, if none of the objective functions can be improved in value without degrading some of the other objective values. Without additional subjective preference information, all Pareto optimal solutions are considered equally good (as vectors cannot be ordered completely).

In IEEE 39 Bus after installation of FCL in network, WLRI shows approximately 0.175 reductions and short circuit current is reduced 17.5 p.u as compared to the case when there is no FCL in the system.

Tables 1–3 represent a typical solution from the Pareto fronts obtained by MOEA/D, MOPSO and NSGA-II. As can be seen from the tables, using MOEA/D algorithm totally 29.35 p.u limiting impedances are inserted in the range of 1.94–4.1636 p.u to 10 lines of the network. The results obtained by this algorithm has more reduction in short circuit current and more improvement in system reliability when it is compared to the other two algorithms. The solutions found by MOPSO algorithm show that it is necessary to insert 20.88 p.u limiting impedances in the range of 0.21475–3.881 p.u to 11 locations of the network. The sample result obtained from NSGA-II injects 25 p.u limiting impedances in the range of 0.28335–4.7651 p.u to 11 lines of power system is more effective than MOPSO algorithm in short circuit current reduction and in the improvement of the reliability of the system.

In summary, the results of the comparisons between these three algorithms show that MOEA/D injects more impedance to the network and is more effective than other algorithms in short circuit reduction and improvement of the system reliability. It is worth mentioning that in multiobjective optimization problem all objective functions are optimized together, hence since the objective functions are conflicting, it is possible that for some solutions one specific objective function becomes large to minimize another objective functions. The use of multiobjective optimization makes it possible to have the complete set of solutions and easily select between the obtained solutions after the optimization process is completed. Moreover, according to Fig. 8 NSGA-II algorithm results are more diverse solutions.

6.2. IEEE 57 Bus SYSTEM

Fig. 3 illustrates the IEEE 57 Bus system. This system is previously introduced in Section 3. Before injecting FCLs to network, system short circuit current was 3.2048 p.u and weighted load reliability index (WLRI) was 0.643. Figs. 9–11 demonstrate the Pareto front obtained by MOEA/D algorithm, MOPSO and NSGA-II for IEEE 57 Bus system. Fig. 12 shows the Pareto front obtained from these three methods are depicted in one figure. The results obtained by MOEA/D algorithm dominate the results obtained by the other two methods.

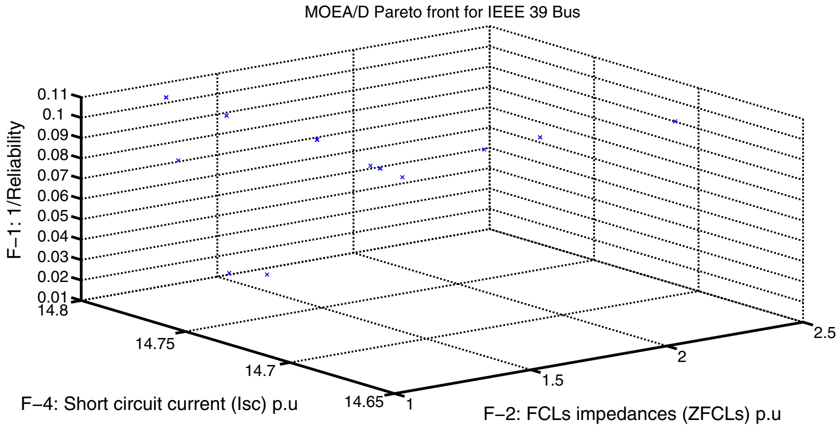

Fig. 5. MOEA/D algorithm Pareto front for IEEE-39 Bus system.

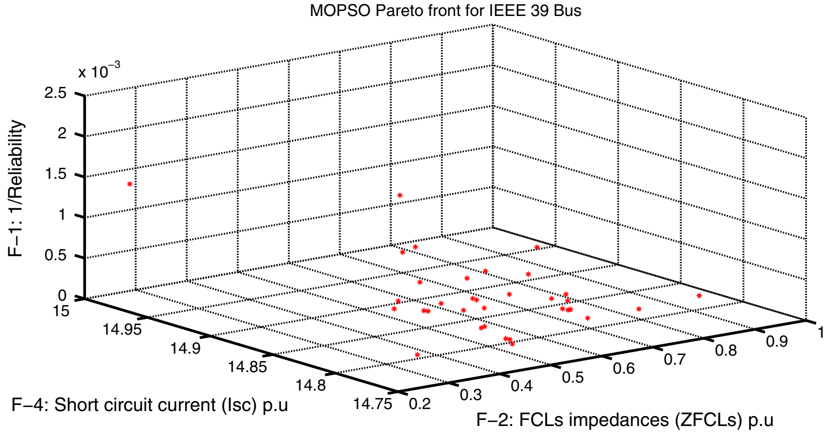

Fig. 6. MOPSO algorithm Pareto front for IEEE-39 Bus system.

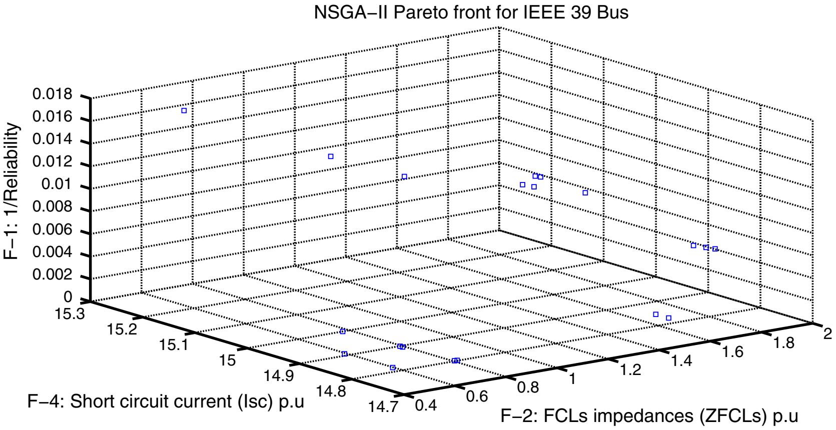

Fig. 7. NSGA-II algorithm Pareto front for IEEE-39 Bus system.

Tables 4–6 show a typical solution from the Pareto fronts obtained by MOEA/D, MOPSO and NSGA-II. As can be seen from the tables, MOEA/D algorithm totally inserts 22.2 p.u limiting impedances in the range of 0.001633–4.6707 p.u to 9 lines of the network. This algorithm has more reduction in short circuit current and more improvement of system reliability than the other two methods. The sample solution found by MOPSO algorithm totally inserts 11.57 p.u limiting impedances in the range of 0.2908–2.6551 p.u to 6 locations of network. NSGA-II totally by injects 27.54 p.u limiting impedances in the range of 0.29152–4.5574 p.u to 11 lines of power system and it is more effective than MOPSO algorithm in short circuit current reduction and improvement of the system reliability.

In IEEE 57 Bus after installation of FCL to network, WLRI shows approximately 0.5 reduction and short circuit current 1.8 p.u (2.3 times) is reduced when it is compared to the case when there exists no FCL in the system.

In this case, MOEA/D injects less impedance to network and has more mitigation in fault current level and improvement in the system reliability. Moreover, since less impedance are added to the

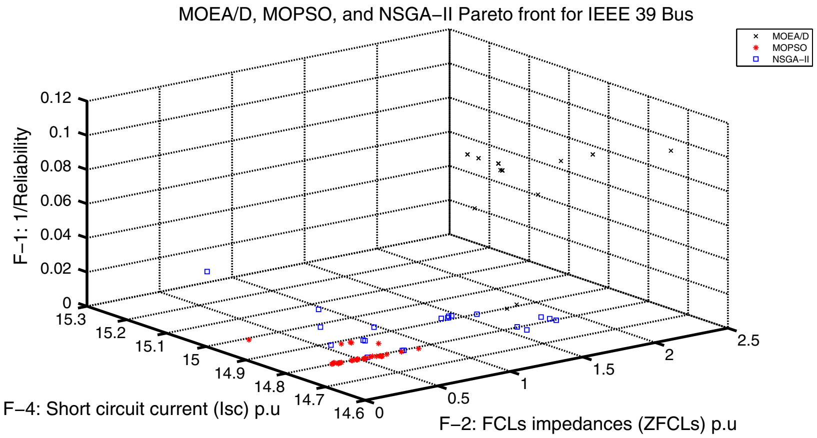

Fig. 8. All used algorithms Pareto front for IEEE-39 Bus system.

Table 1
MOEA/D algorithm result for IEEE-39 Bus system.

WLRI	0.34637
FCL installation candidate lines	2, 12, 16, 17, 23, 24, 28, 31, 36, 39
FCLs impedance corresponding to above installation locations	3.7045, 2.437, 4.1636, 2.6673, 3.3374, 2.3422, 3.6725, 2.7542, 1.94, 2.3336
Number of installed FCLs	10
I_{sc}	14.489 p.u

Table 2
MOPSO algorithm result for IEEE-39 Bus system.

WLRI	0.35874
FCL installation candidate lines	4, 5, 6, 8, 14, 20, 21, 25, 40, 41, 42
FCLs impedance corresponding to above installation locations	0.21475, 0.71438, 2.1772, 2.4213, 0.51202, 0.82634, 2.652, 2.337, 2.776, 3.881, 2.37
Number of installed FCLs	11
I_{sc}	14.797 p.u

Table 3
NSGA-II algorithm result for IEEE-39 Bus system.

WLRI	0.3523
FCL installation candidate lines	1, 6, 16, 17, 19, 20, 21, 31, 38, 43, 46
FCLs impedance corresponding to above installation locations	1.7699, 2.7102, 0.69282, 2.323, 2.3192, 0.28335, 3.5807, 3.573, 4.7651, 2.6245, 0.28697
Number of installed FCLs	11
I_{sc}	14.784 p.u

network, the results obtained by MOEA/D are more economical than that of NSGA-II. Therefore, MOEA/D is more effective than other used algorithms in this case study. However, according to Fig. 12, MOPSO algorithm results are more diverse solutions.

7. Conclusion

The installation of FCLs into a power system has a great effect on short circuit current suppression and system reliability improvement. However, how the installation of FCLs influences the reliability and short circuit current depends on the installation locations and their impedances. The existing approaches in literature use weighted sum of different objective functions to obtain a single objective problem and then apply single objective optimization algorithms to it. Moreover, to the best knowledge of the authors; there does not exist any reported simultaneous structure and parameter value optimization in the allocation problem of FCLs.

In this paper, three multi objectives algorithms are proposed and two case studies are considered to obtain installation locations, impedance and the number of FCLs, simultaneously. The multiobjective algorithms used in this paper are based on dominance concept and result in a Pareto front. These algorithms are MOEA/D, MOPSO and NSGA-II. An adaptive penalty factors for the violation of short circuit current limitation and FCLs impedance margins are considered in the cost functions. One of the main advantages of the proposed approach is that using the proposed method, it is possible to optimize the location and the values of

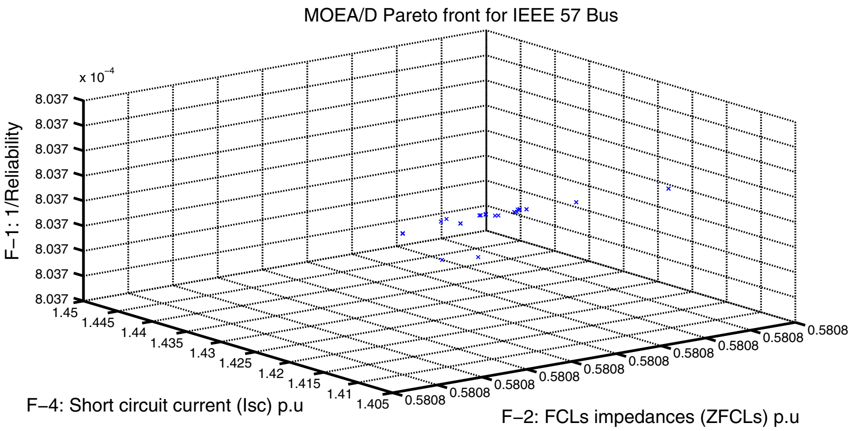

Fig. 9. MOEA/D algorithm Pareto front for IEEE-57 Bus system.

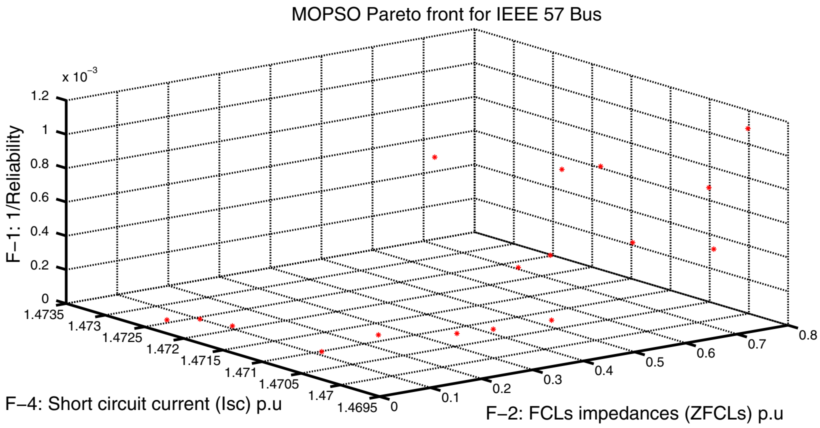

Fig. 10. MOPSO algorithm Pareto front for IEEE-57 Bus system.

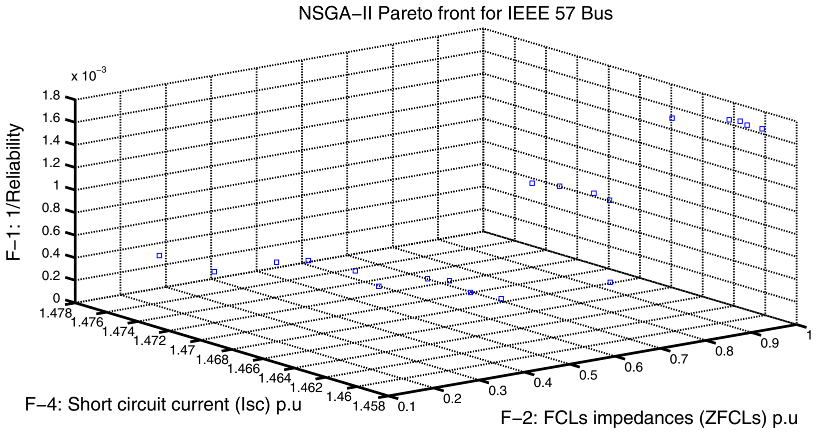

Fig. 11. NSGA-II algorithm Pareto front for IEEE-57 Bus system.

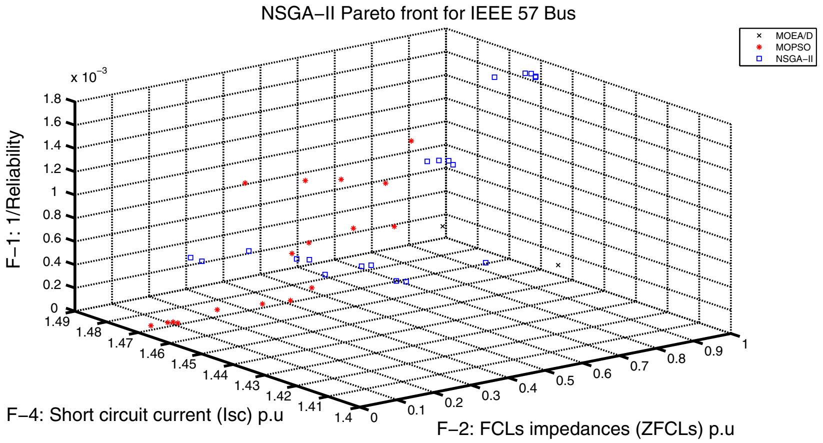

Fig. 12. All used algorithms Pareto front for IEEE-57 Bus system.

Table 4
MOEA/D algorithm result for IEEE-57 Bus system.

WLRI	0.14602
FCL installation candidate lines	8, 10, 14, 43, 45, 62, 74, 77, 79
FCLs impedance corresponding to above installation locations	4.4142, 3.074, 2.0013, 0.46739, 0.001633, 4.6707, 3.8281, 3.7427
Number of installed FCLs	9
I_{sc}	1.4054 p.u

Table 5
MOPSO algorithm result for IEEE-57 Bus system.

WLRI	0.15508
FCL installation candidate lines	6, 21, 44, 50, 54, 68
FCLs impedance corresponding to above installation locations	2.3397, 2.4003, 0.2908, 1.9793, 2.655, 1.9064
Number of installed FCLs	6
I_{sc}	1.4513 p.u

Table 6
NSGA-II algorithm result for IEEE-57 Bus system.

WLRI	0.15303
FCL installation candidate lines	31, 39, 43, 44, 45, 46, 53, 60, 62, 71, 74
FCLs impedance corresponding to above installation locations	2.191, 2.4347, 0.43185, 3.9187, 4.5574, 2.6296, 0.29152, 1.4562, 2.7784, 2.7173, 4.1385
Number of installed FCLs	11
I_{sc}	1.4104 p.u

FCLs, simultaneously. Moreover, a lower bound for the short circuit current of the power system is considered which reduces the need for FCLs which causes less cost for the whole system.

It is observed that among the three multiobjective optimization algorithms MOEA/D most probably generates the solutions which dominate the other two algorithms. However, NSGA-II results in more diverse solutions.

It is worth noting that since the placement and the value of the impedances of the FCLs affect the operation time of directional overcurrent relays, it can be considered as a new objective function. We consider this objective function as a new research topic in future.

Appendix A. MOEA/D algorithm pseudocode

Define [termination condition, N (number of sub-problems), a uniform spread weight vectors, T (number of the weight vectors in the neighborhood of each weight vector)]

```
Initialization
  Generate initial population by uniformly spreading and
  randomly sampling from search space
  Calculate the reference point for the Tchebycheff approach
  Evaluate Objective Values
  Selection using tournament selection method based on
  utility $\pi^i$
  Selection of mating and updating range
  Reproduction
  Repair
Update of solutions
While (not equal to termination condition)
  Evaluate Objective Values
  Selection using tournament selection method base on
  utility $\pi^i$
  Selection of mating and update range
  Reproduction
  Repair - if the searching element is out of boundary
  Update the solutions
If (generation is a multiplication of a pre-set value of x)
  Update utility function;
End
End
```

Appendix B. MOPSO algorithm pseudocode

```
Initialize Swarm
Initialize Leaders Archive
Determine Leaders Quality
Generation = 0
While generation < maximum number of generations
Do
  for each particle
Do
  Select Leader
  Update Position

$x_i(t) = x_i(t-1) + v_i(t)$
$v_i(t) = \omega v_i(t-1) + c_1 r_1 (x_{pbest_i} - x_i) + c_2 r_2 (x_{gbest_i} - x_i)$    (B.1)

  Mutation operation
  Evaluation
  Update best position ($P_{best}$)
  End for
  Update Leaders Archive
  Determine Leaders Quality
  Generation++
End while
Return Archive
```

Appendix C. NSGA-II algorithm pseudocode

```
Initialize N number of population with d genes for each of
  them
For iter = 1 to Maximum number of generations
  Generate offspring
    Select parents
    Perform crossover operation on selected parents
    Perform mutation operation
    Merge parents with offspring to generate a new
  population size equal to 2N
For each individual = 1 to 2N
    Calculate the Pareto front number based on non-
  dominated sorting
    Select the next generation using the rank of each
  chromosome
    For chromosomes in the last Pareto front based on
  crowding distance
End
End
```

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