

# Optimal Location and Determination of Fault Current Limiters in the Presence of Distributed Generation Sources Using a Hybrid Genetic Algorithm

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**Abstract**—Nowadays, the presence of distributed generation (DG) units in the distribution network is increasing due to their advantages. Due to the increasing need for electricity, the use of distributed generation sources in the power system is expanding rapidly. On the other hand, in order to respond to the growth of load demand, the network becomes wider and more interconnected. These factors increase the level of fault current in the power system. Sometimes this increase causes the fault current level to exceed the ability to disconnect the protective devices, which can cause serious damage to the equipment in the power system. Using fault current limiters (FCLs) in power system is very promising solution in suppressing short circuit current and leads use of protective equipment with low capacities in the network. In this paper, in order to solve the problem of increasing the fault current, first using sensitivity analysis, network candidate lines are selected to install the fault current limiter, which helps to reduce the time and search space to solve the problem. Simultaneously finding the optimal number, location and amount of impedance for the installation of a resistive superconductor limiter is solved using the multi-objective Non-dominated genetic algorithm with non-dominated sorting (NSGA-II). The method presented in a 20 kV ring sample network, simulated in PSCAD software, is evaluated in the presence of distributed generation sources and its efficiency is shown.

**Keywords:** Superconducting fault current limiters, Optimal positioning, Multi-objective genetic algorithm, Non-dominated sorting (NSGA-II), Sensitivity analysis, Search space reduction

## 1. Introduction

Due to the growing need for electricity, environmental problems and the high cost of fossil fuels, the use of renewable energy sources in the electricity system is expanding. The network is also broader and more interconnected in response to increasing demand for cargo. These factors increase the fault current level in the electrical system. Sometimes this increase causes the fault current level to exceed the ability of the protective devices to cut off, which can cause serious damage to the equipment in the system [1-3]. Various methods have been proposed, including upgrading protection devices to new fault current levels, isolating bus loads, using higher impedance transformers, and using compatible relays to respond to the problem. Since the above methods have disadvantages such as high cost, reduced reliability, increased power losses and complexity in operation, the use of fault current limiters has been considered today [4]. Fault

current limiters are divided into active and passive categories. In passive methods, the system impedance is constantly increasing, which causes power loss in the system. In contrast, active methods typically add a small impedance to the network and reduce the fault current level by increasing the impedance injected into the network when a fault occurs. The use of fault current limiters delays the need to upgrade existing protection equipment. In addition, fault current limiters have the ability to reduce the fault current level in the first quarter of the cycle and also reduce transient fault current, while conventional protection equipment requires several cycles to cut off fault current [5-15]. Given the advantages mentioned, the use of fault current limiters can be ideal. However, due to the high cost of this equipment, it is not possible to install a limiter for each distributed source of production. To install this equipment in the power grid, the optimal location for installation, the optimal amount of injection series impedance at the time of fault and the problem of coordination of protection with other existing protection equipment must be considered [6].

So far, many studies have been conducted on the location of the limiting fault current. However, none of them selected the number, location and amount of impedance limiting the fault current simultaneously using multi-objective genetic algorithm [7], [8, 9]. The advantage of using multi-objective genetic algorithm over the old

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innovative solving methods such as weighting method, finite constraint method, etc. is that at the end of solving the algorithm, it can get several different optimal answers and allow the user to do so. Choose one of the answers according to your priority.

In this paper, a 20 kV loop sample test network with three distributed production sources is simulated in PSCAD software. By applying a three-phase symmetric fault to the network bus bars, it is observed that in some bus bars, the fault current rate exceeds the allowable level of protective equipment if the distributed generation sources are connected to the network. Using sensitivity analysis, reduction of bus fault current due to change in system branch parameter, candidate locations for fault current limiter installation are identified, which reduces search time and space to solve the problem. Then, using a multi-objective genetic algorithm, the number, location and optimum impedance of the fault current for installation on the candidate lines are determined simultaneously.

**2. Modeling of resistive superconductor limiter**

Equation (1) expresses the limiting behavior of the resistive superconductor considered in this paper in different states [10, 11].

$$R(t) = \begin{cases} 0 & t < t_0 \\ R_n \left[ 1 - \exp\left(-\frac{t-t_0}{\tau}\right) \right]^{1/2} & t_0 \leq t < t_1 \\ a_1(t-t_1) + b_1 & t_1 \leq t < t_2 \\ a_2(t-t_2) + b_2 & t_2 \leq t < t_3 \\ 0 & t \geq t_3 \end{cases} \tag{1}$$

Also shows the steps of loss and recovery of superconductivity based on Equation (1).

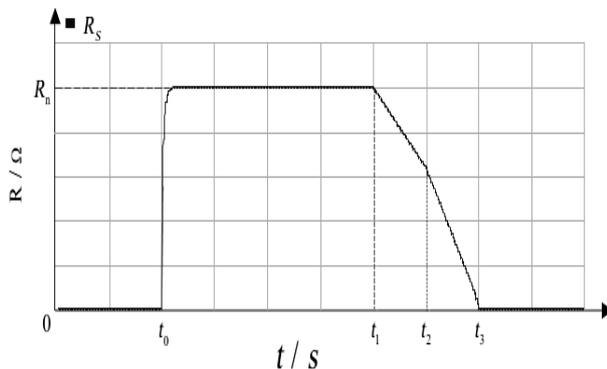


Figure 1. Performance characteristic of a resistive superconductor limiter

The amount of limiting resistance in terms of time is given in Equation (1).  $R_n$  and the final resistance are at normal temperature and time constant, respectively. In

addition,  $t_0$ ,  $t_1$ ,  $t_2$ , and  $t_3$  are the fault occurrence time, the first recovery start time, the second recovery start time, and the limiting return time to their superconducting state, respectively (Figure 1). Other values of the resistance superconductor are considered according to Table 1.

Table 1. Limiting parameters of modeled resistance superconductors

$b_2[\Omega]$	$b_1[\Omega]$	$a_2[1/s]$	$a_1[1/s]$	$\tau$	$R_n[\Omega]$	parameter
$R_n$	$R_n/2$	140-	70-	0.02	variable	amount

**3. Simulated test system in PSCAD software**

The studied network according to Figure 2 is a ring distribution network consisting of two 20 kV feeders equipped with 4 distributed generation units. The data related to the studied network are given in Tables 2 to 6.

Table 2: Network Lines Information

X [Ω]	R [Ω]	To Bus	From Bus
0.0706	0.098	2	1
0.0619	0.074	3	2
0.088	0.174	10	3
0.1425	0.0905	4	4
0.1425	0.1555	5	4
0.082	0.206	11	4
0.1805	0.109	6	5
0.088	0.0925	7	6
0.082	0.106	8	7
0.064	0.0895	16	7
0.0872	0.186	9	8
0.0685	0.238	14	8
0.064	0.0895	12	11
0.064	0.0895	13	11
0.049	0.082	15	14
0.0246	0.0712	17	16
0.049	0.082	18	16
0.039	0.082	19	18
0.0619	0.074	20	1
0.0706	0.088	21	20
0.088	0.184	24	20
0.1825	0.165	22	21
0.082	0.156	25	21
0.1425	0.1555	23	22
0.205	0.069	16	23

**Table 3:** Information of loads

P/Q (MW/MVAR)	Load	P/Q (MW/MVAR)	Load
0.4 / 0.5	L15	0.44 / 0.52	L2
0.27 / 0.37	L16	0.26 / 0.7	L3
0.28 / 0.4	L17	0.32 / 0.6	L4
0.25 / 0.36	L18	0.32 / 0.58	L5
0.22 / 0.31	L19	0.29 / 0.57	L6
0.33 / 0.51	L20	0.36 / 0.55	L7
0.46 / 0.6	L21	0.23 / 0.61	L8
0.42 / 0.58	L22	0.26 / 0.4	L9
0.42 / 0.58	L23	0.43 / 0.62	L10
0.43 / 0.62	L24	0.36 / 0.5	L11
0.36 / 0.5	L25	0.25 / 0.33	L12
0.24 / 0.4	L26	0.82 / 1.13	L13
0.12 / 0.2	L27	0.39 / 0.6	L14
0.15 / 0.3	L29	0.18 / 0.3	L28

**Table 4:** Network information

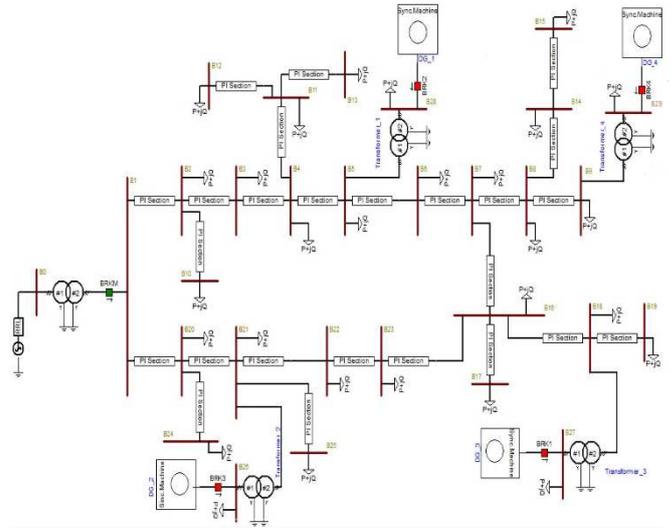
amount	parameter
3500	Power of Short circuit(MVA)
63	Nominal Voltage(KV)
15	X/R
50	Frequency(Hz)

**Table 5:** Parameters of distributed generation sources (DG)

Unit4	Unit3	Unit2	Unit1	
7	6	7	7	Nominal Power(MVA)
4.16	4.16	11	0.69	Nominal Voltage(KV)
0.0036	0.0036	0.0036	0.0036	Ra (pu)
1.56	1.56	1.56	1.56	Xd (pu)
0.25	0.25	0.25	0.25	X'd (pu)
0.17	0.17	0.17	0.17	X''d (pu)

**Table 6:** Information on transformers that increase distributed generation resources

Transformer DG4	Transformer DG3	Transformer DG2	Transformer DG1	
2	2	3	3	Nominal Power(MVA)
4.16:20	4.16:20	11:20	0.69:20	Nominal Voltage(KV)
0.008	0.008	0.01	0.01	Ra (pu)
0.05	0.05	0.04	0.04	X (pu)



**Figure 2:** Test network simulated in PSCAD software

## 4. Problem formulation

### 4.1. Fault current limiter

Although most system faults are asymmetric, the balanced three-phase fault is the worst fault, and the fault current value is used to select the capacity of the protection devices. Equation (2) shows how to calculate the three-phase balanced fault current [12, 13].

$$I_i^{sc} = \frac{E_i}{Z_{ii}} * I_b \tag{2}$$

That  $I_i^{sc}$  the three-phase short-circuit current at bus i and  $E_i$  bus voltage i are before fault. It is  $E_i$  generally equal to 1 per unit.  $Z_{ii}$  Is Shin i the Thevenin impedance and can be obtained from the diameter elements of the impedance matrix (Zbus).  $I_b$  Is the basis current. In the Zbus construction algorithm, when a line with impedance Zb is added between the j and k buses, the  $Z_{xy}$  main element is modified by Equation (3).

$$Z_{xy}^{new} = Z_{xy} - \frac{(Z_{xj} - Z_{xk})(Z_{jy} - Z_{ky})}{Z_{jj} + Z_{kk} - 2Z_{jk} + Z_b} \tag{3}$$

Which  $Z_{xy}^{new}$  and  $Z_{xy}$  are the modified element and the main element of Zbus, respectively.

If a limiter with ZFCL impedance is installed on the lines between the j and k buses and injects its impedance into the line after the faults, the effect of this injection into the network can be considered in the form of adding a new line with the following impedance.

$$Z_p = (-Z_b) \parallel (Z_b + Z_{FCL}) = \frac{Z_b(Z_b + Z_{FCL})}{Z_{FCL}} \tag{4}$$

As a result, the changes in Zbus diameter elements after

ZFCL injection in the branch between the j and k buses are obtained from Equation (5).

$$\Delta Z_{ii} = -\frac{(Z_{ij} - Z_{ik})^2}{Z_{jj} + Z_{kk} - 2Z_{jk} + Z_p} = \frac{G_2}{G_1 + Z_p} \quad (5)$$

fault current changes in a bus after ZFCL injection are calculated from Equation (6).

$$\Delta I_{i,F} = \frac{V_i}{Z_{ii} + \Delta Z_{ii}} - \frac{V_i}{Z_{ii}} \quad (6)$$

By placing relation (5) in relation (6) we have.

$$\Delta I_{i,F} = -\frac{V_i}{Z_{ii}} \frac{G_2}{(G_1 + Z_p)Z_{ii} + G_2} \quad (7)$$

If the limiter used reduces the fault current from the original values of  $I_{i,N}$  to  $I_{i,F}$ , the required  $Z_p$  is easily calculated from Equation (8).

$$Z_p = \frac{I_{i,F}}{I_{i,N} - I_{i,F}} \frac{G_2}{Z_{ii}} - G_1 \quad (8)$$

According to Equations (8) and (4), the required limiting impedance value will be calculated from Equation (9).

$$Z_{FCL} = -\frac{Z_b^2}{Z_b + Z_p} \quad (9)$$

#### 4. 2. Calculation of sensitivity coefficient

If the installation location of a limiter is known, the amount of impedance required to limit the fault current to an acceptable level is calculated by Equation (9) [12]. However, in a large power system, where the fault currents measured at several points in the network are close to or exceed the performance of the protection systems, it is difficult to determine the optimal number, location, and limiting parameters. In order to reduce the search space and time to solve the constraint location problem, sensitivity coefficient calculations are first performed to find suitable candidate locations. In this paper, the sensitivity coefficient is defined as the reduction of the bus fault current by changing the line parameters. Equations (4) and (6) are used to establish the sensitivity coefficient between reducing the bus fault current as a result of increasing the limiting impedance.

For a limiter added to line l between buses j and k with ZFCL impedance, the reduction of the fault current of each bus after the limiter is activated is shown in the following vector.

$$\Delta I_F^l = \left[ \Delta I_{F,1}^l \quad \Delta I_{F,2}^l \quad \dots \quad \Delta I_{F,N_B-1}^l \quad \Delta I_{F,N_B}^l \right] \quad (10)$$

Which  $N_B$  is the number of bus bars of the power system. ZFCL is considered equal to one per unit. From

Equation (10), for each bus, the maximum reduction in bus fault current is obtained. If only the bus bars need to reduce the fault current level, the bus bars are arranged in a vector in order to reduce the fault current changes and are presented as the following vector.

$$S_F^l = [(\Delta I_{F,1}^l, BN(1)) \quad (\Delta I_{F,2}^l, BN(2)) \quad \dots \quad (\Delta I_{F,N_F-1}^l, BN(N_F-1)) \quad (\Delta I_{F,N_F}^l, BN(N_F))] \quad (11)$$

Where  $BN(i)$  is the  $i$ th bus number of biggest fault reductions.

$\Delta I_{F,i}^l$  Is the reduction in fault current is based on the impedance change in line l. As a result, the sensitivity matrix between the limiting location and the reduction of the Bus fault current is presented as follows.

$$S_F = \left[ S_F^1 \quad \Delta I_F^2 \quad \dots \quad \Delta I_F^{N_L-1} \quad \Delta I_F^{N_L} \right]^T \quad (12)$$

$N_L$  is the number of network lines. Suitable candidate locations for the limiter can then be suggested using SF.

#### 4. 3. Objective function

The problem of locating the optimal fault current limiter different goals can be pursued. In this paper, the aim is to simultaneously minimize the number and amount of impedance limiting the fault current, which in turn minimizes the cost. Objective functions and problem constraints are given in Relationships 13 to 15.

$$f_1 = \min \text{NFCL} \quad (13)$$

$$f_2 = \min \sum_{i=1}^{N_{FCL}} Z_{FCL}(i) \quad (14)$$

$$Z_{FCL}^{\min} \leq Z_{FCL}(i) \leq Z_{FCL}^{\max} \quad i=1,2,\dots,N_{FCL} \quad (15)$$

$$I_j^{sc} \leq I_j^{sc,\max} \quad j=1,2,\dots,B_n \quad (15)$$

$I_j^{sc}$  is the bus  $j$ st fault current After installation, the fault current limiter and  $I_j^{sc,\max}$  is the maximum fault current can be cut off by bus  $j$ st protection equipment.

#### 5. Multi-objective genetic algorithm with non-dominated sorting

The multi-objective genetic algorithm with non-dominated sorting is very similar to the genetic algorithm. The difference is in the order of the answers to create the next generation. Figure 3 shows the steps of a multi-objective genetic algorithm with non-dominated sorting [14-15].

In the genetic algorithm, to solve the problem of multi-objective optimization, the objective functions must be converted into a parameter, cost function or competency function, and the answers must be arranged according to the value of this parameter. In the multi-objective genetic algorithm with non-dominated sorting, by defining the concept of non-dominated sorting, the responses in the objective functions are compared separately and divided into several categories. An unresponsive answer is one that is no worse than any other function and is better than at least one function. After categorizing the answers, a control parameter called population distance is used to sort the answers of each category, which indicates the measure of the proximity of the sample to other members of that population.

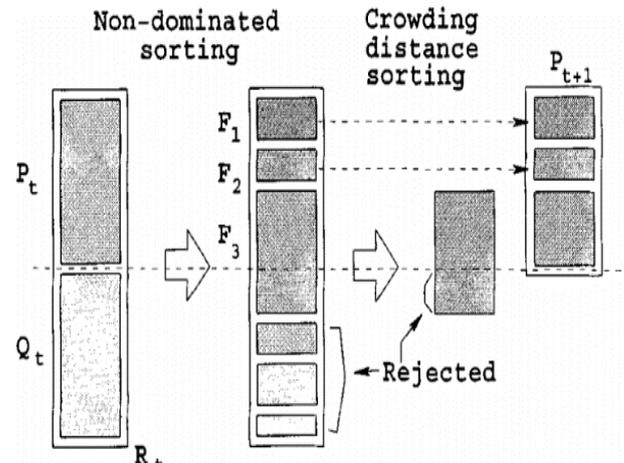


Figure 4. Sorting responses and creating the next generation

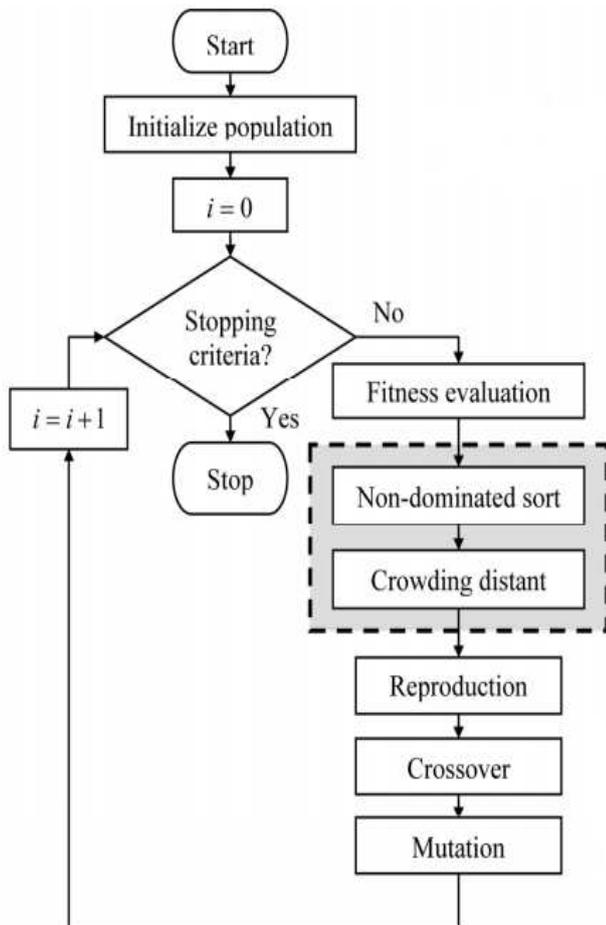


Figure 3. Steps of multi-objective genetic algorithm with non-dominated sorting

Figure 4 shows how to sort the answers and create the next generation. Other stages of the algorithm, such as initial population production, composition, mutation, etc., are similar to the genetic algorithm.

## 6. Simulation results

Using the study network simulated in PSCAD software, the three-phase symmetric fault current in the network bus in the presence and absence of distributed generation sources is calculated. Table 7 shows the effective fault current values of three symmetric phases in the studied network buses with and without DGs. According to the standard cut-out fuses for 20 kV network, protective devices for protection against network loads are 6 and 8 kA cut-out fuses and 10 kA breakers.

In this paper, the maximum allowable current of the equipment is 10 kA. Due to the presence of distributed generation sources in some buses, the fault current approaches or passes the ability to cut off the protective equipment. Fault current limiters are used to reduce the fault current in the target buses.

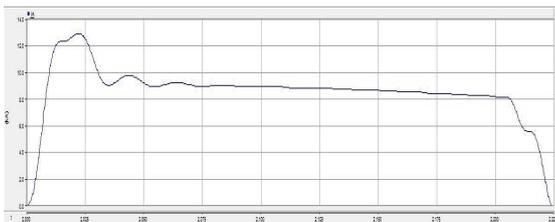
According to Table 7, buses 2, 24, 22, 21, 20, 10, 4, 3 and 25 after installing DGs have the problem of increasing the fault current (more than 10 kA). Figure 5 shows, for example, the fault current in bus 4 in the presence of distributed generation sources that exceeds the protection equipment cut off ability (10 kA).

### 6. 1. Determining the candidate locations for installing the fault current limiter

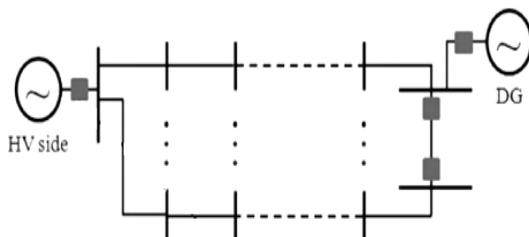
In general, suitable locations for the installation of fault current limiters, as shown in Figure 6, are divided into 3 categories: the high voltage side of the system, the installation site of the DGs, or in the lines near the bus bars.

**Table 7:** The amount of effective fault current (IF) in rails with and without DGs

Bus	IF with / without DG(KA)	Bus	IF with / without DG (KA)
1	12.897 / 9.5648	14	8.2475 / 6.7664
2	11.296 / 9.0817	15	7.8478 / 6.501
3	10.802 / 8.7201	16	9.6484 / 7.6678
4	10.156 / 8.1601	17	9.3723 / 7.4905
5	9.8292 / 7.8154	18	9.2394 / 7.3713
6	9.6181 / 7.6678	19	8.7877 / 7.08
7	9.5913 / 7.6388	20	11.391 / 9.1469
8	8.8813 / 7.1809	21	10.91 / 8.7201
9	8.2389 / 6.7582	22	10.175 / 8.1601
10	10.143 / 8.3661	23	9.7694 / 7.8154
11	9.3805 / 7.655	24	10.271 / 8.4295
12	8.8462 / 7.3006	25	10.046 / 8.1617
13	8.8462 / 7.3006	Bus	IF with / without DG (KA)



**Figure 5:** fault current in bus 1 in the presence of distributed generation sources



**Figure 6:** Candidate locations for SFCL installation

In order to reduce the volume and time of calculations, sensitivity analysis is used to find candidate locations for the installation of the limiter. To calculate the sensitivity coefficient, changes in bus fault currents due to changes in the grid line parameter must first be calculated from the network impedance matrix ( $Z_{bus}$ ). Using MATLAB software and the information of the studied network lines, the network impedance matrix is calculated[16].

Using Equations (4) and (5), the changes in the diameter elements of the impedance matrix are calculated based on the change in the line parameter.  $Z_{FCL}$  is considered equal to 1 per unit. Then, using Equation (6), the sensitivity of changes in bus fault current to changes in line parameter is calculated. Finally, the matrix of Equation (10) is formed. Figure 7 shows the algorithm for determining candidate lines for the installation of a resistive superconductor limiter.



**Figure 7:** Candidate line determination algorithm for installation of resistive superconductor limiter

The SF matrix values are calculated based on  $N_F^S$  equal to 5. Candidate locations for the installation of the limiter for network buses have problems are shown in Table 8.

**Table 8:** Candidate locations for limiter installation

Bus	Candidate lines (from bus / to bus)
2	0 to 1, 1 to 2, 5 to 28, 18 to 27, 21 to 26
3	0 to 1, 1 to 2, 2 to 3, 5 to 28, 18 to 27, 21 to 26
4	0 to 1, 1 to 2, 2 to 3, 3 to 4, 4 to 5, 5 to 28, 18 to 27, 21 to 26
10	0 to 1, 1 to 2, 2 to 10, 5 to 28, 18 to 27, 21 to 26
20	0 to 1, 5 to 28, 1 to 20, 18 to 27, 21 to 26
21	0 to 1, 5 to 28, 1 to 20, 18 to 27, 21 to 21, 21 to 26
22	0 to 1, 5 to 28, 1 to 20, 18 to 27, 20 to 21, 21 to 22, 21 to 26, 22 to 23
24	0 to 1, 5 to 28, 1 to 20, 18 to 27, 20 to 24, 21 to 26
25	0 to 1, 5 to 28, 1 to 20, 18 to 27, 21 to 25, 21 to 26

## 6. 2. Results of multi-objective genetic algorithm

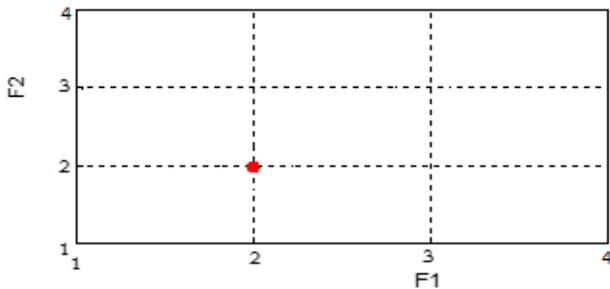
Using multi-objective genetic algorithm with non-dominated sorting and according to the objective functions and constraints expressed in relations (13) to (15) simultaneously determine the number, location and amount of optimal impedance limiting the error current among 15 candidate lines It determines. Since this response minimizes the number of fault current limiters and their impedance value, it can also be a cost-effective answer. In this paper, the maximum allowable fault current of the equipment is 10 kA. The best answer obtained from the multi-objective genetic algorithm considering all candidate lines (mode 1)

and without considering the high voltage side of the system (line 0 to 1) is shown in Table 9.

By placing the fault current limiter in the obtained places, the fault current of the buses returns to the cut-off range of the protective equipment. Figure 8 shows the output of the multi-objective genetic algorithm in condition 2.

**Table 9:** The most optimal answer obtained from the multi-objective genetic algorithm

Amount of impedance[Ω]	location	Number	
1	Line 0 to 1	1	Condition1
Both of 1 and 2	Line 1 to 2 and line 1 to 20	2	Condition2



**Figure 8:** Output of multi-objective genetic algorithm in condition 2

## 7. Conclusion

Due to the advantages of using fault current limiters, they can be used in power systems. However, in distribution networks equipped with distributed generation sources, due to the high cost of this equipment, a limiter cannot be installed for each distributed generation source. To install this equipment in the power network, the optimal location for installation, the optimal value of the injection series impedance at the time of fault must be considered. This paper presents a method for determining the optimal number, location and amount of impedance for the installation of an fault current limiter.

Due to the connection of distributed generation sources, the fault current of some network bus passes through the ability to the protective equipment cut off the fault current. In this paper, in order to reduce the time and volume of calculations, first using the initial sensitivity analysis, changing the fault current of the buses according to the change in the line parameter, suitable candidate locations for installing the fault current limiter are identified. Then, the problem of optimization was solved by using multi-objective genetic algorithm with non-dominated sorting. By using a superconducting fault current limiter installed at the specified location and calculating the optimal impedance value, the fault current of the busbars is reduced to the cut-off capacity of the protective equipment. The proposed method is applied on a ring network with 2 feeders (20 kV)

in the presence of 4 distributed generation sources. The simulation results show that using the proposed method, the number, location and the amount of impedance limiting the fault current can be determined optimally.

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