International Journal of Industrial Electronics, Control and Optimization © 2020 IECO
Vol. 3, No. 1, pp. 91-102, Jan (2020)

Allocation of Fault Current Limiters in Power Systems Considering Fault Current, Cost, and Lost Power Indices Using Imperialist Competitive Algorithm

Shervin Bikdeli[1] and Mohammad Farshad[2,†]

[1] Department of Electrical Engineering, Minoodasht Branch, Islamic Azad University, Minoodasht, Iran
[2] Department of Electrical Engineering, Faculty of Basic Sciences and Engineering, Gonbad Kavous University, Gonbad Kavous, Iran.

ABSTRACT

Developments in power systems like the installation of new generation resources and interconnections may increase short-circuit current levels and consequently, impose additional costs of replacing circuit breakers and equipment. In these cases, one of the best methods to reduce short-circuit currents in power systems and avoid significant replacement costs is to use fault current limiters (FCLs). This paper suggests a new method for optimally locating and sizing FCLs using an imperialist competitive algorithm (ICA). The ICA finds the optimal locations and sizes of FCLs such that not only are short-circuit currents reduced, but the size of the installed FCLs is also minimized, and the system reliability is increased. Indeed, three indices including the short-circuit level, the economic cost of FCLs, and the lost power are integrated into an objective function with a new formulation. The results obtained from multiple executions of the suggested procedure for the 39-bus New England benchmark system confirm that the formulation of indices in the objective function is suitable and the indices can be prioritized easily. Also, the results indicate that the ICA can find the optimal locations and sizes of FCLs with good convergence and accuracy considering the specified objectives and priorities.

Article Info

Keywords:
Fault current limiter, Imperialist competitive algorithm, Power system, Reliability

Article History:
Received 2019-01-19
Accepted 2019-09-08

I. INTRODUCTION

In recent decades, short-circuit current levels in power systems have increased due to the growth of the electric industry, the network interconnections, and the increasing penetration of new generation resources. To endure and interrupt these high short-circuit currents, high tolerance equipment and circuit breakers (CBs) with high breaking capacities are required, but this imposes heavy costs. In these conditions, one of the cost-effective methods to decrease short-circuit currents in power systems and avoid the consequent heavy costs is to install fault current limiters (FCLs) [1]. In power circuits, an FCL is installed in series which has an almost zero impedance under normal conditions and limits the passing fault current by adding a series impedance in the event of a short-circuit fault [2], [3].

Locations and sizes of FCLs can affect important parameters, such as the short-circuit level, the cost of FCLs, and the system reliability. Due to the extent of power systems, optimally locating and sizing FCLs can be a nonlinear and complicated optimization problem with a large number of variables and local optima. Hence, meta-heuristic algorithms with a global optimum search capability are a good choice to solve this problem. The meta-heuristic algorithms have widely been

†Corresponding Author: farshad@gonbad.ac.ir
Tel: +98-1733266700, Department of Electrical Engineering, Faculty of Basic Sciences and Engineering, Gonbad Kavous University, Basirat Blvd., Shahid Fallahi St., Gonbad Kavous 49717-99151, Iran

employed in solving different power system problems [4]-[7].

In [8], the authors have utilized a multi-objective non-dominated sorting genetic algorithm-II (MONSGA-II) for optimal location of FCLs with the objective functions including the short-circuit level, economic cost, and transient stability indices. Also, the objective functions of the FCL allocation problem in [9] comprise the short-circuit level, economic cost, and system reliability indices, which have been optimized employing a modified form of a multi-objective particle swarm optimization algorithm (MOPSOA). Similarly, in [10], the authors have considered the short-circuit level, economic cost, and system reliability indices in the objective functions and have examined a multi-objective evolutionary algorithm based on decomposition (MOEA/D), MOPSOA, and MONSGA-II to search for the optimal locations and sizes of FCLs. The objective functions of the FCL allocation problem in [11] include the economic cost and the short-circuit mitigation effect, which have been optimized using an immune algorithm (IA). The authors in [12] have utilized a multi-objective firework algorithm (MOFA) to optimize the economic cost, bus short-circuit current difference, and system reliability in the FCL placement and sizing problem. The objective function of the FCL allocation problem in [13] includes the economic cost, power loss, and system reliability optimized via a particle swarm optimization algorithm (PSOA). In [14], the authors have considered the short-circuit current limits in the constraints of the FCL placement and sizing problem and have optimized the economic cost employing a genetic algorithm (GA). The objective function of the FCL locating and sizing problem in [15] comprises economic costs of FCLs, fuses, reclosers, and reclosers' directional devices, which has been minimized using a GA as well. The authors in [16] have utilized hybrid and modified versions of a GA to search for the best locations and sizes of FCLs with the minimum cost, considering short-circuit current limits in the constraints. Also, the objective function of the FCL allocation problem in [17] comprises the economic cost and short-circuit level, which has been optimized using a GA. In [18], the authors have recommended a two-step optimization method utilizing a hierarchical fuzzy logic decision algorithm (HFLDA), a modified version of the GA, and PSOA for optimal allocation of FCLs. The objective function proposed in [18] includes the number of FCLs in the first step and comprises the FCL impedance and the network voltage quality in the second step, while the fault current limits have been included in the constraints of both optimization steps. In [19], the authors have considered fault current limits in the constraints of the FCL allocation problem and have minimized the economic cost using the iterative mixed integer nonlinear programming algorithm (IMINPA). The authors of [20] have focused on selecting an FCL type and impedance with the maximum reduction in fault currents and the minimum relevant costs. However, the FCL location has not been considered in the optimization procedure of [20]. In [21], the authors have presented a method for the simultaneous optimization of the location of distributed generations and the size of FCLs in smart grids. Indeed, the authors of [21] have attempted to maintain the fault current levels unchanged after the installation of distributed generations by optimizing a single objective function using a GA without considering other important indices such as the cost and the reliability.

Although these reviewed works have provided fairly desired results with respect to their viewpoints and aims in the FCL allocation problem, research on better formulations and examining more efficient optimization algorithms is still in progress. In other words, there are many alternative methods which can lead to more useful and dependable FCL placement and sizing results. The wise formulation of the FCL allocation problem and the adequate implementation of a powerful global optimization algorithm are the key points to achieve a better alternative method.

The chief purpose of the present paper is to suggest an efficient formulation and solving method for optimally locating and sizing FCLs. The main contributions to the FCL allocation problem are as follows:

- A new formulation is presented, in which the short-circuit level, economic cost, and lost power indices are included in the objective function. This formulation, while allowing controlling the priorities and balancing the objectives easily, can be solved with the broad range of available single-objective optimization algorithms. However, with a minor modification, it can also be handled with the multi-objective ones.

- The imperialist competitive algorithm (ICA), as one of the efficient and powerful meta-heuristic methods, is implemented to solve the formulated optimization problem.

In the next sections, the ICA is introduced in Section II. Then, the proposed formulation of the FCL allocation problem and its solving method are described in Section III. Next, the results of numerical studies and evaluations on a test system are presented in Section IV. Finally, the paper is concluded in Section V.

II. Imperialist Competitive Algorithm

The ICA [22] is an optimization method based on the human social-political evolution inspired by the imperialism. In this algorithm, the countries that represent the solutions of an optimization problem are divided into imperialists and colonies. The total number of countries M_t and the initial number of imperialist countries M_{im} should be determined at the beginning of the algorithm. The initial number of colonies M_{co} is equal to the difference between M_t and M_{im}. As the algorithm starts and M_t initial random countries are generated, imperialists and colonies are designated based on their fitness

or cost function value. In a minimization problem, M_{im} countries with the least costs are selected as imperialists, and consequently, M_{im} empires are formed. The countries that are not imperialist, i.e., colonies, should be allocated to the empires proportionate to the power of their imperialist countries [22]. To allocate the colonies to the empires, the cost differences for the imperialist countries are first calculated as follows:

$$C_n = maxc - cost_n \quad (1)$$

where $cost_n$ is the cost of the n^{th} imperialist country, $maxc$ indicates the maximum cost among the imperialist countries, and C_n is the cost difference of the n^{th} imperialist country. Then, the cost differences are normalized as follows:

$$S_n = \left| \frac{C_n}{\sum_{k=1}^{M_{im}} C_k} \right| \quad (2)$$

where S_n is the normalized cost difference of the n^{th} imperialist country. After obtaining the normalized cost differences, the number of colonies for each imperialist country is determined as follows:

$$N_n = round(S_n \,.\, M_{co}) \quad (3)$$

where $round(.)$ is the rounding function and N_n indicates the number of colonies of the n^{th} imperialist country in the initial iteration of the algorithm.

During the ICA iterations, the imperialist countries try to assimilate the colonies. At each iteration of the algorithm, if the distance between a colony and its imperialist is assumed to be X, this colony moves towards the imperialist by x [22]. The value of x is determined randomly at each iteration as follows:

$$x = rand([0\,,\ \beta\,.\ X]) \quad (4)$$

where $rand(.)$ generates a random number based on the uniform distribution on the input interval. In addition, β is an adjusting coefficient greater than 1, which makes it possible for the colony to get close to its imperialist from two sides.

Movement of a colony towards its imperialists is not necessarily in a straight trajectory. In order to model the non-straight movement, the movement angle φ is defined with respect to the straight trajectory [22]. The value of φ is determined randomly at each iteration as follows:

$$\varphi = rand([-\gamma,\ \gamma]) \quad (5)$$

where γ should be determined at the beginning of the algorithm.

The revolution is another operator in the ICA, which increases its exploration ability. By applying this operator, some colonies may revolve and reach higher powers, and even they may take over their imperialists and become the empire centers. The revolution rate is an adjusting parameter and should be determined at the beginning of the algorithm, too. This rate indicates the percentage or proportion of colonies that can revolve at each iteration [22]. For better convergence of the algorithm, the revolution rate is reduced during the iterations using a predetermined damping coefficient.

After the computation of the colonies' movements and revolutions, the cost function should be calculated for all the countries. If the cost of a colony is less than the cost of its imperialist, that colony takes the place of its imperialist [22]. In this step, the total cost of each empire is obtained based on the following equation:

$$T_n = cost_n + \xi\,.\,\overline{costcol_n} \quad (6)$$

where $\overline{costcol_n}$ is the average cost of colonies in the n^{th} empire, ξ is the impact factor of colonies, and T_n indicates the total cost of the n^{th} empire. The adjusting parameter ξ which should be determined at the beginning of the algorithm is usually smaller than 1.

One of the operations that can improve the performance of the ICA is the integration of similar empires. If the norm of the distance between two arbitrary empires is less than a specific percentage of the norm of the search space size, they will be united.

At the end of each iteration, the colony with the highest cost is selected from the empire with the highest total cost, and it is absorbed by one of the stronger empires. The absorption is performed through a random imperialistic competition among the imperialist countries. The use of a method like the roulette wheel for determining the winner imperialist country gives higher chances to the stronger imperialist countries with fewer costs [22]. If no colony remains for an empire, the imperialist country of that empire is also absorbed by the winner imperialist country.

If the ICA is executed for an adequate number of iterations, only one empire will remain at the end, which will give the final optimal solution. However, in most cases, the optimal solution can be reached at the best imperialist country before this stage.

III. Proposed Formulation and Solving Method

In this paper, the general formulation of the FCL placement and sizing problem is as follows:

$$\min_{l_j, Z_j}(k_1\,.\,f_1 + k_2\,.\,f_2 + k_3\,.\,f_3) \quad (7.1)$$

subject to:

$$1 \le l_j \le L \quad (7.2)$$

$$Z^{min} \le Z_j \le Z^{max} \quad (7.3)$$

where l_j is the line number related to the location of the j^{th} FCL, Z_j is the impedance of the j^{th} FCL, L indicates the total number of transmission lines, and Z^{min} and Z^{max} are the minimum and maximum impedances of FCLs, respectively. The cost function shown in Equ. (7.1) includes three elements of f_1, f_2, and f_3 denoting short-circuit level, economic cost, and lost power indices, respectively. These three indices in the cost function are weighted and prioritized by the coefficients of k_1, k_2, and k_3. The constraints shown in Equs. (7.2) and (7.3) determine the permitted ranges of the optimization variables

and ensure that the solutions remain in the feasible ranges.

This paper solves the optimization problem (7) using an ICA. The general procedure of the problem-solving method is presented in Fig. 1. Based on this procedure, each country in the ICA represents a solution for the optimization problem; that is, it contains information about FCLs' locations and sizes. Indeed, the structure of each country is as follows:

$$country = [l_1, l_2, \dots, l_j, \dots, l_{nf}, Z_1, Z_2, \dots, Z_j, \dots, Z_{nf}] \quad (8)$$

where nf indicates the maximum expected number of FCLs that can be installed, and l_j and Z_j are the decision variables that take integer and real values, respectively. It should be noted that during the ICA iterations, the decision variables are selected to remain in the boundaries defined in Equs. (7.2) and (7.3).

In the next subsections, each element of the cost function is defined.

A. Short-Circuit Level Index

Since the main purpose of installing FCLs in power systems is to minimize fault currents, one of the elements in the cost function is defined based on the three-phase short-circuit current level. Three-phase solid short circuits on buses are usually the most severe faults in power systems. The three-phase short-circuit currents neglecting the pre-fault currents can be obtained as follows:

$$I_i^{sc} = \frac{U_i}{Zbus_{ii}} \quad (9)$$

where I_i^{sc} is the short-circuit current for the three-phase solid fault on the i^{th} bus, U_i indicates the pre-fault voltage of the i^{th} bus, and $Zbus_{ii}$ is the diagonal element of the i^{th} row and column in the network's bus impedance matrix. The pre-fault voltages can be assumed to be 1 p.u. The short-circuit level index f_1 in the cost function (7.1) is calculated as follows:

$$f_1 = \frac{\sum_{i=1}^{B} I_i^{sc\,(after)}}{\sum_{i=1}^{B} I_i^{sc\,(before)}} \quad (10)$$

where B indicates the total number of buses. Also, $I_i^{sc\,(before)}$ and $I_i^{sc\,(after)}$ are the short-circuit currents for the three-phase solid faults on the i^{th} bus before and after the installation of FCLs, respectively. It is worthy to note that to calculate $I_i^{sc\,(after)}$ based on Equ. (9), the limiting impedances of the allocated FCLs should be added to the impedance of the corresponding branches, and the network's bus impedance matrix should be recalculated.

B. Economic Cost Index

To minimize the economic cost of FCLs, the smallest possible components should be used for them. Thus, the economic cost index f_2 in the cost function (7.1) is defined as follows:

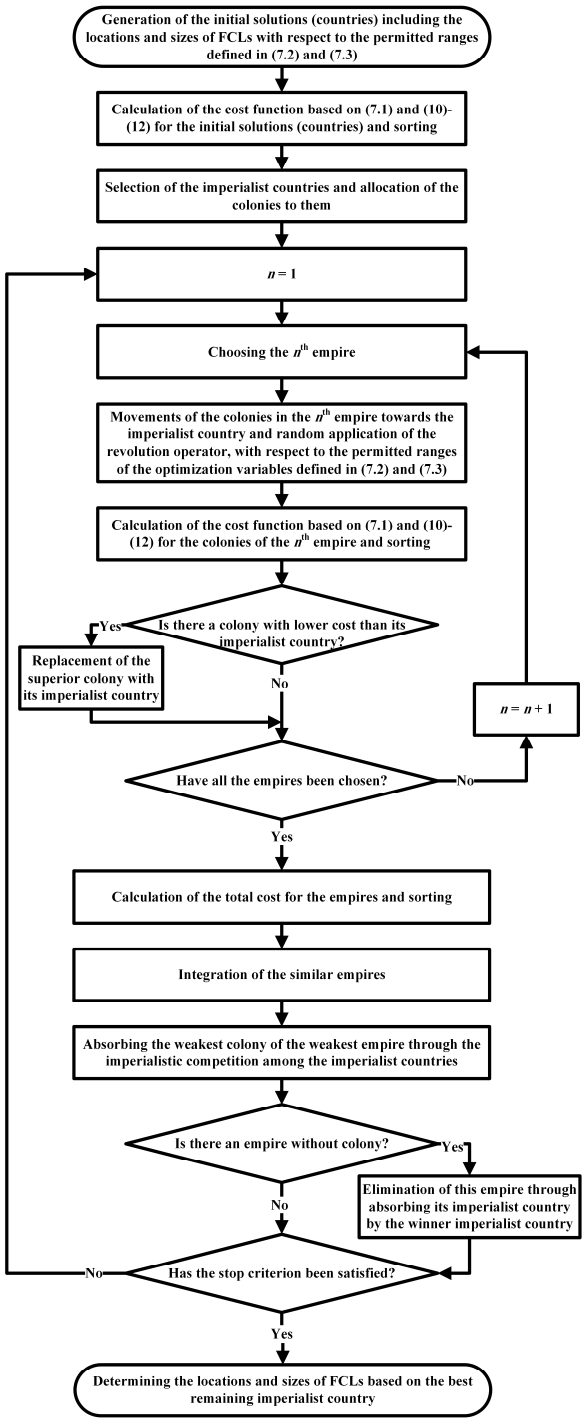

Fig. 1. The general procedure of the FCL allocation problem-solving method based on the ICA.

$$f_2 = \frac{\sum_{j=1}^{nf} Z_j}{nf \,.\, Z^{max}} \quad (11)$$

The index presented in Equ. (11) includes both the number and impedance of FCLs. Therefore, it can reflect the economic cost of the FCL installation without requiring the actual prices. Furthermore, the normalization helps to determine the

weighting coefficients and priorities with more ease and a better sense for any system.

There are two main types of FCL – the bidirectional type and the unidirectional type [23]. The conventional FCLs mostly have a bidirectional function and limit the passing fault currents in both directions. The conventional bidirectional FCLs have been considered in this paper as well. However, based on the recently published literature [24], [25], the use of the unidirectional FCLs can be useful if both the downstream microgrid and the main upstream grid are simultaneously considered in the FCL allocation studies. Although this paper has only focused on the FCL allocation in the main upstream grids, the future studies will also consider the downstream microgrids and the utilization of both the FCL types.

C. Lost Power Index

As stated in Section III.A, three-phase bus faults are typically the most severe ones in power systems. The high-voltage substations usually use modern bus/switching configurations that are capable of isolating bus faults without permanent disconnection of input and output feeders [26]. If a bus fault current is larger than the breaking capacities of bus CBs, then they cannot interrupt it, and other adjacent CBs in the network should isolate the fault. In this circumstance, some consumers and generators will be cut off from the network, depending on the faulty bus location and the network connections. In this paper, by calculating the overall power disconnected due to the inability of bus CBs to isolate bus faults, the lost power index is considered in the optimization problem. The smaller this index is, the higher the system reliability is. According to these explanations, the lost power index f_3 in the cost function (7.1) is defined as follows:

$$f_3 = \frac{\sum S_{lost}}{S_{total}} \tag{12}$$

where S_{total} is the total consumption and generation apparent power of the network and $\sum S_{lost}$ indicates the overall apparent power of the consumers and generators disconnected due to the inability of bus CBs to interrupt bus fault currents. As mentioned before, thanks to the modern bus/switching configurations of the high-voltage substations, it is possible to isolate bus faults without permanent disconnection of bus feeders. Therefore, if the short-circuit currents of all buses are less than the breaking capacities of the main responsible CBs, then $\sum S_{lost}$ will be zero, i.e.,

$f_3 = 0$.

IV. Numerical Studies

Here, the proposed FCL allocation method is programmed in MATLAB [27] and applied to a test system.

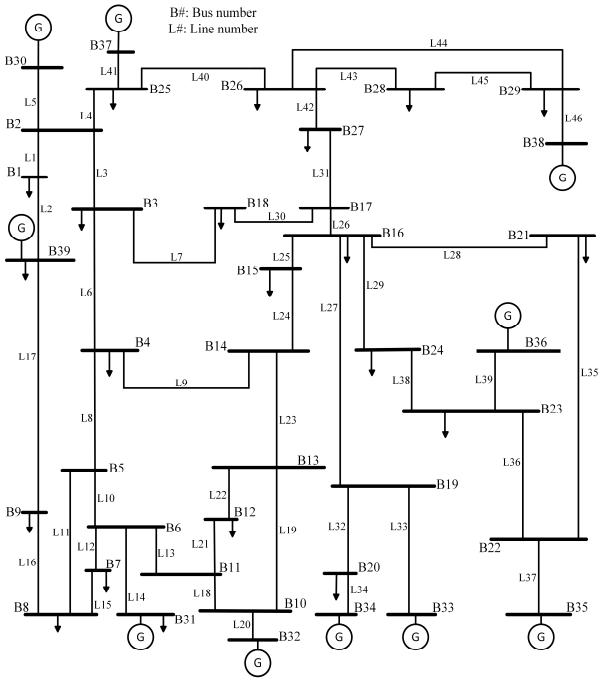

Fig. 2. The single-line diagram for the New England benchmark network.

A. Test System

The 10-unit 39-bus 46-line New England test network [28], [29] is considered for evaluating the proposed method. The single-line diagram of this network is illustrated in Fig. 2. The exact specifications of the test system considered in this study are available in MATPOWER [30], [31] with some modifications applied by the data provider. The base power of the system is 100 MVA. The permitted short-circuit current for the CBs installed in the test system is assumed to be 21.5 p.u. It should be noted that the total short-circuit current of the system before installing FCLs, i.e., $\sum_{i=1}^{B} I_i^{sc\,(before)}$, is about 617 p.u. In this study, the limiting impedances of FCLs are assumed to be pure reactances.

B. Parameters of ICA

In this study, the maximum expected number of FCLs is set at about 25% of the number of lines, i.e., *nf*=11. Hence, considering the structure (8), each country contains 11 locations and 11 impedances (reactance values). Obviously, a better sense about the maximum expected number of FCLs in the system and lowering *nf* will make the solution area smaller and lead to a better convergence speed. The ICA should determine the optimal locations and impedances of FCLs considering the defined objective function. The minimum and maximum impedances of FCLs are 0 and 0.4 p.u, respectively. When an FCL impedance is determined to be zero, it means that there is no need to install an FCL in the corresponding location. In other words, the number of finally allocated FCLs

may be lower than *nf*. The values of the ICA parameters introduced in Section II are given in Table I. These parameters are adjusted through several executions, the trial-and-error process, and also considering the suggestions and recommendations provided in [22].

TABLE I
THE ADJUSTED VALUES FOR THE ICA PARAMETERS

Parameter	Adjusted value
Total number of countries M_t	80
Initial number of imperialist countries M_{im}	8
β	2
γ	0.5 rad
ξ	0.02
Initial revolution rate	30%
Damping coefficient of the revolution rate	0.99
Threshold percentage of similarity for the integration of similar empires	2%
Stop criterion	Maximum 1000 iterations or remaining only one empire

C. Optimization Results

The optimization results of applying the proposed method to the test system with different values for the weighting coefficients in the objective function (7.1) are presented in Table II. Information regarding before the allocation of FCLs is also given in the first row of this table for comparison.

The first point which can be understood from Table II is that the short-circuit level and lost power indices have decreased after the allocation of FCLs, where the economic cost has reasonably increased.

According to the results of this table, the proposed method has satisfactorily taken the priorities specified by the weighting coefficients into account. For instance, in executions #1 to #5, in which the coefficient of short-circuit level index k_1 has increased while the other two coefficients have decreased, the algorithm has identified the priorities very well, and the short-circuit level index has decreased with the lowest possible increases in the economic cost index given the determined priorities. Expectedly, this has also reduced the lost power index and improved the system reliability to some extent. In other words, the proposed method has provided a balance among the short-circuit level, the economic cost, and the system reliability based on the determined priorities. In the same way, the correct identification of priorities is also

TABLE II
THE OPTIMIZATION RESULTS FOR DIFFERENT VALUES OF THE WEIGHTING COEFFICIENTS IN THE COST FUNCTION

Run No.	Coefficient of short-circuit level index k_1	Coefficient of economic cost index k_2	Coefficient of lost power index k_3	Line number and impedance of corresponding FCL in p.u	Short-circuit level index f_1	Economic cost index f_2	Lost power index f_3	Satisfied stopping criterion
#0	-	-	-	-	1	0	0.345	-
#1	0.240	0.380	0.380	**L27:** 0.191, **L46:** 0.104	0.871	0.067	0.098	Max. iteration
#2	↑ 0.280	↓ 0.360	↓ 0.360	**L27:** 0.206, **L46:** 0.111	0.863	0.072	0.098	Max. iteration
#3	↑ 0.333	↓ 0.333	↓ 0.333	**L27:** 0.227, **L46:** 0.121	0.855	0.079	0.098	Max. iteration
#4	↑ 0.384	↓ 0.308	↓ 0.308	**L14:** 0.140, **L27:** 0.400, **L46:** 0.131	0.815	0.152	0.043	Max. iteration
#5	↑ 0.500	↓ 0.250	↓ 0.250	**L14:** 0.400, **L27:** 0.299, **L39:** 0.159, **L46:** 0.156	0.780	0.230	0	Max. iteration
#6	0.400	0.200	0.400	**L14:** 0.400, **L27:** 0.299, **L39:** 0.400, **L46:** 0.400	0.762	0.341	0	One empire
#7	↓ 0.360	↑ 0.280	↓ 0.360	**L27:** 0.250, **L39:** 0.135, **L46:** 0.133	0.825	0.118	0.055	One empire
#8	↓ 0.250	↑ 0.500	↓ 0.250	**L27:** 0.176, **L46:** 0.096	0.880	0.062	0.098	One empire
#9	0.380	0.380	0.240	**L27:** 0.227, **L46:** 0.121	0.855	0.079	0.098	One empire
#10	↓ 0.315	↓ 0.315	↑ 0.370	**L14:** 0.130, **L27:** 0.227, **L46:** 0.400,	0.824	0.172	0.043	One empire
#11	↓ 0.290	↓ 0.290	↑ 0.420	**L14:** 0.130, **L27:** 0.227, **L39:** 0.124, **L46:** 0.400	0.803	0.200	0	One empire

obvious for the economic cost index in executions #6 to #8 and for the lost power index in executions #9 to #11.

Another remarkable point that can be understood from the results of Table II is the necessity of installing FCLs on the lines L27 and L46 because in all the executions from #1 to #11, these lines have been selected as the optimal locations for installing FCLs. Looking at Fig. 2, it can be understood that the line L27 is the sole link between the bus B16 and the subarea including the buses B19, B20, B33, and B34 with two generators. It should be noted that if a fault in the bus B16 with a short-circuit current of higher than the breaking capacity of its CBs causes it to be separated, a relatively large subarea will be cut off from the network as well. Also, the line L46 is the sole link between the bus B38 with a large generation power and the rest of the network. Hence, the lines L27 and L46 seem reasonable choices to install FCLs. In addition, considering the results obtained in different executions with various weighting coefficients, the lines L14 and L39 are the next priorities for installing FCLs. As can be seen from Fig. 2, the lines L14 and L39 are the sole connection links of the generation buses B31 and B36 to the rest of the network, respectively. Therefore, these FCL places seem to be logical as well.

According to the results presented in Table II, in executions #5, #6, and #11 which are related to higher priorities of the short-circuit index and lost power indices, the optimal value of the lost power index f_3 is zero. As explained in Section III.C, the zero value of this index means that short-circuit currents in all the buses are lower than the CBs' permitted short-circuit current. Comparing executions #5, #6, and #11, the result of execution #11 seems to be more appropriate due to its lower economic cost.

Fig. 3 depicts the variations of the minimum cost value during the ICA iterations for some executions. As can be seen from this figure, the algorithm has converged to the final solution in a smaller number of iterations before meeting the stopping criteria, which implies the promising capability of the ICA in solving the formulated FCL allocation problem.

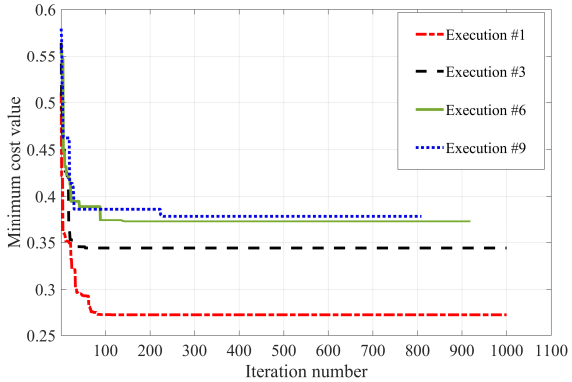

Fig. 3. The variations of the minimum cost value during the ICA iterations.

To further investigate the effects of FCLs, the short-circuit current values for three-phase solid faults on the network's buses before and after allocating FCLs are shown in Figs. 4 to 7 for executions #1, #4, #7, and #11, respectively. In these figures, the CBs' permitted short-circuit current, i.e., 21.5 p.u, is also indicated.

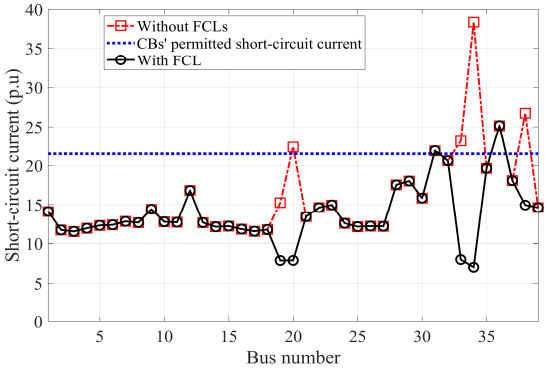

Fig. 4. The short-circuit current values for three-phase faults on the buses before and after allocating FCLs for execution #1: k_1=0.240, k_2=0.380, k_3=0.380.

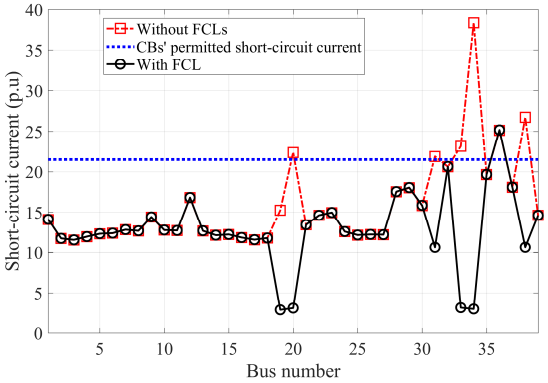

Fig. 5. The short-circuit current values for three-phase faults on the buses before and after allocating FCLs for execution #4: k_1=0.384, k_2=0.308, k_3=0.308.

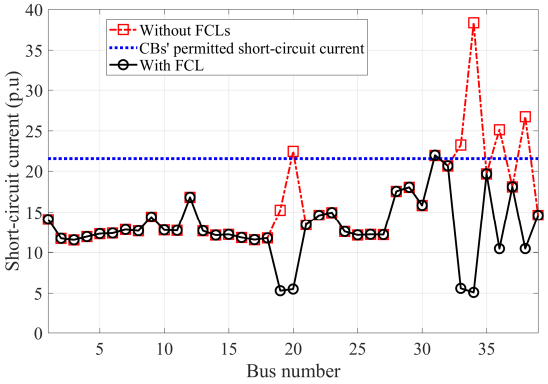

Fig. 6. The short-circuit current values for three-phase faults on the buses before and after allocating FCLs for execution #7: k_1=0.360, k_2=0.280, k_3=0.360.

TABLE III
THE MINIMUM COST FUNCTION VALUES ACHIEVED BY THE PSOA AND THE ICA UNDER DIFFERENT WEIGHTING COEFFICIENTS

Run No.	Coefficient of short-circuit level index k_1	Coefficient of economic cost index k_2	Coefficient of lost power index k_3	Minimum cost function value $k_1f_1+k_2f_2+k_3f_3$ achieved by PSOA	Minimum cost function value $k_1f_1+k_2f_2+k_3f_3$ achieved by ICA
#1	0.240	0.380	0.380	0.407	0.272
#2	↑ 0.280	↓ 0.360	↓ 0.360	0.323	0.303
#3	↑ 0.333	↓ 0.333	↓ 0.333	0.409	0.344
#4	↑ 0.384	↓ 0.308	↓ 0.308	0.426	0.373
#5	↑ 0.500	↓ 0.250	↓ 0.250	0.465	0.448
#6	0.400	0.200	0.400	0.419	0.373
#7	↓ 0.360	↑ 0.280	↓ 0.360	0.403	0.350
#8	↓ 0.250	↑ 0.500	↓ 0.250	0.287	0.275
#9	0.380	0.380	0.240	0.384	0.379
#10	↓ 0.315	↓ 0.315	↑ 0.370	0.401	0.330
#11	↓ 0.290	↓ 0.290	↑ 0.420	0.343	0.291

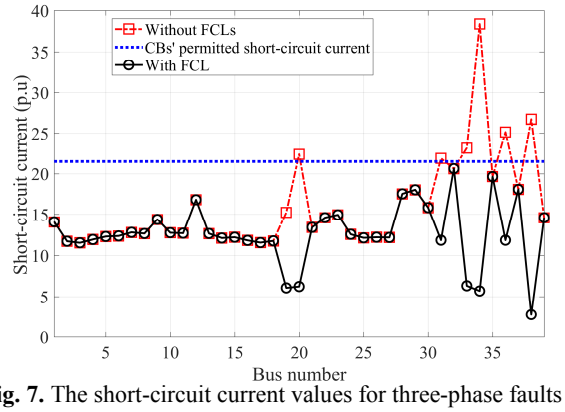

Fig. 7. The short-circuit current values for three-phase faults on the buses before and after allocating FCLs for execution #11: k_1=0.290, k_2=0.290, k_3=0.420.

As can be understood from Figs. 4 to 7, before installing FCLs, the short-circuit currents for three-phase faults on the buses B20, B31, B33, B34, B36, and B38 exceed the CBs' permitted short-circuit current. According to Fig. 4, by installing the FCLs allocated in execution #1, exceeding the CBs' permitted value occurs only for the buses B31 and B36. Based on Fig. 5, the use of the outcome of execution #4 results in only one violation of the CBs' permitted limit in the bus B36. As can be seen from Fig. 6, by installing the FCLs allocated in execution #7, exceeding the CBs' permitted value occurs only for the bus B31. Furthermore, Fig. 7 shows that the use of the FCL allocation result of execution #11 keeps all the bus fault currents below the CBs' permitted limit.

Based on the results presented in this section, it can be inferred that the cost function components of the formulated optimization problem can be prioritized readily. Also, the implemented ICA has an excellent performance in solving this problem. Indeed, the proposed method provides useful information for analysis and decision-making about the optimal locations and sizes of FCLs considering the quantified priorities.

D. Comparison with the Particle Swarm Optimization Algorithm

Here, the PSOA [32], as one of the most popular and powerful meta-heuristic algorithms, is also implemented to solve the formulated FCL allocation problem in the introduced test system, and the results are compared with the ones obtained using the recommended ICA. In the implemented PSOA, the population size and the maximum number of iterations are considered to be 80 and 1000, respectively. In addition, the PSOA has some tuning parameters that are selected based on the suggestions given in [33] (initial inertia weight=0.7298, inertia damping factor=0.1, personal acceleration factor=1.4962, and social acceleration factor=1.4962).

Table III provides the minimum cost function values achieved by the PSOA and the ICA under different weighting coefficients. As can be seen from this table, the PSOA has not reached any better solution at all versus the ICA. So, it can be said that the PSOA has been trapped in some local optimum points.

Fig. 8 presents the variations of the minimum cost value during the PSOA and ICA iterations for execution #11. This figure represents the premature convergence of the PSOA in the FCL allocation problem. Several modified versions of the PSOA have been proposed so far to tackle this drawback, while the ICA does not suffer from this drawback, at least in solving the formulated FCL allocation problem.

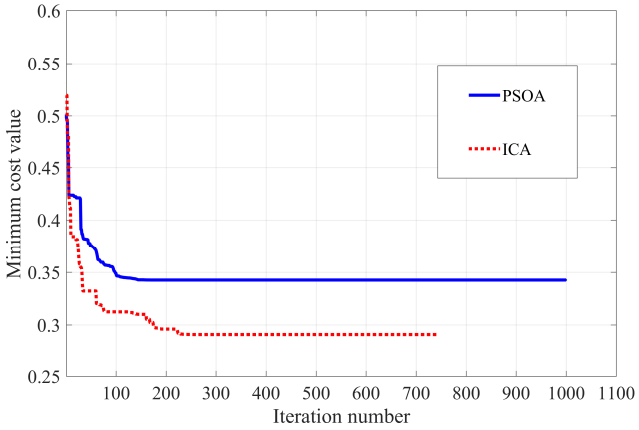

Fig. 8. The variations of the minimum cost value during the PSOA and ICA iterations for execution #11: k_1=0.290, k_2=0.290, k_3=0.420.

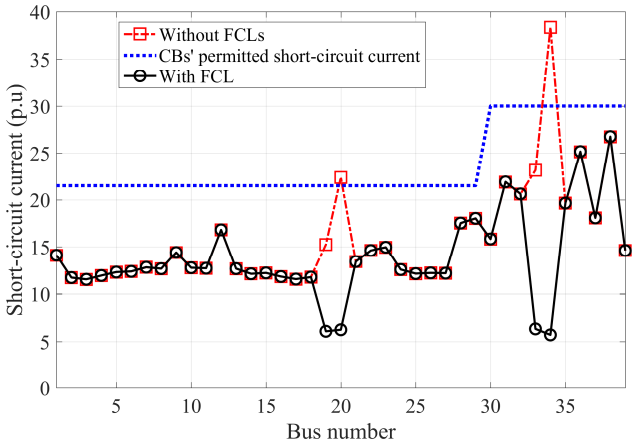

Fig. 9. The short-circuit current values for three-phase faults on the buses before and after allocating FCLs, k_1=0.290, k_2=0.290, k_3=0.420.

E. Effect of CBs' Breaking Capacity

As stated in Section IV.A, the New England test network has been considered for evaluating the recommended method. However, unfortunately, the specifications of its CBs are not available. Hence, the permitted short-circuit current for the CBs installed in the test system has been assumed to be 21.5 p.u. Although any assumption may affect the optimal solutions for the test system, it will not violate the generalizability and applicability of the proposed method. Here, the permitted short-circuit current for the CBs of the generator buses, i.e., B30-B39, increases to 30 p.u, while it does not change for the other CBs. In this case, given k_1=0.290, k_2=0.290, and k_3=0.420, the introduced algorithm suggests the installation of an FCL with an impedance equal to 0.227 p.u on the line L27.

Fig. 9 presents the short-circuit current values for three-phase solid faults on the network's buses before and after allocating FCLs for this test.

As can be seen from Fig. 9, the short-circuit currents for three-phase faults on the buses B20 and B34 exceed the CBs' permitted current before installing FCLs. Moreover, it is clear that installing the FCL based on the suggestion of the proposed algorithm keeps all the bus fault currents below the CBs' permitted limit.

V. CONCLUSIONS

In this paper, a new efficient method has been suggested for optimally locating and sizing FCLs in power systems by combining an appropriate formulation with a powerful optimization algorithm. First, the FCL allocation problem has been formulated considering the short-circuit level, economic cost, and lost power indices so that it can be solved by the numerous available single-objective optimization algorithms, while the three indices can readily be prioritized. Then, the ICA, as one of the powerful optimization methods, has been implemented to solve the formulated problem. The proposed method has been applied to the 39-bus New England test network. According to the results obtained from different executions with different combinations of the indices' weighting coefficients, the proposed method can effectively take the specified priorities into account and can find the optimal locations and sizes of FCLs with good convergence speed. Indeed, the proposed method can offer suitable and useful results for decision making about the FCL allocation in the network considering the preferred objectives.

REFERENCES

[1] G. R. F. Q. Mafra, R. M. Vidaurre, F. Z. Fortes, M. Z. Fortes, and G. G. Sotelo, "Application of a resistive superconducting fault current limiter in a distribution grid," Electric Power Components and Systems, Vol. 44, No. 18, pp. 2084-2098, Nov. 2016.

[2] S. M. Modaresi and H. Lesani, "Analysis of the effect of location and failure rates of fault current limiters on substations reliability," International Transactions on Electrical Energy Systems, Vol. 27, No. 11, p. e2379, Nov. 2017.

[3] L. Zhengyu, J. Daozhuo, and W. Zhaolin, "A new topology of fault-current limiter and its parameters optimization," in IEEE 34th Annual Power Electronics Specialist Conference (PESC '03), 2003, pp. 462-465.

[4] H. Barati and M. Shahsavari, "Simultaneous optimal placement and sizing of distributed generation resources and shunt capacitors in radial distribution systems using crow search algorithm," International Journal of Industrial Electronics, Control and Optimization, Vol. 1, No. 1, pp. 27-40, 2018.

[5] P. Fakhrooeian, m. Abedi, and p. karimyan, "Optimal allocation and sizing of dynamic VAR support to improve short-term voltage stability considering wind farm and dynamic load model," International Journal of Industrial Electronics, Control and Optimization, Vol. 1, No. 1, pp. 41-51, 2018.

[6] R. Safipour and M. Oukati Sadegh, "Optimal Planning of energy storage systems using symbiotic organisms search algorithm," International Journal of Industrial Electronics, Control and Optimization, Vol. 1, No. 1, pp. 19-26, 2018.

[7] M. Sheibani, A. Ketabi, and M. Nosratabadi, "Optimal power quality meters placement with consideration of single line and meter loss contingencies," International

Journal of Industrial Electronics, Control and Optimization, Vol. 1, No. 2, pp. 81-89, 2018.

[8] C. Ye and M. Huang, "Multi-objective optimal configuration of current limiting strategies," Science China Technological Sciences, Vol. 57, No. 9, pp. 1738-1749, Sept. 2014.

[9] Y. Hashemi and K. Valipour, "FDM based multi-objective optimal sitting and design of TC-FLSFCL for study of distribution system reliability," International Journal of Electrical Power & Energy Systems, Vol. 61, pp. 463-473, Oct. 2014.

[10] A. Mahmoudian, M. Niasati, and M. A. Khanesar, "Multi objective optimal allocation of fault current limiters in power system," International Journal of Electrical Power & Energy Systems, Vol. 85, pp. 1-11, Feb. 2017.

[11] B. Chen, L. Wei, Y. Zhu, Y. Zhong, J. Yuan, and Y. Lei, "Pareto optimal allocation of fault current limiter based on immune algorithm considering cost and mitigation effect," Journal of Modern Power Systems and Clean Energy, Vol. 5, No. 5, pp. 820-829, Sept. 2017.

[12] H. Bahramian-Habil, E. Azad-Farsani, B. Vahidi, H. Askarian-Abyaneh, and G. B. Gharehpetian, "Fault current limiter placement using multi-objective firework algorithm," Electric Power Components and Systems, Vol. 45, No. 17, pp. 1929-1940, Oct. 2017.

[13] H. Bahramian-Habil, E. Azad-Farsani, and H. Askarian-Abyaneh, "A novel method for optimum fault current limiter placement using particle swarm optimization algorithm," International Transactions on Electrical Energy Systems, Vol. 25, No. 10, pp. 2124-2132, Jun. 2015.

[14] T. Ngoc Pham and G. Singh Jai, "Short circuit current level reduction in power system by optimal placement of fault current limiter," International Transactions on Electrical Energy Systems, Vol. 27, No. 12, p. e2457, Dec. 2017.

[15] S. A. A. Shahriari, A. Y. Varjani, and M. R. Haghifam, "Cost reduction of distribution network protection in presence of distributed generation using optimized fault current limiter allocation," International Journal of Electrical Power & Energy Systems, Vol. 43, No. 1, pp. 1453-1459, Dec. 2012.

[16] K. Hongesombut, Y. Mitani, and K. Tsuji, "Optimal location assignment and design of superconducting fault current limiters applied to loop power systems," IEEE Transactions on Applied Superconductivity, Vol. 13, No. 2, pp. 1828-1831, Jun. 2003.

[17] A. Golzarfar, A. Sedighi, and A. Asadi, "Optimal placement and sizing of fault current limiter in a real network: a casestudy," IJE Transactions, Vol. 28, No. 3, pp. 402-409, Mar. 2015.

[18] H. T. Yang, W. J. Tang, and P. R. Lubicki, "Placement of fault current limiters in a power system through a two-stage optimization approach," IEEE Transactions on Power Systems, Vol. 33, No. 1, pp. 131-140, Jan. 2018.

[19] P. Yu, B. Venkatesh, A. Yazdani, and B. N. Singh, "Optimal location and sizing of fault current limiters in mesh networks using iterative mixed integer nonlinear programming," IEEE Transactions on Power Systems, Vol. 31, No. 6, pp. 4776-4783, Nov. 2016.

[20] M. Modaresi and H. Lesani, "New method to determine optimum impedance of fault current limiters for symmetrical and/or asymmetrical faults in power systems," Frontiers of Information Technology & Electronic Engineering, Vol. 19, No. 2, pp. 297-307, Feb. 2018.

[21] A. S. Hoshyarzadeh, B. Zaker, A. A. Khodadoost Arani, and G. B. Gharehpetian, "Optimal DG allocation and thyristor-FCL controlled impedance sizing for smart distribution systems using genetic algorithm," Iranian Journal of Electrical and Electronic Engineering, Vol. 14, No. 3, pp. 289-298, Sep. 2018.

[22] E. Atashpaz-Gargari and C. Lucas, "Imperialist competitive algorithm: An algorithm for optimization inspired by imperialistic competition," in IEEE Congress on Evolutionary Computation, 2007, pp. 4661-4667.

[23] P. Zolfi, F. Barmoudeh, and N. Taghizadegan Kalantari, "Bidirectional non-superconducting fault current limiter (BNSFCL) for smart grid applications," Journal of Energy Management and Technology, Vol. 3, No. 3, pp. 60-66, 2019.

[24] A. E. Dahej, S. Esmaeili, and H. Hojabri, "Co-optimization of protection coordination and power quality in microgrids using unidirectional fault current limiters," IEEE Transactions on Smart Grid, Vol. 9, No. 5, pp. 5080-5091, Sep. 2018.

[25] T. Ghanbari and E. Farjah, "Unidirectional fault current limiter: an efficient interface between the microgrid and main network," IEEE Transactions on Power Systems, Vol. 28, No. 2, pp. 1591-1598, May 2013.

[26] M. J. Bio, "Air-Insulated Substations: Bus/Switching Configurations," in Electric Power Substations Engineering, 3rd ed, J. D. Mcdonald, Ed., Boca Raton: CRC Press, 2012, pp. 3.1-3.7.

[27] "MATLAB User's Guide: R2017a Documentation," MathWorks Inc, Natick, MA, USA, 2017.

[28] A. Pai, Energy Function Analysis for Power System Stability, 1st ed. Boston/Dordrecht/London: Kluwer Academic Publishers, 1989.

[29] T. Athay, R. Podmore, and S. Virmani, "A practical method for the direct analysis of transient stability," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 2, pp. 573-584, Mar. 1979.

[30] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, "MATPOWER: steady-state operations, planning, and analysis tools for power systems research and education," IEEE Transactions on Power Systems, Vol. 26, No. 1, pp. 12-19, Feb. 2011.

[31] 39-bus New England case [Online]. Available: https://egriddata.org/dataset/39-bus-new-england-case. Accessed: Jun. 2018.

[32] O. Bozorg-Haddad, M. Solgi, and H. A. Loáiciga, Meta-heuristic and Evolutionary Algorithms for Engineering Optimization. Hoboken, NJ, USA: John Wiley & Sons, 2017.

[33] M. Clerc and J. Kennedy, "The particle swarm - explosion, stability, and convergence in a multidimensional complex space," IEEE Transactions on Evolutionary Computation, Vol. 6, No. 1, pp. 58-73, February 2002.

Shervin Bikdeli was born in Kalaleh, Iran, in 1988. He received the B.Sc. degree in Electrical Engineering from Sadjad University of Technology, Mashhad, Iran, in 2011, and the M.Sc. degree in Power Engineering from Minoodasht Branch, Islamic Azad University, Minoodasht, Iran, in 2017.

He works as a Power Engineer at the Mazandaran and Golestan Regional Electric Company. His current research interest is the power system optimization.

Mohammad Farshad was born in Gonbad Kavous, Iran, in 1981. He received the B.Sc. degree in Power Transmission and Distribution Networks Engineering from Power and Water University of Technology (PWUT), Tehran, Iran, in 2003, and the M.Sc. and Ph.D. degrees in Power System Engineering from Ferdowsi University of Mashhad, Mashhad, Iran, in 2006 and 2013, respectively.

He is currently an Assistant Professor in the Department of Electrical Engineering, Faculty of Basic Sciences and Engineering, Gonbad Kavous University. His main research interest is the application of soft-computing techniques in power system protection and operation problems.

IECO

This page intentionally left blank.