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Multi-Objective Optimal Placement of Fault Current Limiter in IEEE RTS 24-Bus System: A Case Study Review

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ABSTRACT

By increasing load demands and extending power networks to respond to customers' needs, the complexity and integration of power systems have been boosted, increasing the system's short circuit current level, which may threaten the network's reliability. Over the years, some approaches have been proposed to deal with this issue. Proper examples are reconfiguring networks, increasing circuit breakers (CBs) capacity, and implementing fault current limiters (FCLs). Reconfiguration and increasing CB rating have applied exorbitant costs to the system, and in some cases, it may be infeasible. Hence, FCLs can play a pivotal role in the mitigation of the fault current level, but the effectiveness of FCLs depends on the numbers and impedance of FCLs. In this paper, a novel and multi-objective approach is presented to optimize three objective functions simultaneously: decreasing the short circuit level, increasing the systems reliability level, and minimizing the costs of FCL installation. The adaptive penalty factor and Pareto-based multi-objective evolutionary algorithm based on decomposition are used to optimize the objectives mentioned above. Numerical and graphical results of optimization studies in MATLAB software on the IEEE RTS 24-Bus system confirm the proposed method's competence.

***Index Terms*—**fault current limiter, multi-objective optimization, IEEE RTS, fault current, reliability

I. INTRODUCTION

These days, with the increasing demands for electricity and in order to address these electricity deficits, power systems have become larger and more complex. Consequently, the short circuit current level has soared, so to deal with this problem, some methods, such as network reconfigurations and circuit breaker (CB) rating increases have been proposed [1]. However, these techniques may be uneconomical and even impractical. To that end, some types of fault current limiters (FCLs) have been introduced in the literature [2-4]. Fault current limiters are installed serially with other bays equipment and has an insignificant resistance in normal conditions, but when a short circuit occurs, the FCL will be triggered and reveals a considerable resistance to suppress the fault [5, 6]. In the literature, many applications and benefits of FCLs have been investigated [7-10]. Hatata et al. [11] studied the effects of superconducting fault current limiters (SFCLs) on a directional relay in the network integrated with distributed generations. Moreover, in [12], a single objective optimal allocation of SFCL in a reconfigurable smart grid was evaluated. The imperialist competitive algorithm was employed to optimize the allocation of FCL on the New England benchmark network by Bikdeli and Farshad [13]. In addition, the Pareto front optimization for short circuit current and capital costs of FCL installation with a limited number of FCLs were discussed in [14]. In [15], non-dominated sorting genetic algorithm II (NSGA-II) was used to optimize the power losses and costs of FCLs, while FCL effects on the buses' voltage sag due to short circuits was investigated in [16]. As found in the previous studies, the authors only considered the allocation of FCLs as a single objective function or restricted the number of FCLs that can be installed on the studied networks. Haifeng Hong [17] introduced a new short circuit current calculation approach in a power grid integrated with HTS-FCLs. Also, in [18], directional FCLs were used in a microgrid to maintain overcurrent relays coordination without any relay setting changes or adaptive protection schemes. Superconductive FCL locations and impedance effect on a microgrid were investigated in [19]. In [20], the authors presented a magnetic-based FCL which could control the power flow between the upstream AC network and the microgrid side. As can be seen from literature investigations, multi-objective Pareto-based optimization and adaptive penalty factor have not been considered in the previous papers.

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This paper introduces a novel approach to solving three objective functions simultaneously. These objectives are included in fault current reduction, minimizing the costs of FCL implementation, and increasing the network's reliability. This study has two significant contributions. Firstly, objectives are solved based on the Pareto front optimization technique and a combination of multi-objectives, which include compromising objectives. The adaptive penalty factor is also considered to increase the optimizations' accuracy level as the second novel approach. Multi-objective evolutionary algorithm based on decomposition algorithm, which decomposes multi-objectives into single types and solves them simultaneously [21], is used in this research. This algorithm is faster and more accurate than NSGA-II [21]. An updated version of the IEEE RTS 24-Bus system [22] is used as a study case to investigate the objectives of optimal placement of FCLs. The rest of the paper is structured as follows: short circuit current calculations and FCL impedance impacts on the networks impedance matrix are analyzed in Section II. The IEEE RTS network is introduced in Section III. In Section IV, objective functions are investigated. Section V is assigned to describe the optimization algorithm used in this paper. Simulation and study results are presented in Section VI. Finally, Section VII concludes the paper.

II. SHORT CIRCUIT CURRENT CALCULATION AND EFFECT OF FCLS IMPEDANCES ON Z_{BUS} MATRIX

The symmetrical three-phase short circuit is the most significant type of fault, so its results have been used for protective device selection [23], and in this paper, it has been applied to the IEEE RTS network to calculate the maximum fault current of the system. The short circuit current at bus *i* can be calculated as:

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

where I_i^{sc} presents the three-phase short circuit current at bus *i* and E_i is the voltage of *ith* bus before the fault occurrence. Z_{ii} is the diagonal impedance of Z_{bus} matrix, and I_b is the base current [24]. When a line with impedance Z_b is added between buses *j* and *k*, each element of Z_{bus} will be modified as follows [24]:

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

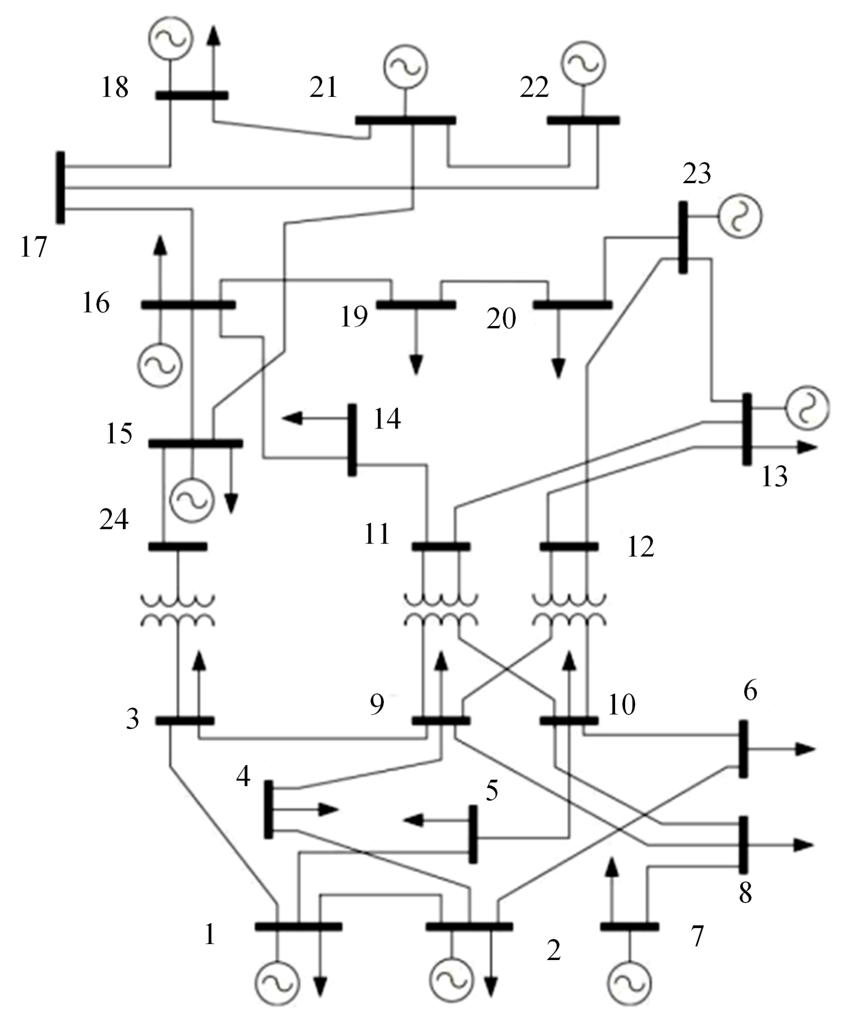

Fig. 1. Single line diagram of IEEE RTS 24-Bus system.

Z_{xy}^{new} and Z_{xy}^{old} are the modified and old elements of Z_{bus}, respectively. The effect of adding impedance Z_b in series with the transmission line can also be considered as a parallel impedance Z_p with the network, leading to the following equation being obtained:

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

After the FCL is taken out, the diagonal element of Z_{bus} is modified as:

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

III. CASE STUDY

In this paper, the FCL optimal allocation problem is studied on the IEEE RTS 24-Bus system. This network is vast and complex, and some modifications have been made to prepare it for studies [22, 25]. It consists of 24 buses, 38 lines, 32 generators, and 17 loads [22]. The single line diagram of the system is depicted in Fig. 1.

According to the IEC 62271-214 standard, the CB initial rating for systems with voltage levels of more than 52 kV is 1250 A, and the short circuit breaking current is assumed to be 21.5 kA.

IV. OBJECTIVES FORMULATION

The FCL optimum allocation problem is a nonlinear problem and includes some objective functions. This paper's objectives are to improve the network reliability, minimize the economic aspects of FCL installation, and reduce the short circuit current level. The explanations of these objectives are as follows.

A. Reliability Enhancement

1) Influence of Fault Current Limiter on System Reliability

When a series element is added to the power system, it deteriorates the reliability indices [26]. However, FCL reduces the failure rate of equipment by decreasing the frequency of the excessive fault current [27, 28]. Fault current limiter installation locations play a pivotal role in their effectiveness. The degraded operation, being worn down, arcing, and fault current are reasons for the failure of protective devices function [29].

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

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

Equation (5) illustrates some terms of system failure rate, and (6) represents the failure rate for the failure event f at kth load after FCL installation on the lth line. The parameter $\lambda^{faultcurrent}_{0,k,f}$ is the failure rate that is only caused by fault current for the 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 the failure rate for failure event f at k^{th} load when FCL is installed on the lth line [29].

2) System Reliability Estimation

There have been various indices to evaluate the network's reliability, such as system average interruption frequency index, average service unavailability index, and average energy not supplied. However, none of these aspects can effectively evaluate the reliability criteria. Therefore, the weighted load reliability index (WLRI), which includes the impacts of the above index, is used to estimate the system reliability [29]. It should be mentioned that the lower value of WLRI indicates the more accurate value of reliability. Equations (7) and (8) represent this index.

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

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

w_m is the normalization factor for the value of mth reliability index in (7) and (8), 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 the installation location of FCLs. 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

$$w_k = \frac{CIC \quad of \quad k^{th} load \quad point}{average \quad CIC \quad of \quad all \quad types \quad of \quad customers} \tag{11}$$

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

RS is an index that determines the effect of the installation location of FCLs on system reliability. The weighting factor w_k indicates the importance of kth load and is determined by considering the interruption cost of each customer [30]. The 2n-dimensional vector X reveals the location and impedance of FCLs. The parameter sl_i is either one or zero, indicating the existence or absence of the FCLs on the i_{th} line. The parameter RS(X = 0) is the system reliability index when there are no FCLs in the power system.

B. Economic Aspects of Fault Current Limiter Utilization

In the optimal allocation of FCLs, the benefits greatly outweigh the costs of installation. It is necessary to compromise the number and impedance of FCLs and the amount of the fault current mitigation [31]. These objective functions are formulated in (13) and (14).

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

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

$Z_{i,fcl}$ and N_{fcl} are the impedance of the ith FCL and the number of FCLs 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 into the system. Expected impedance and the number of FCLs are used to normalize their corresponding cost functions. These are a prediction of the required numbers and impedances of FCLs. Furthermore, pf_z is the penalty factor and is defined as:

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

C. Short Circuit Current Alleviation

As evident, the main goal of FCL installation is suppressing the short circuit current [24, 32, 33]. Although unsymmetrical fault occurrence is more probable than the three-phase symmetrical fault, the symmetrical fault has been chosen to determine the rating of CBs because it is the most considerable type of fault. The fault current mitigation objective can be found in (16).

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

Z_{ii} is the diagonal entry of the impedance matrix (Z_{bus}) after FCL injection into the system. pf_I is the imposed penalty factor that can be defined as:

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

In this paper, the amount of imposed penalty to the objective functions depends on the amount of violation of constraints called the adaptive penalty factor.

V. MULTI-OBJECTIVE EVOLUTIONARY ALGORITHM BASED ON DECOMPOSITION ALGORITHM AND OPTIMIZATION STEPS

The multi-objective evolutionary algorithm based on decomposition (MOEA/D) is used in this paper to optimize the objective functions. This algorithm is briefly described as follows.

With the MOEA/D algorithm, the multi-objective problem is decomposed into several scalar optimization sub-problems optimized simultaneously. Each sub-problem exchanges its information with its neighbors and will be optimized by evolutionary optimization operators [21, 34]. This algorithm's computational sophistication is lower than NSGA-II at each generation [21, 35, 36]. The pseudocode of this algorithm can be found in Appendix A.

A. Procedure for Optimization

The procedure of the FCL optimal selection is illustrated in Fig. 2.

1) The systems impedance matrix Z_{bus} is made.
2) A symmetrical three-phase short circuit fault is applied to all buses.
3) This paper investigates three objective functions: 1) Network reliability enhancement. 2) Number of FCLs and impedance are the costs of FCL installation and minimizing these costs are considered the second objective. 3) Short circuit current mitigation. These functions are nonlinear and are functions of X. X is the vector of control variables, which is a 2n-dimensional vector that represents the location and impedance of FCLs. Also, n is the number of lines in the network.

   $X=[X_1,X_2] \quad X_1=[sl_1,sl_2,\dots,sl_n] \quad X_2=[z_{1,fcl},z_{2,fcl},\dots,z_{n,fcl}]$ sl_i is either one or zero, indicating the presence or absence of FCL in the i_{th} line.
4) The above objectives are functions of X. A penalty factor is used based on the short circuit current's limitation criteria.

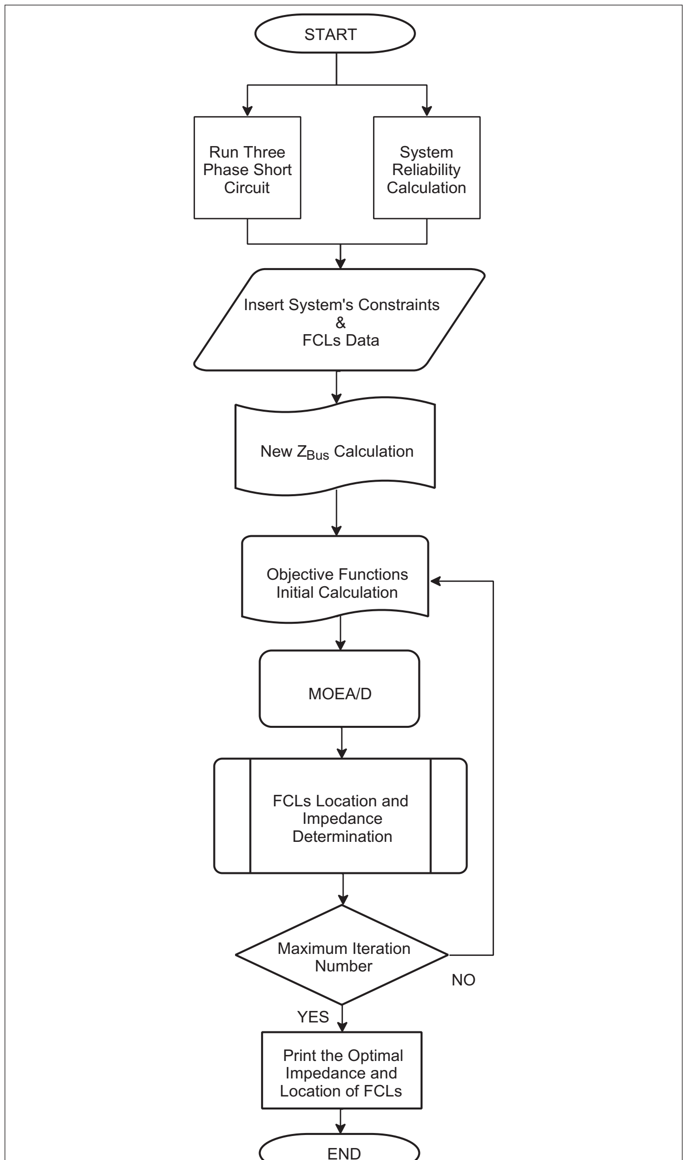

Fig. 2. General flowchart of the proposed optimum FCL allocation.

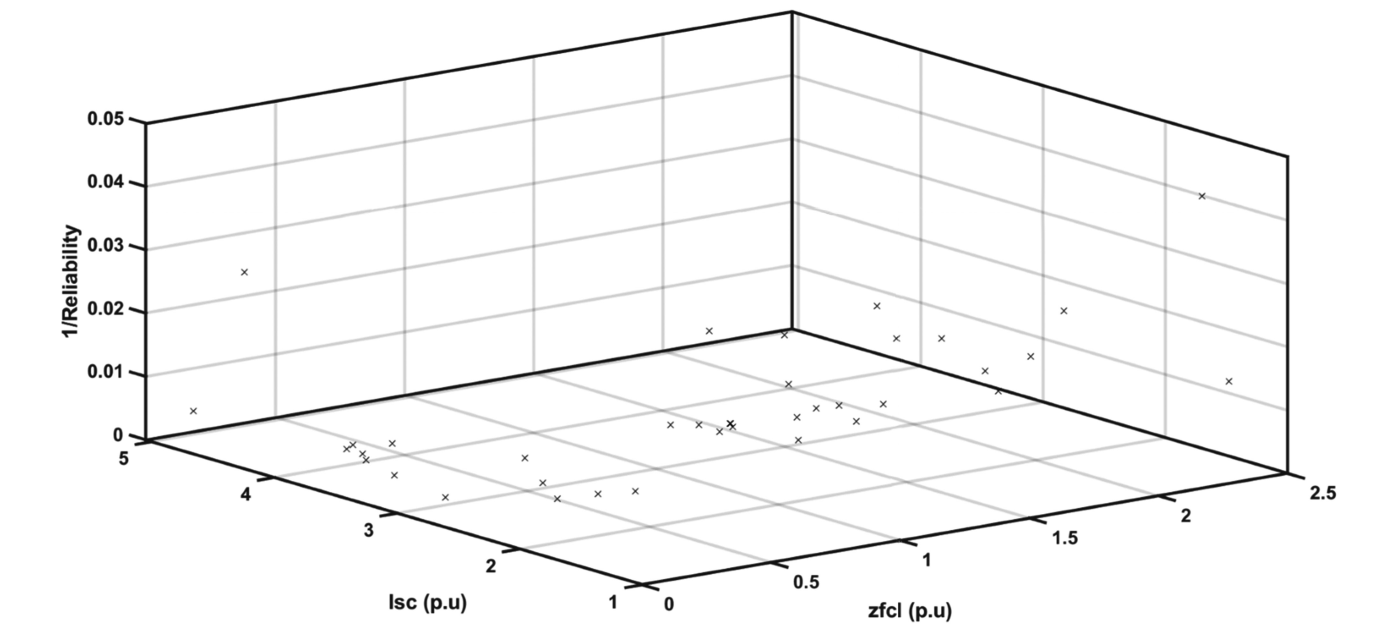

Fig. 3. MOEA/D algorithm Pareto front for IEEE RTS 24-Bus system.

TABLE I. MOEA/D ALGORITHM RESULT FOR IEEE RTS 24-BUS SYSTEM

WLRI	0.474
FCL installation candidate lines	3,5,8,11,13, 35
FCLs impedance corresponding to above installation locations	2,1.8937,4.105,1.077, 5,2.88
Number of installed FCLs	6
Isc	1.479 p.u

MOEA/D, multi-objective evolutionary algorithm based on decomposition; WLRI, weighted load reliability index; FCL, fault current limiter.

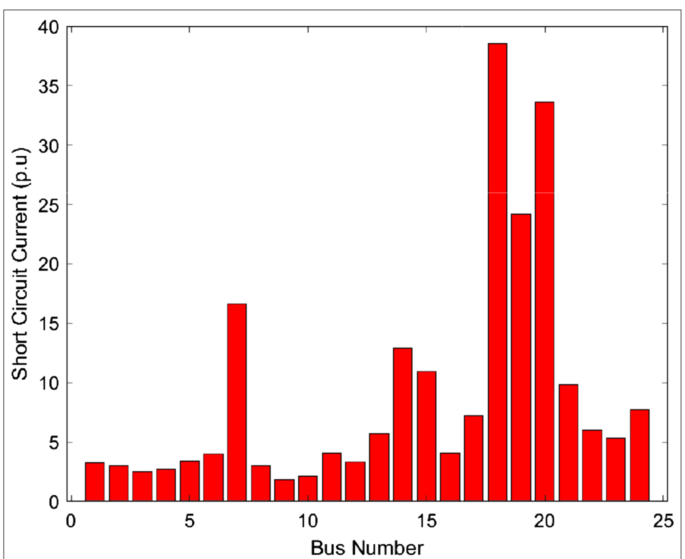

Fig. 4. Three-phase short-circuit current level without FCLs.

VI. SIMULATIONS AND RESULTS

The objectives mentioned above are investigated and optimized on the IEEE RTS 24-Bus system. Figure 1 represents this system. Before FCL injection, the system short circuit current was 9 p.u, and the weighted load reliability index (WLRI) was 0.542. Fig. 3 represents the Pareto front obtained by the MOEA/D algorithm for the IEEE RTS 24-Bus system.

In this IEEE benchmark after the installation of FCL, WLRI shows approximately 0.068 reductions and the short circuit current is reduced by around 7.5 p.u compared to when there are no FCLs in the system.

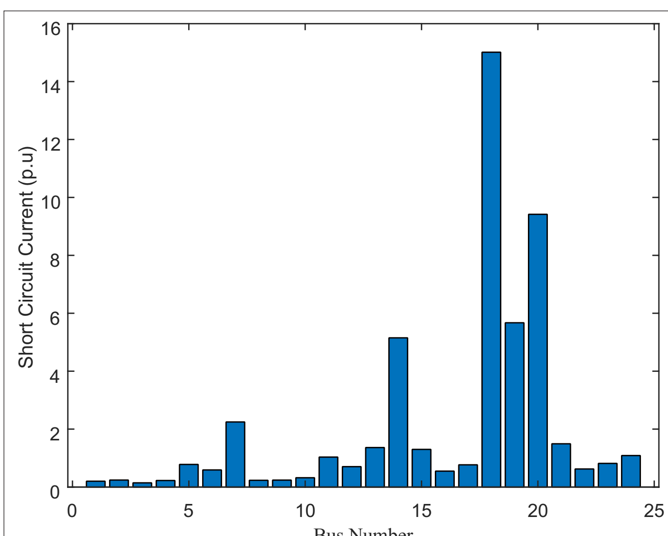

Fig. 5. Three-phase short-circuit current level in the presence of FCLs.

Table I illustrates a typical solution from the Pareto fronts obtained by MOEA/D.

Figs. 4 and 5 describe the symmetrical three-phase short circuit current level at each bus before FCL installation and after their presence in the network. These figures properly illustrate the effect of FCLs on reducing the network's short circuit current.

As can be found from the above figures and table, FCL utilization can play a pivotal role in the power system short circuit current mitigation and network's reliability improvement. Furthermore, the efficiency of FCL strongly depends on their size and location. Although this network consists of 38 lines, the MOEA/D algorithm optimized and specified 6 lines as candidates for FCL installation, verifying the proposed algorithm's efficiency.

VII. CONCLUSION

In this paper, the impacts of FCL on the mitigation of the fault current and improvement of the system reliability indices are discussed. The efficiency of FCLs depends on their number and location. To this end, the MOEA/D algorithm is used to optimize the effectiveness of FCLs.

The multi-objective algorithm used is based on the dominance concept, and the result is shown in a Pareto front. As monetary policy has played a focal point in power system operation and reconstruction, for the violation of short circuit current limitation and FCL impedance margins, adaptive penalty factors are applied to the cost functions to alleviate the needs of more or bigger FCLs. Both numerical and graphical optimization results show that the proposed approach has a significant efficiency on the fault current level reduction and the system's reliability improvement by considering the economic aspect of FCL utilization.

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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 the 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 π^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 based on utility π^i
  - Selection of mating and update range
  - Reproduction
  - Repair – if the searching element is out of the boundary, update the solutions
- If (generation is a multiplication of a pre-set value of x)
  - Update utility function;
- End
- End