# Optimum Fault Current Limiter Placement

**Jen-Hao Teng** **Chan-Nan Lu**

***Abstract:*** Due to the difficulty in power network reinforcement and the interconnection of more distributed generations, fault current level has become a serious problem in transmission and distribution system operations. The utilization of fault current limiters (FCLs) in power system provides an effective way to suppress fault currents and result in considerable saving in the investment of high capacity circuit breakers. In a loop power system, the advantages would depend on the numbers and locations of FCL installations. This paper presents a method to determine optimum numbers and locations for FCL placement in terms of installing smallest FCL parameters to restrain short-circuit currents under circuit breakers' interrupting ratings. In the proposed approach, sensitivity factors of bus fault current reduction due to changes in the branch parameters are derived and used to choose candidates for FCL installations. A genetic-algorithm-based method is then designed to include the sensitivity information in searching for best locations and parameters of FCL to meet the requirements. Test results demonstrate the efficiency and accuracy of the proposed method.

***Keywords:*** Short-Circuit Current, Circuit Breaker, Fault Current Limiter, Sensitivity Analysis, Genetic Algorithm

## I. INTRODUCTION

With the increasing demand for power, electric power systems have become greater and are interconnected. Generation units of independent power producers (IPPs) and renewable energy have been interconnected to power systems to support the rising demands. As a result, faults in power networks incur large short-circuit currents flowing in the network and in some cases may exceed the ratings of existing circuit breakers (CB) and damage system equipment The problems of inadequate CB short-circuit ratings have become more serious than before since in many locations, the highest rating of the CB available in the market has been used. To deal with the problem, fault current limiters (FCLs) are often used in the situations where insufficient fault current interrupting capability exists [1-10].

Active FCL is a variable-impedance device connected in series with a CB to limit the current under fault conditions. It has very low impedance under normal operating conditions and high impedance under fault conditions. Active FCLs with different operation mechanism such as based on superconductor, power electronics, polymer positive temperature coefficient resistors and techniques of arc control [1-10] have been introduced. Depending on the location of installation, FCL could offer other advantages such as 1) increasing the interconnection of renewable energy and independent power units; 2) increasing the energy transmission capacity over longer distances; 3) reducing the voltage sag caused by the fault; 4) improving the system stability, and 5) improving the system security and reliability.

In radial power systems, the placement of FCL is not difficult, but in loop power system, FCL placement becomes much more complex when more than one location that have high fault current problems. In such a system, short-circuit currents could come from many directions and are not easily blocked by a single FCL. Therefore, from power system operation and planning points of view, a technique that can choose optimum number and locations for FCL placement with smallest circuit parameters changes to constrain fault currents under CB rating is becoming necessary. For this purpose, rectifier-type superconducting FCL model has been included in short-circuit current analysis and a method to find FCL locations suitable for short-circuit current reduction was proposed in [11]. Refs. [12, 13] used a hierarchical genetic algorithm combined with a micro-genetic algorithm to search for the optimal locations and smallest FCL circuit parameters simultaneously.

This paper proposes a new method to find the optimum numbers and locations for FCL placement. For large loop system applications, in order to reduce the search space in finding the optimum FCL locations, a sensitivity analysis is first conducted to find better candidate locations for FCL placement. A genetic-algorithm-based method is then designed and used to solve the optimum FCL placement problem. Test results demonstrate the efficiency and accuracy of the proposed method.

## II. FAULT CURRENT REDUCTION AND IMPEDANCE REQUIRED

Although, most power system faults are unsymmetrical, balanced three-phase faults are often the worst and are used to determine the CB capacity. For a balanced three-phase fault at bus $i$, the short-circuit current can be calculated by

$$I_i^{sc} = \frac{E_i}{Z_{ii}} * I_b \qquad (1)$$

where $I_i^{sc}$ is the three phase short-circuit current at bus $i$. $E_i$ is the voltage before the fault at bus $i$. Commonly, $E_i$ can be set as 1.0 p.u. $Z_{ii}$ is the Thevenin impedance at bus $i$, it can be obtained from diagonal entries of the impedance matrix ($Z_{bus}$). $I_b$ is the base current.

In the $Z_{bus}$ building algorithm, when adding a line with impedance $Z_b$ between bus $j$ and $k$, the original element of $Z_{xy}$ will be modified as

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

where $Z_{xy}^{new}$ and $Z_{xy}$ are the modified and original elements of $Z_{bus}$, respectively.

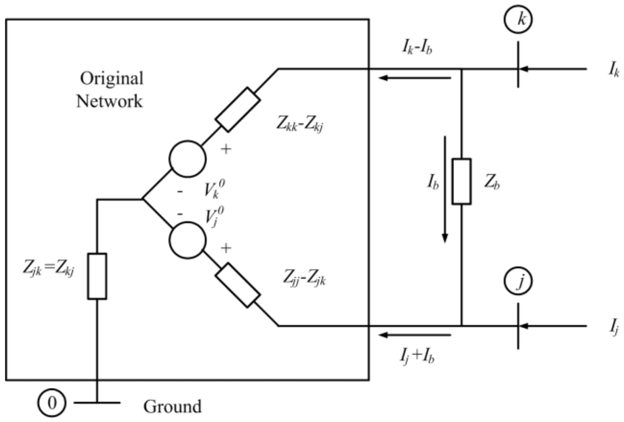

Fig. 1: Thevenin equivalent circuit of adding a line between two existing buses

Fig. 1 shows the Thevenin equivalent circuit by looking into the system from two existing buses. If a FCL with impedance $Z_{FCL}$ were installed on line between bus *k* and *j* and fired after the faults, then Thevenin equivalent circuit can be expressed as Fig. 2.

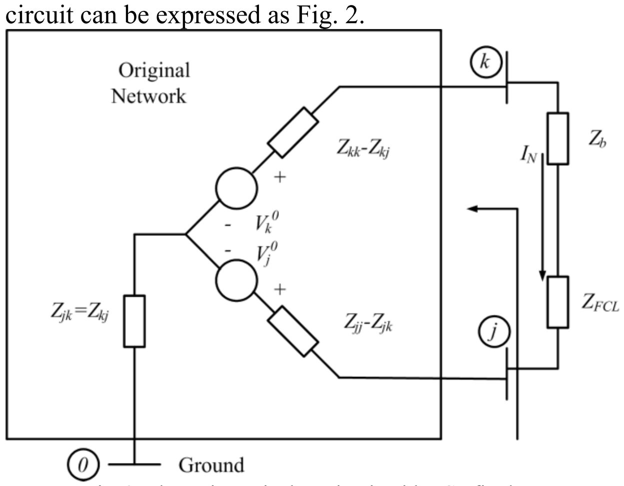

Fig. 2: Thevenin equivalent circuit with FCL fired up

The total effect of inserting $Z_{FCL}$ into the system can be considered as adding a new branch with the following impedance to the system:

$$Z_P = (-Z_b) // (Z_b + Z_{FCL}) = -\frac{Z_b(Z_b + Z_{FCL})}{Z_{FCL}} \quad (3)$$

Therefore, the modification to the diagonal entries of $Z_{bus}$ after FCL is fired up at a branch between bus *j* and *k* is

$$\Delta Z_{ii} = -\frac{(Z_{ij} - Z_{ik})^2}{Z_{jj} + Z_{kk} - 2Z_{jk} + Z_P} = \frac{C_2}{C_1 + Z_P} \quad (4)$$

The fault current deviation at a bus after FCL is fired up can be written as

$$\Delta I_{i,F} = \frac{V_i}{Z_{ii} + \Delta Z_{ii}} - \frac{V_i}{Z_{ii}} \quad (5)$$

Substituting (4) into (5), (5) can be rewritten as

$$\Delta I_{i,F} = -\frac{V_i}{Z_{ii}} \frac{C_2}{(C_1 + Z_P)Z_{ii} + C_2} \quad (6)$$

If the FCL is used to constrain the fault current from original $I_{i,N}$ to $I_{i,F}$, then $Z_P$ required can be easily calculated by (6) and expressed as [7]

$$Z_P = \frac{I_{i,F}}{I_{i,N} - I_{i,F}} \frac{C_2}{Z_{ii}} - C_1 \quad (7)$$

Substituting (7) into (3), the FCL impedance required is

$$Z_{FCL} = -\frac{Z^2}{Z + Z_P} \quad (8)$$

## III. Problem Formulation

If the location for FCL placement has been decided, the FCL impedance required to constrain the fault current to acceptable level could be easily calculated by (8). However, in a large power system, it could be difficult to determine optimal number, locations and FCL parameters when fault currents calculated at several locations are approaching and/or have exceeded the ratings of existing CBs. Therefore, the objective is to find a minimum number of FCLs and/or the smallest circuit FCL parameters that are more economical while keeping fault currents within CBs' ratings. The problem can be formulated as follows:

$$\min \ J = \sum_{i=1}^{N_{FCL}} Z_{i,FCL} + w_{FCL} * N \quad (9a)$$

$$s.t.$$

$$Z_{i,FCL}^{\min} \le Z_{i,FCL} \le Z_{i,FCL}^{\max} \quad i = 1 \cdots N_{FCL} \quad (9b)$$

$$I_j^{sc} \le I_j^{sc,\max} \quad j = 1 \cdots B_N$$

where $Z_{i,FCL}$ is the impedance of the *i*-th FCL. $N_{FCL}$ is the number of installed FCL. $w_{FCL}$ is the weighting factor for trading off between the number of required FCL and the summation of circuit parameters of FCLs. $w_{FCL}$ is used to make sure that the minimum numbers of FCL can be achieved. $Z_{i,FCL}^{\min}$ and $Z_{i,FCL}^{\max}$ are the minimum and maximum impedance allowable for the *i*-th FCL, respectively. $I_j^{sc}$ and $I_j^{sc,\max}$ is the short-circuit current and maximum allowable CB rating for bus *j*, respectively. $B_N$ is the number of buses that have dangerous fault current levels.

To minimize the solution time, in this paper, a sensitivity analysis technique is used to find the better candidate locations for FCL placement. Eqs. (3)-(5) are used to build the sensitivity relation of bus fault current reductions with respect to FCL impedance addition. For a FCL with impedance $Z_{FCL}^{sa}$ that is added to branch $l$ between bus $j$ and $k$, the fault current reduction for each bus after the FCL is activated can be expressed in vector form as

$$\Delta \mathbf{I}_F^l = \left[\Delta I_F^l \quad \Delta I_F^l \quad \cdots \quad \Delta I_{F,N_B-1}^l \quad \Delta I_{F,N_B}^l\right] \tag{10}$$

where $N_B$ is the number of bus in the power system. It is assumed that $Z_{FCL}^{sa}$ is 1.0 p.u. in the following derivation.

From (10), for each bus, the largest bus fault current reductions achieved due to branch impedance changes can be obtained. If only $N_F^C$ buses are required for fault level mitigation, buses are arranged into a vector based on decreasing order of the fault current level reduction and expressed as

$$\begin{aligned}\mathbf{S}_F^l = [&(\Delta I_{F,1}^l, BN(1)) \quad (\Delta I_{F,2}^l, BN(2)) \quad \cdots \\ &(\Delta I_{F,N_F^c-1}^l, BN(N_F^C-1)) \quad (\Delta I_{F,N_F^c}^l, BN(N_F^C))]\end{aligned} \tag{11}$$

where $BN(i)$ is the bus number for the $i$-th largest short-circuit current reduction. $\Delta I_{F,i}^l$ is the current reduction due to impedance change at branch $l$. Therefore, the sensitivity matrix between FCL placement and bus fault current reduction can be expressed as

$$\mathbf{S}_F = \left[\mathbf{S}_F^1 \quad \mathbf{S}_F^2 \quad \cdots \quad \mathbf{S}_F^{N_L-1} \quad \mathbf{S}_F^{N_L}\right]^T \tag{12}$$

where $N_L$ is the number of line in the power system. The best candidate locations for FCL placement can be sought for by using $\mathbf{S}_F$.

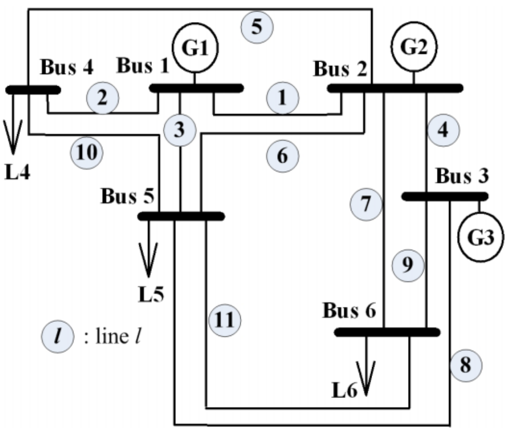


Fig. 3: A six-bus test system [15]

Using the six-bus system shown in Fig. 3 as an example [15], the $\mathbf{S}_F$ is shown in (13), in this case $N_F^C$ is 3. From (13), for example, if bus 2 fault current has exceeded CB rating, then it can be found that line 5 is the best location to install FCL. If the system planner intends to find two candidate locations for bus 2, then line 5 and line 7 are better choices for FCL placement.

$$\mathbf{S}_F = \begin{bmatrix} (0.298,1) & (0.042,2) & (0.013,4) \\ (0.292.1) & (0.091,4) & (0.020,5) \\ (0.197,1) & (0.063,5) & (0.035,4) \\ (0.176,3) & (0.132,2) & (0.046,4) \\ (0.541,4) & (0.257,2) & (0.055,6) \\ (0.101,5) & (0.080,2) & (0.010,4) \\ (0.225,6) & (0.186,2) & (0.066,4) \\ (0.147,3) & (0.138,5) & (0.018,6) \\ (0.490,3) & (0.422,6) & (0.001,5) \\ (0.076,4) & (0.060,5) & (0.005,2) \\ (0.120,5) & (0.118,6) & (0.012,3) \end{bmatrix} \begin{matrix} l \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \end{matrix} \tag{13}$$

For a large loop power system the problem formulation becomes a combinatorial constrained problem with a non-linear and non-differential objective function. In this study a genetic algorithm (GA) is used to solve the problem. Main steps of the GA used in this study are:

1. Coding: representing the problem by bit strings. Each possible parameters and candidate locations for FCL placement needs to be integrated into each population. For each candidate location, the FCL parameters or types should be coded. For example, if we have six types of FCL that are available in the market; three bits can be used to code FCL type choices. In this case, "000" means no FCL will be installed in this location and "111" has no meaning. FCL parameters are also coded. If maximum available parameter for FCL is $Z_{FCL}^{\max}$ and the variation between two adjacent parameter is $\Delta Z_{FCL}$, the relation between $Z_{FCL}^{\max}$ and $\Delta Z_{FCL}$ can be expressed as

$$\Delta Z_{FCL} = \frac{Z_{FCL}^{\max}}{2^n - 1} \tag{14}$$

   $n$ bits can be used to code FCL parameters.

2. Initialization: initializing the population. GA operates with a set of populations. The populations go through the process of evaluation to produce new generation. To begin with, the initial populations could be seeded with heuristically chosen strings or at random. In our test systems, all initial populations are randomly generated.

3. Evaluation: determining which population is better and deciding who mates. The evaluation is a procedure to determine the fitness value of each population and is very much application oriented. Since the GA proceeds in the direction of better-fit strings and the fitness value is the only information available to the GA algorithm, the performance of the algorithm is highly sensitive to the fitness value. In the proposed

optimization problem, the fitness value is the objective function as described in (9). The fitness function with constraints can be expressed as

$$f = \sum_{i=1}^{N_{FCL}} Z_{i,FCL} + w_{FCL} * N + \sum_{i=1}^{N_{FCL}} K_{i,p} + \sum_{j=1}^{B_N} K_{j,q} \quad (15)$$

where $K_{i,p}$ and $K_{j,q}$ are the penalty values and are defined in (16).

$$\begin{aligned} & if\ \ Z_{i,FCL}^{\min} \le Z_{i,FCL} \le Z_{i,FCL}^{\max} \\ & then\ \ K_{i,p} = 0 \\ & else\ \ K_{i,p} = 500 \\ & if\ \ I_j^{sc} \le I_i^{sc,\max} \\ & then\ \ K_{j,q} = 0 \\ & else\ \ K_{j,q} = 1000 \end{aligned} \quad (16)$$

4. Crossover: exchanging information between two mates. Mating is a probabilistic selection process in which populations are selected to produce offspring based on their fitness values. Populations with high fitness values should have a higher probability of generating offspring and are simply copied into the next generation.

5. Mutation: integrating random information into GA. Mutation is the process of randomly modifying the value of a string position with a small probability. It ensures that the probability of searching any region in the problem space is never zero and prevents complete loss of genetic material through mate and crossover.

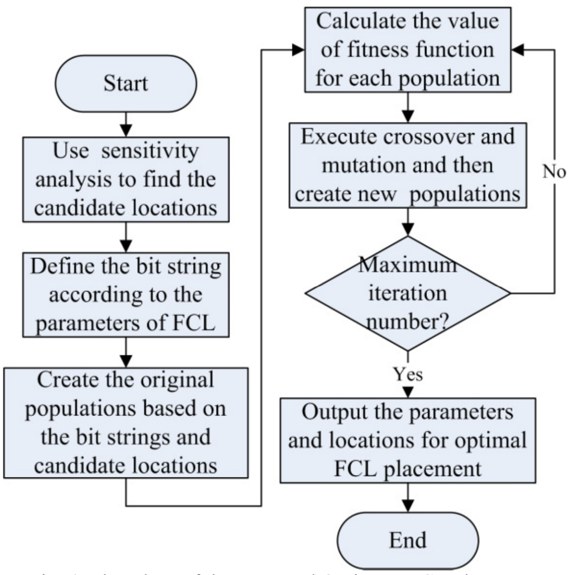


Fig. 4: Flowchart of the Proposed Optimum FCL Placement

Genetic parameters are the entities that help to tune the performance of the FCL placement. The following parameters are used in this study:

- Population Size: 190
- Crossover Rate: 0.5
- Mutation Rate: 0.05

Fig. 4 shows the flowchart of the proposed procedure.

## IV. Test Results

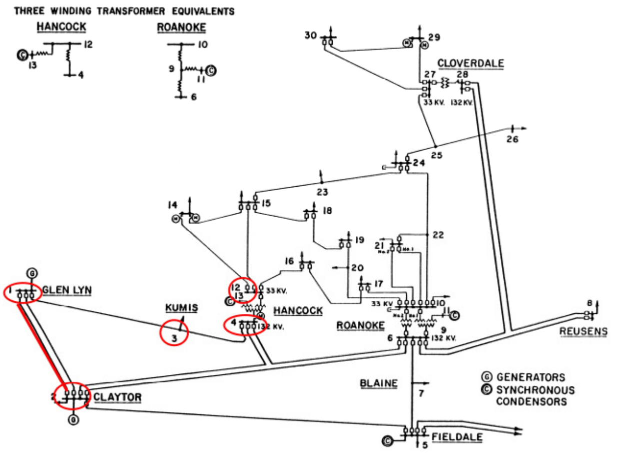


Fig. 5: The IEEE 30-bus Test System [18]

The proposed algorithm was implemented with Borland C++ on a Windows based PC. IEEE 30-bus [18] as shown in Fig. 5 is used in the following tests. The line data for IEEE 30-bus test system is listed in the Appendix; other data used in the test can be found in [18]. The S/N transition-type superconducting FCLs are used in the following test. Using the proposed sensitivity technique, $\mathbf{S}_F$ can be built and Table 1 shows the bus numbers correspond to entries in $\mathbf{S}_F$. In this case $N_F^C$ is 5. From Table 1, it can be seen that if a FCL is installed in line 1, then the five largest bus fault current reductions in decreasing order are at buses 1, 3, 2, 4 and 12. These buses are marked in Fig. 5. Thus, the candidate locations for FCL placement can be arranged and is shown in Table 2. Using the information shown in Table 2, if the bus 16 fault current exceeds or near its CB rating; good locations for installing FCL in order to constrain the bus fault current would be at line 19, 21 and 26.

Table 1: Bus Number of $\mathbf{S}_F$ while $N_F^C$ is 3

| Line Number | Bus Number | | | | |
|---|---|---|---|---|---|
| 1 | 1 | 3 | 2 | 4 | 12 |
| 2 | 1 | 3 | 2 | 4 | 12 |
| 3 | 2 | 4 | 1 | 3 | 6 |
| 4 | 3 | 1 | 4 | 2 | 6 |
| 5 | 5 | 2 | 1 | 4 | 3 |
| 6 | 2 | 6 | 1 | 8 | 28 |
| 7 | 4 | 3 | 6 | 8 | 28 |
| 8 | 5 | 7 | 6 | 8 | 28 |
| 9 | 7 | 6 | 5 | 8 | 28 |
| 10 | 8 | 28 | 27 | 6 | 4 |
| 11 | 9 | 10 | 6 | 11 | 21 |
| 12 | 10 | 21 | 22 | 6 | 17 |
| 13 | 11 | 9 | 10 | 6 | 4 |
| 14 | 9 | 10 | 21 | 22 | 11 |
| 15 | 12 | 4 | 15 | 3 | 13 |
| 16 | 13 | 12 | 15 | 4 | 6 |
| 17 | 14 | 15 | 12 | 13 | 23 |
| 18 | 15 | 12 | 23 | 18 | 19 |
| 19 | 16 | 17 | 12 | 10 | 13 |
| 20 | 14 | 15 | 23 | 18 | 19 |

| | | | | | |
|---|---|---|---|---|---|
| 21 | 16 | 17 | 12 | 10 | 21 |
| 22 | 18 | 19 | 20 | 15 | 12 |
| 23 | 18 | 19 | 20 | 15 | 12 |
| 24 | 19 | 20 | 18 | 10 | 15 |
| 25 | 20 | 19 | 18 | 10 | 21 |
| 26 | 17 | 16 | 10 | 21 | 22 |
| 27 | 21 | 22 | 24 | 10 | 17 |
| 28 | 22 | 21 | 24 | 10 | 17 |
| 29 | 22 | 21 | 24 | 23 | 25 |
| 30 | 23 | 24 | 15 | 12 | 14 |
| 31 | 24 | 22 | 21 | 10 | 23 |
| 32 | 23 | 24 | 15 | 12 | 22 |
| 33 | 25 | 27 | 24 | 26 | 29 |
| 34 | 26 | 25 | 27 | 24 | 6 |
| 35 | 25 | 27 | 24 | 26 | 29 |
| 36 | 27 | 25 | 29 | 30 | 28 |
| 37 | 29 | 30 | 27 | 6 | 28 |
| 38 | 30 | 29 | 27 | 6 | 28 |
| 39 | 30 | 29 | 27 | 6 | 28 |
| 40 | 28 | 8 | 27 | 25 | 29 |
| 41 | 28 | 27 | 25 | 29 | 30 |

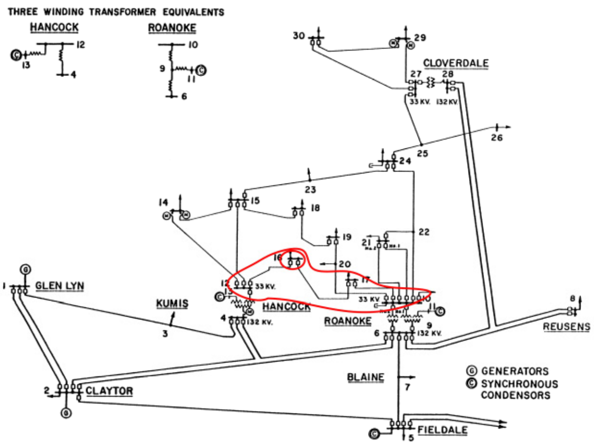


Fig. 6: The Candidate Locations for Bus 16

Table 2: The Candidate Locations for FCL Placement

| Bus Number | Candidate Locations (Line Number) |
|---|---|
| 1 | 1,2,3,4,5,6 |
| 2 | 1,2,3,4,5,6 |
| 3 | 1,2,3,4,5,7,15 |
| 4 | 1,2,3,4,5,7,10,13,15,16 |
| 5 | 5,8,9 |
| 6 | 3,4,6,7,8,9,10,11,12,13,16,34,37,38,39 |
| 7 | 8,9 |
| 8 | 6,7,8,9,10,40 |
| 9 | 11,13,14 |
| 10 | 11,12,13,14,19,21,24,25,26,27,28,31 |
| 11 | 11,13,14 |
| 12 | 1,2,15,16,17,18,19,21,22,23,30,32 |
| 13 | 15,16,17,19 |
| 14 | 17,20,30 |
| 15 | 15,16,17,18,20,22,23,24,30,32 |
| 16 | 19,21,26 |
| 17 | 12,19,21,26,27,28 |
| 18 | 18,20,22,23,24,25 |
| 19 | 18,20,22,23,24,25 |
| 20 | 22,23,24,25 |
| 21 | 11,12,14,21,25,26,27,28,29,31 |
| 22 | 12,14,26,27,28,29,31,32 |
| 23 | 17,18,20,29,30,31,32 |
| 24 | 27,28,29,30,31,32,33,34,35 |
| 25 | 29,33,34,35,36,40,41 |
| 26 | 33,34,35 |
| 27 | 10,33,34,35,36,37,38,39,40,41 |
| 28 | 6,7,8,9,10,36,37,38,39,40,41 |
| 29 | 33,35,36,37,38,39,40,41 |
| 30 | 36,37,38,39,41 |

To show the effectiveness of the proposed method for solving more complex problems, in the following example, three buses fault currents already exceed their CB ratings, they are

- Bus 10 with short-circuit current 10.11551kA;
- Bus 11 with short-circuit current 15.82295kA;
- Bus 13 with short-circuit current 19.99105kA.

The CB rating in this test case is assumed to be 10 kA. From Table 2, the candidate locations for FCL placement are

- for bus 10, good candidate locations are lines 11, 12, 13, 14, 19, 21, 24, 25, 26, 27, 28, 31;
- for bus 11, good candidate locations are lines 11, 13, 14; and
- for bus 13 good candidate locations are lines 15, 16, 17, 19.

With the help from sensitivity analysis the total number of candidate location is reduced from 41 to 15. This minimizes the computational efforts in searching for optimal locations and FCL parameters to resolve simultaneously the fault current problems at buses 10, 11 and 13.

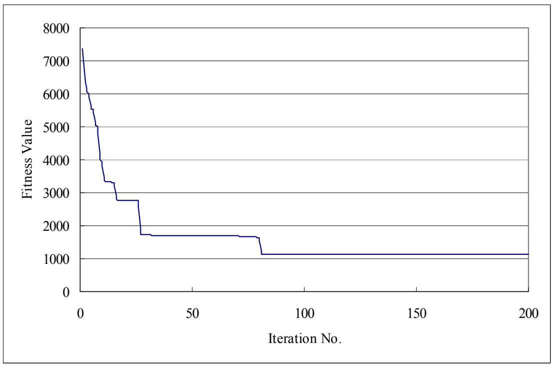


Fig. 7: Fitness Value for Each Iteration

Fig. 7 shows the fitness value variations of GA iterations. The optimal solution obtained for this case is

- A FCL with an impedance of 0.400 p.u. should be installed on line 13;
- A FCL with an impedance of 0.800 p.u. should be installed on line 16.

The short-circuit currents at buses 10, 11 and 13 after FCLs installations are reduced to 9.75256kA, 9.81937kA and 9.78321kA, respectively. Note that only two FCLs are required to suppress fault currents at three buses. Using the proposed GA technique to solve the optimization problem, the computational times required when with and without the proposed sensitivity analysis are 43s and 3599s, respectively.

## V. Conclusions and Discussions

The integration of FCLs into power system provides an effective way to suppress large fault currents and may bring to considerable reduction in investment on higher capacity CBs. For a large loop system, its effectiveness would depend on the proper choice of the impedance and location of FCL. Sensitivity analysis technique proposed in this paper was found effective in minimizing computational efforts for searching the optimal solution. Test results have demonstrated the efficiency and accuracy of the proposed method. It can be used to find the minimum number of FCLs and select the possible smallest circuit parameters of FCLs to ensure that bus fault currents are within CB interrupting ratings.

## VI. Appendix

Line Data of IEEE 30-Bus Test System

| Line Number | From Bus | End Bus |
|---|---|---|
| 1 | 1 | 2 |
| 2 | 1 | 3 |
| 3 | 2 | 4 |
| 4 | 3 | 4 |
| 5 | 2 | 5 |
| 6 | 2 | 6 |
| 7 | 4 | 6 |
| 8 | 5 | 7 |
| 9 | 6 | 7 |
| 10 | 6 | 8 |
| 11 | 6 | 9 |
| 12 | 6 | 10 |
| 13 | 9 | 11 |
| 14 | 9 | 10 |
| 15 | 4 | 12 |
| 16 | 12 | 13 |
| 17 | 12 | 14 |
| 18 | 12 | 15 |
| 19 | 12 | 16 |
| 20 | 14 | 15 |
| 21 | 16 | 17 |
| 22 | 15 | 18 |
| 23 | 18 | 19 |
| 24 | 19 | 20 |
| 25 | 10 | 20 |
| 26 | 10 | 17 |
| 27 | 10 | 21 |
| 28 | 10 | 22 |
| 29 | 21 | 22 |
| 30 | 15 | 23 |
| 31 | 22 | 24 |
| 32 | 23 | 24 |
| 33 | 24 | 25 |
| 34 | 25 | 26 |
| 35 | 25 | 27 |
| 36 | 27 | 28 |
| 37 | 27 | 29 |
| 38 | 27 | 30 |
| 39 | 29 | 30 |
| 40 | 8 | 28 |
| 41 | 6 | 28 |

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## VIII Biographies

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