Multi-Objective Optimal Placement of FCL in IEEE RTS 24 Bus System: a Case Study Review

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Abstract

By increasing load demands and extending power networks to response customers need the complexity and integration of power systems have been boosted which increases the short circuit current level of the system that may be a threaten for network's reliability. Over these years, some approaches have been proposed to deal with this issue, reconfiguration of networks, increasing circuit breakers (CBs) capacity, and implementation of fault current limiter (FCL) is as proper examples. Reconfiguration and increasing CBs 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 fault current level, but the effectiveness of FCLs is depended to the numbers and impedance of FCLs. In this paper, a novel and multi-objective approach are presented to optimize three objective functions including decreasing short circuit level, increasing the systems reliability level, and minimizing costs of FCL installations. Adaptive penalty factor and Pareto based Multi-objective Evolutionary Algorithm Based on Decomposition (MOEA/D) is used to optimize the aforementioned objectives. Numerical and graphical results of optimization studies in MATLAB software on IEEE RTS 24-Bus system are confirmed the proposed approach efficiency.

Keywords: FCL; Multi objective optimization; IEEE RTS ; Fault Current;Reliability

Acronyms List:

∗ *FCL:* Fault Current Limiter

∗ *CB:* Circuit Breaker

* *MOEA/D:* Multi-objective Evolutionary Algorithm Based on Decomposition
* *DG:* Distributed Generation
* *SFCL:* Superconducting Fault Current Limiter
* *NSGA-II:* Non-Dominated Sorting Genetic Algorithm II
* *SAIDI:* System Average Interruption Frequency Index
* *AENS:* Average Energy Not Supplied
* *WLRI:* Weighted Load Reliability Index

1. Introduction

These days with increasing the demands of electricity and in order to address these deficits power systems have become larger and more twisted, as a consequence short circuit current level has soared, so to deal with this problem some methods like networks reconfiguration and CB rating increasing have been proposed [1]. However, these techniques may be uneconomical and even unpractical. Therefore some types of FCLs have been introduced [2, 3, 4]. FCL is installed serially with other bays equipment and in normal condition has an insignificant resistance, but when a short circuit occurs the FCL will be triggered and reveals a large resistance to suppress the fault [5, 6]. In the literature, many applications and benefits of FCL have been investigated [7, 8, 9, 10]. A.Y. Hatata [11] studied effects of SFCL on a directional relay in the network integrated with distributed generations (DGs). In ref. [12], single objective optimal allocation of superconducting fault current limiter (SFCL) in reconfigurable smart grids is evaluated. Imperialist Competitive Algorithm is employed to optimize the allocation of FCL on New England benchmark network by Bikdeli and Farshad [13]. Pareto front optimization for short circuit current and capital costs of FCLs installation with a limited number of FCLs are discussed in [14]. In ref. [15], non-dominated sorting genetic algorithm II (NSGA-II) has been used to optimize the power losses and costs of FCL. FCL effects on buss voltage sag due to short circuit is investigated in [16]. As it can be 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 emerge throughout the understudies networks if they solve this problem as a multi-objective function. HaifengHong [17] introduced a new approach for short circuit current calculation in a power grid integrated by high temperature superconducting fault current limiters (HTS-FCL). In [18] directional FCL (DFCL) is used in a microgrid to maintain over current relays coordination without any changes in relay setting or using adaptive protection schemes. Superconductive FCLs locations and impedance effect on a microgrid is investigated in [19]. In [20], authors present a magnetic-based FCL which can control the power flow between upstream AC network and microgrid side. As can be found from the literature, multi-objectives Pareto based optimization and adaptive penalty factor are not considered in the previous papers.

In this paper, a novel approach is introduced to solve three objective functions simultaneously. These objects are included in fault current minimization, costs of implementation of FCL minimization, and increasing the network's reliability. Two novelties are considered in this paper. The first one, objectives are solved based on Pareto front optimization technique and completely multi-objectives which made a compromise between objectives. Adaptive penalty factor is also considered to increase the optimizations accuracy level as the second novelty. MOEA/D algorithm which decomposes multi-objectives to single types and solve them simultaneously [21] is used in this research, and in regards to NSGA-II, this algorithm is faster and more accurate [21]. An updated version of IEEE RTS 24-Bus system [22] is used as a study case to investigate the objectives of optimal placement of FCL.

The rest of the paper are included: Short circuit current calculations and FCLs impedances impacts on the networks impedance matrix are analyzed in Section 2 IEEE RTS network is introduced in Section 3. In Section 4 objective functions are investigated. Section 5 is assigned to describe the optimization algorithm used in this paper. Simulation and studies results are presented in Section 6. Finally, Section 7 concludes the paper.

2. Short Circuit Current Calculation and Effect of FCLs Impedances on Z_{BUS} Matrix

As the symmetrical three-phase short circuit is the worst type of faults, and its results have been used for protective device selection [23] it has been applied on 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 voltage of i th bus before the fault has been occurred. 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]:

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

where 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 which can be obtained by the following equation:

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

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

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

3. Study Case

In this paper, FCL optimal allocation problem is studied on IEEE RTS 24-Bus system. This network is a vast and complex network and some modifications have been done on it to prepare it for studies purposes [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 IEC $62271 - 214$ standard, the CB initial rating for upper 52 kV systems is $1250A$ and short circuit breaking current assumed to be $21.5KA$.

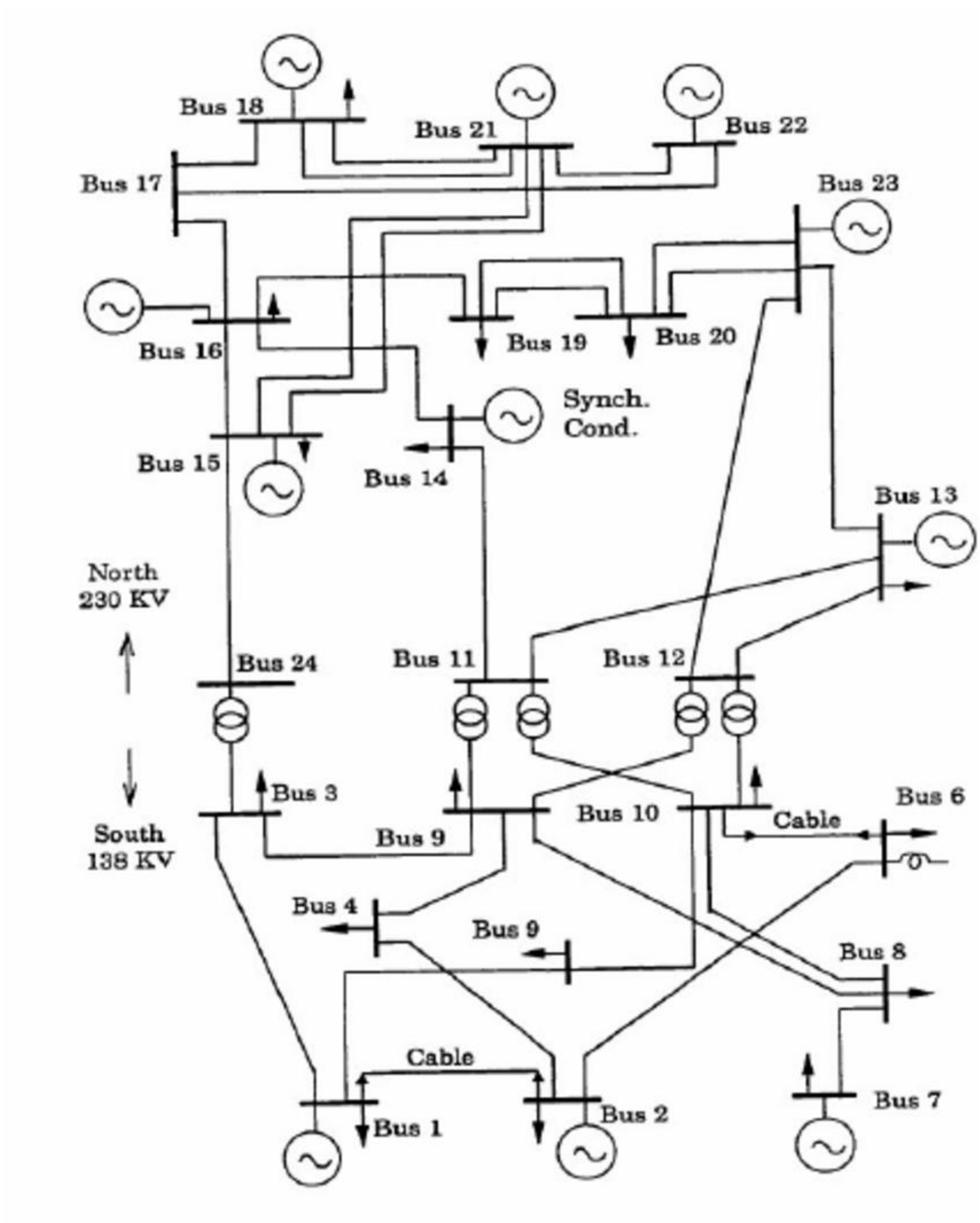

Figure 1: Single Line Diagram of IEEE RTS 24-Bus system

4. Objective Problems Formulation

FCL optimum allocation problem is a nonlinear problem and can be included some objective functions. Short circuit current level reduction, networks reliability improvement, and economic aspects of FCLs installation are considered as objectives of this paper. The explanation of the aforesaid objectives are as follows:

4.1. Reliability enhancement

4.1.1. 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]. FCLs installation locations play a pivotal role in their effectiveness. Protective devices function may be failed due to various reasons. Degraded operation, worn, arcing, and fault current areas proper examples [29].

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

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

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

4.1.2. System reliability estimation

There have been various indices to evaluate the network's reliability such as system average interruption frequency index (SAIDI), Average service unavailability index (ASUI) and average energy not supplied (AENS). However, all aspects of a system cannot be considered by one of these system reliability criteria. Therefore, weighted load reliability index (WLRI) which includes the impacts of the aforementioned indices is used to estimate the system reliability [29]. It should be mentioned that the lower value of WLRI indicates the greater value of reliability. Equations (7) and (8) represent this index.

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

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

w_m is the normalization factor for the value of m_{th} 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 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:

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

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

where RS is an index that determines the effect of the installation location of FCL on the system reliability. The weighting factor w_k indicates the importance of k^{th} load and is determined by considering customer 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 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.

4.2. Economic aspects of FCL utilization

The optimal allocation of FCL is a mixed blessing problem. In this problem, it is necessary to make a compromise between the number and impedance of FCLs and the amount of the fault current mitigation [31]. These objective function 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 i_{th} FCL and the number of FCL 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 the number of FCLs are used to normalize their corresponding cost functions. These are a prediction of required numbers and impedances of FCLs. Furthermore, pf_z is the penalty factor and is defined as:

$$\begin{array}{ll} if & Z_{i,fcl}^{min} \leq Z_{i,fcl} \leq Z_{i,fcl}^{max} \qquad i = 1, ...N_{fcl} \\ & then \qquad pf_z = 0 \\ else & pf_z = max((Z_{i,fcl} - Z_{i,fcl}^{min}), (Z_{i,fcl}^{max} - Z_{i,fcl})) \end{array} \tag{15}$$

4.3. Short circuit current alleviation

As it is obvious, the main goal of FCL installation is suppressing short circuit current [32, 24, 33]. Although unsymmetrical faults occurrence is more probable than three-phase symmetrical faults, this type of fault has been considered to determine the rating of CBs because it is the worst 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 FCLs injection to the system. pf_I is the imposed penalty factor that can be defined as:

$$\begin{array}{ll} if & I_j^{sc} \leq I_j^{sc,max} \qquad j = 1, ..., N_b \\ & pf_I = 0 \\ else & pf_I = 500 * (\mid I_j^{sc} - I_j^{sc,max} \mid) \end{array} \tag{17}$$

In this paper, the amount of imposed penalty to the objective functions are depended on the amount of violation of constraints which is called the adaptive penalty factor.

5. MOEA/D Algorithm and Optimization Steps

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 MOEA/D algorithm, the multi-objective problem will be decomposed into several scalar optimization sub-problems which will be optimized simultaneously. Each sub-problem exchanges its information with its neighbors and will be optimized by evolutionary optimization operators [34, 35]. This algorithms computational sophistication is lower than NSGA-II at each generation [34, 36, 37]. The pseudo-code of this algorithm can be found in Appendix A.

5.1. Procedure on Optimization

1. The systems impedance matrix Z_{bus} will be made.
2. Symmetrical three-phase short circuit fault will be applied to all buses.
3. In this paper, three objective functions are investigated: 1) Network reliability enhancement. 2) FCLs number and their impedance are considered as costs of FCLs installation and these costs minimization is one the objective. 3) Short circuit current mitigation. These functions are nonlinear and are functions of X. X is the vector of control variables, which is 2n-dimensional vector and represents the location and impedance of FCLs respectively, and n is the number of the lines in the network. $X = [X_1, X_2]$ $X_1 = [sl_1, sl_2, ..., sl_n]$ $X_2 = [z_{1,fcl}, z_{2,fcl}, ..., z_{n,fcl}]$
   sl_i is either one or zero, the value of which indicates the presence or absence FCL in i_{th} line.
4. Above objective are functions of X. A penalty factor is used based on the short circuit current's limitation criteria.

6. Simulations and Results

The aforementioned objectives are investigated and optimized on IEEE RTS 24-Bus system.

Figure 1 represents this system. Before FCLs injection, the system short circuit current was $9p.u$ and weighted load reliability index (WLRI) was 0.542.

Figure 3 represents the Pareto front obtained by MOEA/D algorithm, for IEEE RTS 24-Bus system.

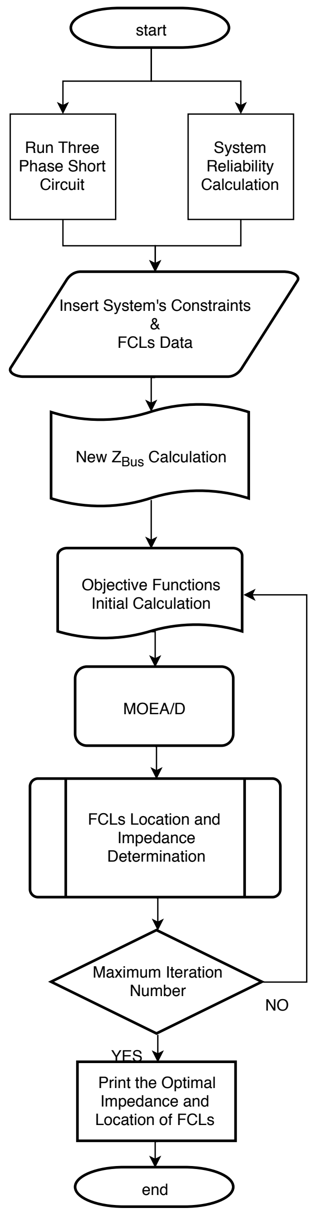

Figure 2: General flowchart of the proposed optimum FCL allocation

Table 1: 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
I_{sc}	1.479 p.u

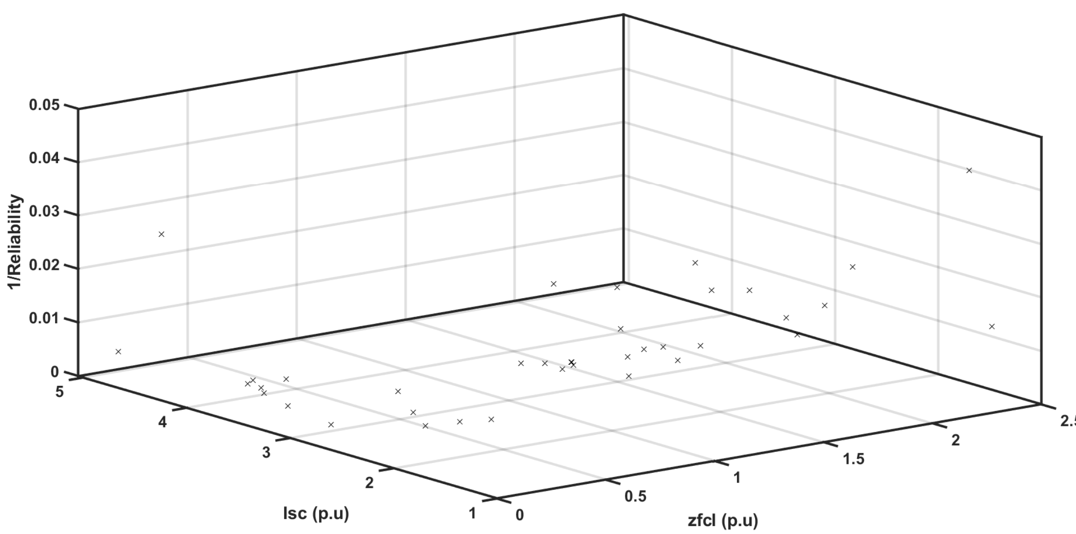

Figure 3: MOEA/D algorithm Pareto front for IEEE RTS 24-Bus system

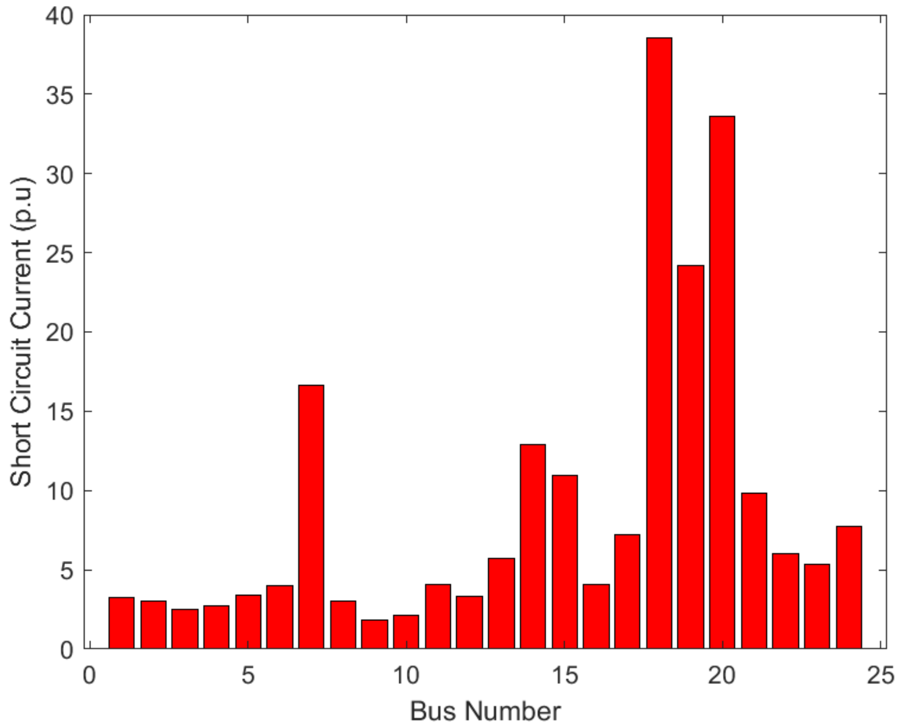

Figure 4: Three phase short-circuit current level without FCLs

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

Table 1 illustrates a typical solution from the Pareto fronts obtained by MOEA/D.

Figures 4 and 5 describe the symmetrical three-phase short circuit current level at each bus before FCLs installation and after the presence of them in the network respectively. These figures properly reveal the effect of FCLs on the reduction of the network's short circuit current.

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

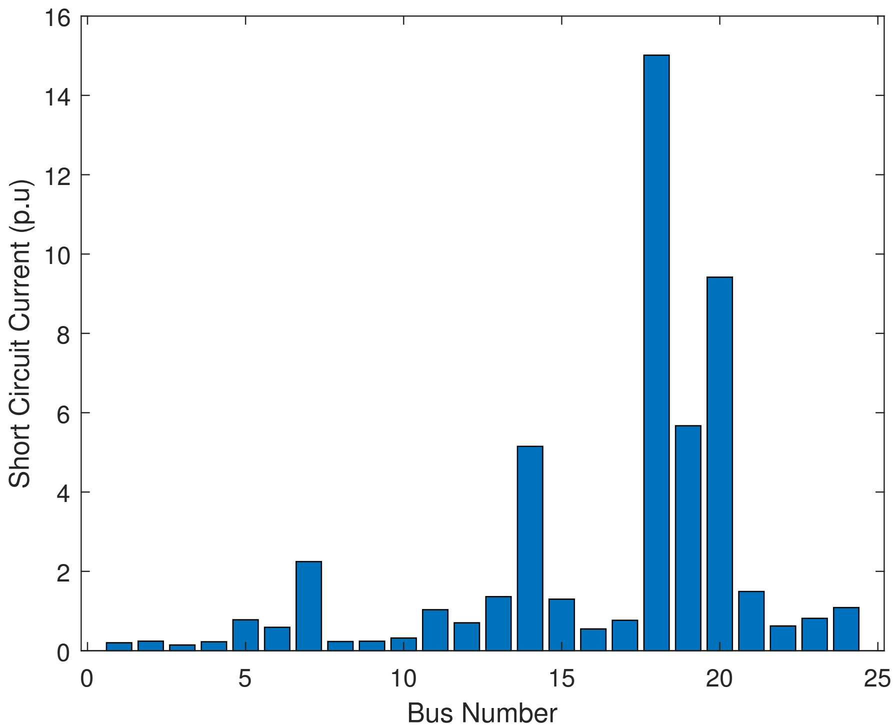

Figure 5: Three phase short-circuit current level in Presence of FCLs

installation verifying the efficiency of the proposed algorithm.

7. CONCLUSION

In this paper, FCL impacts on the mitigation of fault current and improvement of the system reliability indices are discussed. But also the amount of FCLs influence depend on the number, and location of them. Due to this reason, 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 monumental role in power system operation and reconstruction, for the violation of short circuit current limitation and FCLs impedance margins adaptive penalty factors are applied into the cost functions to alleviate the needs of more or bigger FCLs. Both numerical and graphical results of optimization show that the proposed approach has a significant efficiency on the fault current level reduction and system's reliability improvement by considering the economic aspect of FCLs 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 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 base on utility π^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