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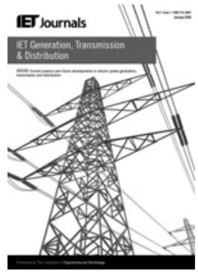

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Optimum fault current limiter placement with search space reduction technique

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Abstract: A fault occurring in power networks normally results in a large short-circuit current flow in the system, which may exceed the rating of existing circuit breakers and can damage system equipments. Because of 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 utilisation of fault current limiters (FCLs) in power systems could provide an effective way to suppress fault currents. In a loop transmission or distribution system, the advantages would greatly depend on the number and locations of FCL installations. The authors propose a method to determine the optimum number and locations for FCL placement in terms of installing smallest FCLs circuit parameters to restrain short-circuit currents under circuit breakers' interrupting ratings. In the proposed approach, the sensitivity factor, defined as the reduction of bus fault currents because of a given variation in the branch parameter, is derived and used to choose better candidates for active FCL installations. The search space for FCL installations can be reduced by using the proposed sensitivity factor calculation; therefore the computational efficiency and accuracy can be improved. A genetic-algorithm-based method is then designed to include the sensitivity information in searching for the best locations and parameters of FCLs. The test results demonstrate the efficiency and accuracy of the proposed method.

1 Introduction

With the increasing demand for power, electric power systems have become greater and are far more complicatedly interconnected than ever. As a result, faults in power networks may incur larger short-circuit currents flowing in the network and, in some cases, may exceed the ratings of existing circuit breakers (CBs) and damage system equipments, especially, for those with continuous growth in network size and electricity demand. Therefore generation units of independent power producers and renewable energy have been interconnected to power systems to support the rising demands. 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 keep the power systems operating in a higher degree of security and reliability, fault current limiters (FCLs), which can limit current prior to the first peak of short-circuit current, have the potential to be used in situations where insufficient fault current interrupting capability exists [1–16]. FCLs can be categorised into two types: passive and active. The commonly used passive FCLs are fault current limiting reactors. They limit the fault current by restricting the voltage drop across the terminals of FCL's reactor. The main drawback of passive FCL is that the fault current limiting reactor always causes voltage drop and power consumption even in normal operating conditions. Active FCL can be treated as 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 mechanisms such as those based on superconductor, power electronics, polymer positive temperature coefficient resistors and techniques of arc control have been introduced. Most active FCLs are not commercially available in the present day; however, researches show that they can be used in power systems in the foreseeing future. The possible reasons include higher investment cost, inadequate breaking current and voltage rating for high-voltage applications, impacts on the existing protective relaying and influences on stability, reliability and security of power system operation and so on. However, FCLs still have great potential to be used to mitigate short-circuit currents for bulky power systems, where insufficient CB rating exists in the near future [1–16].

Depending on the location of installation, active FCLs could offer other advantages such as (i) increasing the interconnection of renewable energy and independent power units; (ii) increasing the energy transmission capacity over longer distances; (iii) reducing the voltage sag caused by the fault; (iv) improving the system stability and (v) improving the system security and reliability. Although FCLs can offer many advantages, their advantages greatly depend on the number and locations of FCL placement. In radial transmission and distribution systems, the placement of FCLs is not difficult, but in loop transmission or distribution system, FCL placement becomes much more complex when more than one location 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 point of view, a technique that can choose optimum number and locations for active 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 [17]. References [18, 19] used a hierarchical genetic algorithm (GA) 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 number and locations for FCL placement. In the proposed approach, the sensitivity factor, defined as the reduction of bus fault currents due to a given variation in the branch parameter, is derived and used to choose better candidates for active FCL installations. The search space for FCL installations can be reduced by using the proposed sensitivity factor calculation; therefore, the computational efficiency and accuracy can be improved. A genetic-algorithm-based method is then designed to include the sensitivity information in searching for the best locations and parameters of FCLs. The test results demonstrate the efficiency and accuracy of the proposed method.

2 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

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

where I_i^{sc} is the three-phase short-circuit current at bus i and 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 and can be obtained from diagonal entries of the impedance matrix ($\boldsymbol{Z}_{\mathrm{bus}}$). I_{b} is the base current.

In $\boldsymbol{Z}_{\mathrm{bus}}$ building algorithm, when adding a line with impedance Z_{b} between buses j and k, the original element of Z_{xy} can be modified as [20]

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

where Z_{xy}^{new} and Z_{xy}, respectively, are the modified and original elements of $\boldsymbol{Z}_{\mathrm{bus}}$.

Fig. 1 shows the Thevenin equivalent circuit by looking into the system from two existing buses. If an FCL with impedance Z_{FCL} is installed on line between buses k and j and fired after the faults, then the Thevenin equivalent circuit as shown in Fig. 2 can be illustrated. Note that the S/N transition-type superconducting FCLs are used in the following derivation and test. 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

$$Z_{\mathrm{P}} = (-Z_{\mathrm{b}})//(Z_{\mathrm{b}} + Z_{\mathrm{FCL}}) = -\frac{Z_{\mathrm{b}}(Z_{\mathrm{b}} + Z_{\mathrm{FCL}})}{Z_{\mathrm{FCL}}} \qquad (3)$$

Therefore the modification to the diagonal entries of $\boldsymbol{Z}_{\mathrm{bus}}$ after the active FCL fired up at a branch between buses j and k is

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

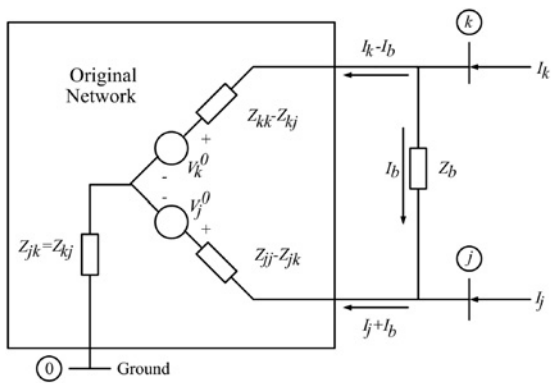

Figure 1 *Thevenin equivalent circuit by adding a line between two existing buses*

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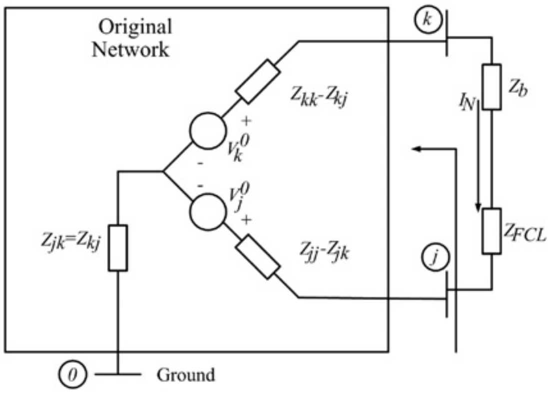

Figure 2 *Thevenin equivalent circuit with the FCL fired up*

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

$$\Delta I_{i,\mathrm{F}} = \frac{V_i}{Z_{ii} + \Delta Z_{ii}} - \frac{V_i}{Z_{ii}} \tag{5}$$

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

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

If the FCL is used to constrain the fault current from original $I_{i,\mathrm{N}}$ to $I_{i,\mathrm{F}}$, then Z_P required can be easily calculated by (6) and expressed as [17–19]

$$Z_\mathrm{P} = \frac{I_{i,\mathrm{F}}}{I_{i,\mathrm{N}} - I_{i,\mathrm{F}}} \frac{C_2}{Z_{ii}} - C_1 \tag{7}$$

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

$$Z_\mathrm{FCL} = -\frac{Z_\mathrm{b}^2}{Z_\mathrm{b} + Z_\mathrm{P}} \tag{8}$$

3 Sensitivity factor calculation

If the location for an FCL placement has been decided, the FCL impedance required to constrain the fault current to an acceptable level can be determined by (8). However, in a large power system, it would be difficult to determine optimal number, locations and parameters for FCLs when fault currents calculated at several locations are approaching and/or have exceeded the ratings of existing CBs. In order to reduce the search space and to minimise the solution time in finding the optimum FCL locations, a sensitivity factor calculation is first conducted to find better candidate locations for FCL placement. Commonly, the sensitivity factor can be treated as the relative variation of the result produced by a given variation of an input parameter. In this paper, the sensitivity factor is defined as the reduction of bus fault currents due to a given variation in the branch parameter. Equations (3)–(5) are used to build the sensitivity relation of bus fault current reductions with respect to active FCL impedance addition. For an active FCL with impedance $Z_\mathrm{FCL}^\mathrm{sa}$ that is added to branch l between buses j and k, the fault current reduction for each bus after the FCL is activated and can be expressed in vector form as

$$\Delta \boldsymbol{I}_\mathrm{F}^l = \begin{bmatrix} \Delta I_{\mathrm{F},1}^l & \Delta I_{\mathrm{F},2}^l & \cdots & \Delta I_{\mathrm{F},N_\mathrm{B}-1}^l & \Delta I_{\mathrm{F},N_\mathrm{B}}^l \end{bmatrix} \tag{9}$$

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

From (9), for each bus, the largest bus fault current reductions achieved because of 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 deviation and expressed as

$$\boldsymbol{S}_\mathrm{F}^l = [\,(\Delta I_{\mathrm{F},1}^l, \mathrm{BN}(1)) \quad (\Delta I_{F,2}^l, \mathrm{BN}(2)) \quad \cdots \quad (\Delta I_{\mathrm{F},N_\mathrm{F}^\mathrm{C}-1}^l, \mathrm{BN}(N_\mathrm{F}^\mathrm{C}-1)) \quad (\Delta I_{\mathrm{F},N_\mathrm{F}^\mathrm{C}}^l, \mathrm{BN}(N_\mathrm{F}^\mathrm{C}))\,] \tag{10}$$

where BN(i) is the bus number for the ith largest short-circuit current reduction. $\Delta I_{\mathrm{F},i}^l$ 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

$$\boldsymbol{S}_\mathrm{F} = \begin{bmatrix} \boldsymbol{S}_\mathrm{F}^1 & \boldsymbol{S}_\mathrm{F}^2 & \cdots & \boldsymbol{S}_\mathrm{F}^{N_\mathrm{L}-1} & \boldsymbol{S}_\mathrm{F}^{N_\mathrm{L}} \end{bmatrix}^\mathrm{T} \tag{11}$$

where N_L is the number of line in the power system.

The better candidate locations for FCL placement can then be sought by using $\boldsymbol{S}_\mathrm{F}$. Using the six-bus system shown in Fig. 3 as an example [15], the $\boldsymbol{S}_\mathrm{F}$ is obtained as

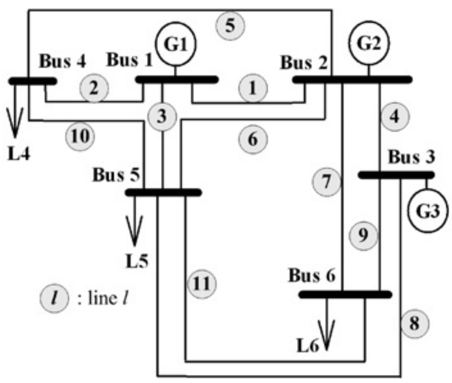

Figure 3 *Six-bus test system [15]*

in (12). In this case, N_F^C is 3.

$$S_F = \begin{bmatrix} (0.298, 1) & (0.042, 2) & (0.013, 4) \\ (0.292.1) & (0.091, 4) & (0.020, 5) \\ (0.197, 1) & (0.063, 5) & (0.035, 4) \\ (0.176, 3) & (0.132, 2) & (0.046, 4) \\ (0.541, 4) & (0.257, 2) & (0.055, 6) \\ (0.101, 5) & (0.080, 2) & (0.010, 4) \\ (0.225, 6) & (0.186, 2) & (0.066, 4) \\ (0.147, 3) & (0.138, 5) & (0.018, 6) \\ (0.490, 3) & (0.422, 6) & (0.001, 5) \\ (0.076, 4) & (0.060, 5) & (0.005, 2) \\ (0.120, 5) & (0.118, 6) & (0.012, 3) \end{bmatrix} \begin{matrix} l \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \end{matrix} \quad (12)$$

For example, if a fault current at bus 2 has exceeded its CB rating, then it implies that line 5 is the best location for FCL installation from (12). If the system planner intends to find two candidate locations for bus 2, then lines 5 and 7 are the better choices for FCL placement since these two lines take larger fault current reductions. Besides, if fault currents at buses 2 and 4 have exceeded their CB ratings and the planner intends to find two candidate locations for each bus, then lines 5 and 7, and lines 5 and 2 are the better locations for buses 2 and 4, respectively. The candidate locations should be lines 5, 7 and 2 sequentially; therefore the search space can be reduced and the computational performance can be improved consequently.

4 Problem formulation and solution procedure

The objective of this paper is to find a minimum number of active FCLs and/or the smallest FCL circuit parameters that are more economical while keeping fault currents within CBs' ratings. This problem is a multi-objective optimisation. It can be formulated by multi-objective weighting, utility function and Pareto factor and so on [21]. The multi-objective weighting approach is used in this paper and therefore the problem can be formulated as follows

$$\min J = \sum_{i=1}^{N_{FCL}} Z_{i,FCL} + w_{FCL} \times N \quad (13a)$$

s.t.

$$Z_{i,FCL}^{min} \le Z_{i,FCL} \le Z_{i,FCL}^{max} \quad i = 1 \cdots N_{FCL}$$
$$I_j^{sc} \le I_j^{sc,max} \quad j = 1 \cdots B_N \quad (13b)$$

where $Z_{i,FCL}$ is the impedance of the ith FCL, N_{FCL} is the number of installed FCL and 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 number of FCL can be achieved. $Z_{i,FCL}^{min}$ and $Z_{i,FCL}^{max}$ are the minimum and maximum impedance allowable for the ith active FCL, respectively. I_j^{sc} and $I_j^{sc,max}$ are the short-circuit current and maximum allowable CB rating for bus j, respectively. B_N is the number of buses that undergo dangerous fault current levels.

The objective function can also be modified to take into account the financial expenditure. For example, if only the installation cost of FCL placement is considered, then $Z_{i,FCL}$ represented in (13a) can be modified as $IC_{FCL}(Z_{i,FCL})$. The $IC_{FCL}(\bullet)$ is the installation cost function of FCL. Other constraints can be modified accordingly as well. After the modification, the proposed sensitivity factor calculation can also be applied to the FCL placement with financial expenditure problem, since the proposed sensitivity factor calculation would have already found the better candidates for FCL placement. Other constraints such as protective relay coordination and system stability and so on can also be considered in the computation by calculating the effects of each possible FCL placement on those constraints. If an FCL placement makes the constraints violated, then penalty factor can be used to punish the FCL placement. However, this paper emphasises on finding a minimum number of active FCLs and/or the smallest FCL circuit parameters; therefore the protective relay coordination and system stability constraints are not considered here.

For a loop system, the problem formulation becomes a combinatorial constrained problem with a non-linear and non-differential objective function. In this study, GA is used to solve the problem. Main steps of GA used in this study are as follows [21, 22]:

1. Coding: representing the problem by bit strings. Each possible parameter and candidate location for FCL placement needs to be integrated into each population. For each candidate location, the FCL parameters or types should be coded. Two coding categories according to available FCL types or available FCL parameters are proposed in this paper. For example, if we have six types of FCL that are available in the market, three bits are enough to code FCL type choices. In this case, '000' means no FCL will be installed in this location and '111' has no meaning. In the same way, FCL parameters can also be coded. Therefore different types of FCLs can also be coded and integrated into the proposed method. If maximum available parameter for active FCL is Z_{FCL}^{max} and the variation between two adjacent parameter is ΔZ_{FCL}, the relation between Z_{FCL}^{max} and ΔZ_{FCL} can be expressed as

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

where n is the bit number used to code the FCL parameters.

2. Initialisation: initialising 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

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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 which to mate. The evaluation is a procedure to determine the fitness value of each population and is very much application-oriented. Since 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 optimisation problem, the fitness value is the objective function as described in (13). The fitness function with constraints can be expressed as

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

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

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

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.

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
- Maximum iteration number: 200.

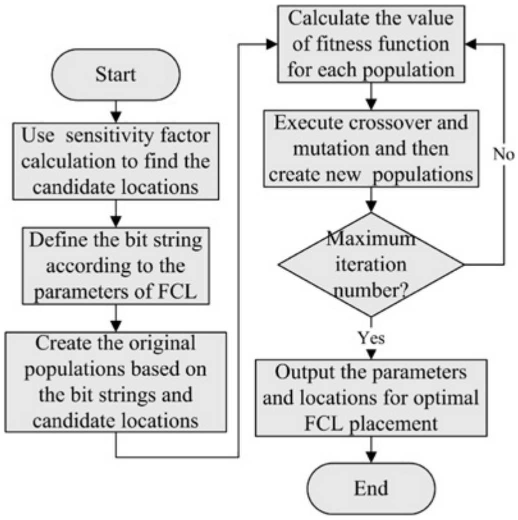

Figure 4 *Flowchart of the proposed optimum FCL placement*

Fig. 4 shows the flowchart of the proposed procedure.

5 Test results and discussions

The proposed algorithm was implemented with Borland C++ on a Windows-based PC. IEEE 30-bus [23], as shown in Fig. 5, is used in the following tests. The line data for IEEE 30-bus test system are listed in Appendix; other data used in the test can be found in [23]. Using the proposed sensitivity factor calculation, $\boldsymbol{S}_{\text{F}}$ can be built and Table 1 shows the bus number corresponding to entries in $\boldsymbol{S}_{\text{F}}$. In this case, N_{F}^{C} is 5. Table 1 shows that if an FCL is installed on 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 are shown in Table 2. Using the information shown in Table 2, if the fault current at bus 16, as shown in Fig. 6, exceeds or nears its CB rating, better locations for installing FCL to constrain the bus fault current would be at lines 19, 21 and 26.

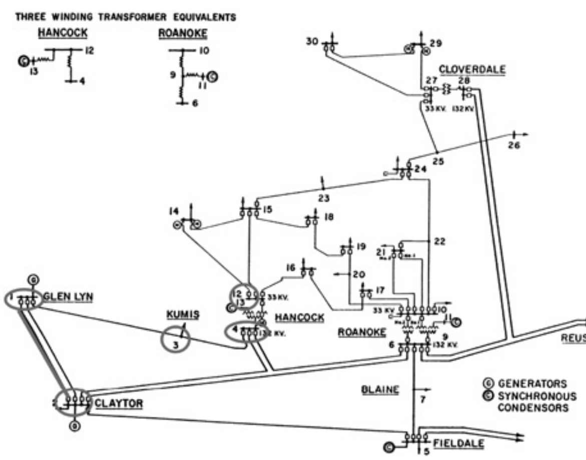

Figure 5 *IEEE 30-bus test system [24]*

Table 1 Bus number of $\boldsymbol{S}_F$ while N_F^C is 5

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

The CB rating in this test case is assumed to be 10 kA. The fault currents at six 33-kV buses already exceed their CB ratings. They are

- Bus 10 with short-circuit current 15.068 kA
- Bus 12 with short-circuit current 14.267 kA
- Bus 15 with short-circuit current 11.492 kA
- Bus 17 with short-circuit current 11.066 kA
- Bus 21 with short-circuit current 12.479 kA
- Bus 22 with short-circuit current 12.179 kA

If the candidate location for each bus is set as 5, then from Table 2, the candidate locations for each bus in decreasing sensitivity factor order are:

- For bus 10, candidate locations are lines 14, 26, 11, 27 and 25
- For bus 12, candidate locations are lines 15, 18, 16, 19 and 21
- For bus 15, candidate locations are lines 18, 15, 22, 30 and 23
- For bus 17, candidate locations are lines 26, 21, 19, 27 and 12
- For bus 21, candidate locations are lines 27, 29, 14, 31 and 28
- For bus 22, candidate locations are lines 29, 27, 28, 31 and 14.

The total candidate locations are lines 14, 26, 11, 27, 25, 15, 18, 16, 19, 21, 22, 30, 23, 12, 29, 31 and 28. With the help from sensitivity factor calculation, the total number of candidate location is reduced from 41 to 17. This minimises the computational efforts in searching for optimal locations and FCL parameters.

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Table 2 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

Fig. 7 shows the fitness value variations of GA iterations. The optimal solutions obtained for this case are as follows:

- An FCL with an impedance of 1.0 p.u. should be installed on line 14.

- An FCL with an impedance of 0.8 p.u. should be installed on line 26.

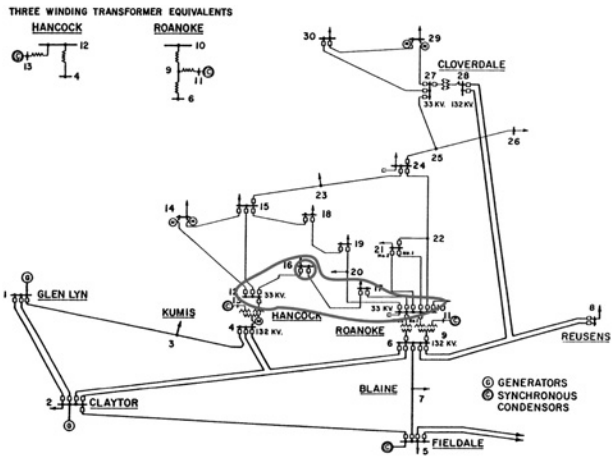

Figure 6 *Candidate locations for bus 16*

- An FCL with an impedance of 0.6 p.u. should be installed on line 15.

- An FCL with an impedance of 0.7 p.u. should be installed on line 16.

- An FCL with an impedance of 0.8 p.u. should be installed on line 12.

The short-circuit currents at buses 10, 12, 15, 17, 21 and 22 after the active FCL installations are reduced to 9.995, 9.956, 9.666, 5.304, 9.483 and 9.396 kA, respectively. Note that only five FCLs are required to suppress fault currents at six buses. The computational times required with and without the proposed sensitivity factor calculation are 53 and 1599 s, respectively. The computational time without the proposed sensitivity factor calculation is tremendous, since the search space becomes larger and the maximum iteration number will be increased accordingly in order to find the same solution.

To further clarify the number of candidate location based on the performance of the proposed method, 100 runs for the different number of candidate location for bus exceeding its CB rating are conducted. The number of

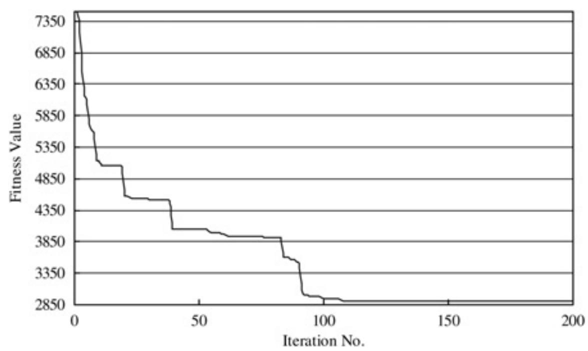

Figure 7 *Best fitness value for each iteration*

Table 3 Different number of candidate locations based on the performance of the proposed method

No. of candidate location[a]	Fitness value			
	AVG	MAX	MIN	St_De
5	3191	4020	2890	327.9
6	3228	4090	2890	333.8
7	3237	4190	2890	341.8
8	3385	4200	2890	363.1
9	3480	4260	2900	375.3
10	3676	4510	2930	409.1

[a]Number of candidate locations means the number of candidate locations for bus that exceeded its CB rating

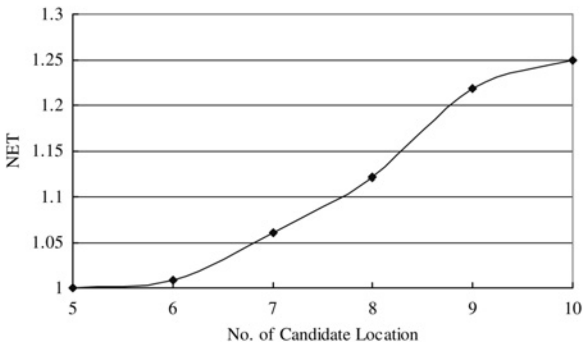

Figure 8 *Normalised execution time for different number of candidate location*

candidate location is changed from 5 to 10. Table 3 shows the fitness values with respect to different number of candidate location. AVG, MAX, MIN and St_De shown in Table 3 denote the average, maximum, minimum and standard derivation of the 100 runs. It can be seen that the smaller number of candidate location has better results and smaller standard derivations. It means that the smaller number of candidate location has higher probability to find the best solutions. Besides, if the maximum iteration number is 200, then the larger number of candidate location, for example 9 and 10, cannot find the optimal solution in the 100 runs. Fig. 8 shows the normalised execution time for the different number of candidate location. Fig. 8 shows that smaller number of candidate location has better solution efficiency. From the test results shown above, the efficiency and accuracy of the proposed method can be demonstrated. Note that after the optimum number and locations of FCL are solved, other issues including the transient recovery voltages and impacts on existing protective relaying, power system stability, security and so on should all be investigated to make sure that the FCL placement can still substantiate the safe and effective operation of power system.

6 Conclusions

The integration of FCLs into a power system may provide an effective way of suppressing large fault currents and brings about considerable reduction in investment on higher capacity CBs. For a large loop system, its effectiveness would greatly depend on the proper choice of the impedance and location of FCLs. The proposed method can be used to find the minimum number of active FCLs and select the possible smallest circuit parameters to ensure that bus fault currents are within CB interrupting ratings. A sensitivity factor calculation was proposed in this paper to find better candidate locations for FCL placement. With the sensitivity factor calculation, the search space for FCL installations can be reduced and the efforts for searching the optimal solution can be minimised consequently. The test results demonstrated the efficiency and accuracy of the proposed method. Other issues including the integration of the power system stability and existing protective relaying into the proposed method and the utilisation of the proposed sensitivity factor calculation for other artificial intelligent algorithms and multi-objective optimisation approaches will be discussed in the future research.

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9 Appendix: line data for IEEE 30-bus test system are shown in Table 4

Table 4 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

Continued

Table 4 *Continued*

Line number	From bus	End bus
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

Continued

Table 4 *Continued*

Line number	From bus	End bus
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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