Paper

Allocation and Circuit Parameter Design of Superconducting Fault Current Limiters in Loop Power System by a Genetic Algorithm

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In near future, many Independent Power Producers (IPPs) will participate in power generations according to their own strategic contracts by the deregulation. Loop or mesh systems can be designed to balance the power flow and to regulate the voltage resulting to the flexibility of power system operation, improvement of reliability and economical efficiency. Nevertheless, they bring to the problem of increased fault levels which may raise beyond the withstand capability of existing circuit breakers in the power systems. Short-circuit current is strongly related to the cost of apparatus and the effective use of power transmissions. Therefore, the introduction of Superconducting Fault Current Limiters (SFCLs) becomes an effective way for suppressing such a large short-circuit current. In this paper, first the authors evaluate the behavior of the S/N transition-type SFCL by considering the sub-transient and transient effects of generators in order to obtain smaller SFCL circuit parameters, i.e. the resistance of the superconducting coil and the reactance of the current-limiting inductor. Then the authors propose a method by using a hierarchical genetic algorithm (HGA) combined with a micro-genetic algorithm (micro-GA) to search for the optimal locations and the smallest SFCL circuit parameters simultaneously. The flexibility in defining the required objective function by using the proposed method makes it possible to evaluate the requirement of SFCLs in large power systems. Analysis by computer simulation has been carried out in an example loop power system.

Keywords: genetic algorithm, hierarchical genetic algorithm (HGA), loop power system, micro-genetic algorithm (micro-GA), superconducting fault current limiter (SFCL)

1. Introduction

With the premise that transmission system loading will continue to increase driven to a significant extent by the deregulation of the electricity industry, the trend will be toward to fully exploit the inherent capabilities of transmission networks. Many Independent Power Producers (IPPs), in near future, will be connected to power systems to meet the challenge of supplying the rising demand with minimization of operating cost while keeping systems with increased security and reliability as of paramount importance and the premiere objective. The benefit of using loop or mesh power system configurations and series compensation of transmission lines to balance the power flow, to regulate the voltage, to improve the reliability and economical efficiency has been recognized for many years (1). It has been shown that loop power flow control by series controllable reactances can contribute to the cost reduction of power flow management in deregulated power markets (2). However, with an increasing number of participants in power markets and the pace of series compensation of transmission lines, the existing installation of power system apparatus may no longer cope with the increased short-circuit current level. A possible option to combat the increased fault is to adapt new technologies as high-temperature superconducting equipment. Among them, Superconducting Fault Current Limiters (SFCLs) are attractive because they bring benefits such as a fast limiting the large short-circuit current without sensors and no effects to the system during normal power system operation making it easy to realize in power system operation and planning. Since short-circuit current is strongly related to the cost of apparatus and the effective use of power transmissions, the introduction of SFLCs into power systems may bring to the considerable reduction of investment cost for high capacity circuit breakers and construction for upgrade systems (3)~(5).

In a radial system, SFCL location is easily assigned. In a loop power system, SFCL location selection becomes much more complex when the number of fault location is large and faults are widespread throughout the system. Particular to a loop power system, when a fault occurs in a system, short-circuit currents may come from many directions and are not easily blocked by one SFCL in one area. In addition, the magnitude of large short-circuit currents and flow directions may be changed dependent of power flow conditions. These issues might be solved by using more than one SFCL to protect the

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installations. It is emphasized that the requirement of more than one SFCL in power system networks depends on specific network requirements such as safety margins of the electric system, ability of equipment to sustain fault currents, new functional capabilities of networks and restricted networks of interconnections and links.

From the power system operation and planning viewpoints, it is important to develop a method that should be flexible to determine the suitable location and to select economical circuit parameters of SFCLs, i.e. the resistance value of the superconducting coil and the reactance value of the current-limiting inductor. A preliminary bibliographical survey showed that only a few studies have been done to identify suitable SFCL locations in large and mesh power systems. For instance, in Ref. (6), a method to select suitable locations of rectifier-type SFCLs in a large-scale power system was proposed. This method is based on required equivalent impedances of SFCLs to reduce fault currents. The SFCL configuration obtained by that method is not optimal and does not consider other loading conditions. In addition, the equivalent impedance of SFCL is assumed to have only reactances for a simplification.

In this paper, first the authors evaluate the behavior of the S/N transition-type SFCL by taking the subtransient and transient effects of generators into account in order to obtain smaller circuit parameters of SFCL which should be associated with the reduction of SFCL cost. Based on this concept, then the authors propose a method by using a hierarchical genetic algorithm (HGA) idea combined with a micro genetic algorithm (micro-GA) to simultaneously search for the optimal location and the smallest SFCL circuit parameters. The evolution of better solutions by the proposed GA evaluates from how good or bad the solution is, not depending on how to solve or get those solutions directly. Therefore, the main algorithm of the proposed method can be kept the same while the objective function can be varied in different styles depending on the purpose of designers. The proposed method is flexible from the viewpoint of its easiness in modifying the objective function to make it suitable for a given problem. With the proposed approach, the flexibility in defining the required objective function, which might include short-circuit current calculations obtained from any kind of faults, makes it possible to evaluate the requirement of SFCLs in power systems. To demonstrate the idea of the proposed method and to simplify the study, in this paper, the authors have studied an example to find the most effective solution on improvement of the short-circuit current limitation during three-phase to ground fault, taking 5 fault points that have the problem of increased fault levels into account in an example loop power system. The efficiency and effectiveness of the proposed method are shown by numerical examples.

2. Loop Power System and Short Circuit Current

The model loop power system shown in Fig. 1 is used to investigate the requirement of SFCLs in a power system. This system was modified from the data in Ref. (2) by putting generators, transformers and adding three loading conditions. The generator, transformer and load data are shown in Table 1, Table 2 and Table 3 respectively. Two IPPs are installed in the system at bus 110 and 130 to supply for new loads at bus 9 and bus 16

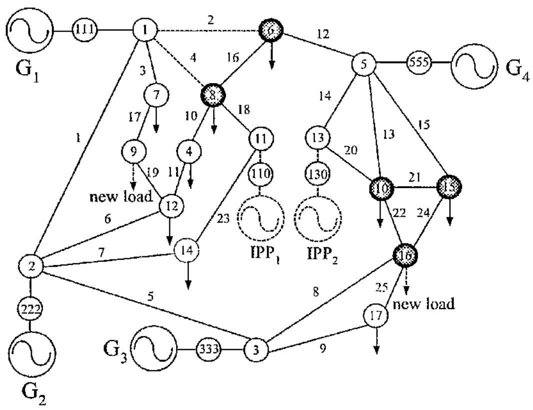


Fig. 1. Configuration of study loop power system

Table 1. Generator data (100 MVA base, 138 kV base)

	G_1	G_2	G_3	G_4	IPP_1	IPP_2
X_d pu	0.5576	0.5807	0.3955	0.4774	2.3600	0.9077
X'_d pu	0.1040	0.1083	0.0737	0.0890	0.4400	0.1692
X''_d pu	0.0685	0.0714	0.0486	0.0587	0.0290	0.1115
X_q pu	0.4961	0.5167	0.3519	0.4248	2.1000	0.8077
X'_q pu	0.1796	0.1870	0.1274	0.1537	0.7600	0.2923
X''_q pu	0.0685	0.0714	0.0486	0.0587	0.0290	0.1115
T'_{do} sec	4.800	4.800	4.700	4.750	7.000	5.150
T''_{do} sec	0.038	0.038	0.037	0.0375	0.043	0.0395
T'_{qo} sec	0.770	0.770	0.750	0.760	0.900	0.785
T''_{qo} sec	0.092	0.092	0.090	0.091	0.135	0.047
H sec	8.45	8.15	10.00	9.90	2.00	5.20

Table 2. Transformer data (100 MVA base, 138 kV base)

Bus no.		R (pu)	X (pu)	Tap
From	To			
111	1	0.00	0.01	1.00
222	2	0.00	0.01	1.00
333	3	0.00	0.01	1.00
555	5	0.00	0.01	1.00
110	11	0.00	0.01	1.00
130	13	0.00	0.01	1.00

Table 3. Load data (100 MVA base, 138 kV base)

Bus no.	Nominal	Heavy	Light
4	1.2+j0.3	1.80+j0.45	0.72+j0.15
6	0.9+j0.3	1.35+j0.45	0.45+j0.15
7	0.5+j0.3	0.90+j0.45	0.25+j0.15
8	0.6+j0.3	0.96+j0.45	0.36+j0.18
9	1.0+j0.3	1.50+j0.45	0.50+j0.15
10	0.6+j0.3	2.40+j0.45	0.80+j0.15
12	0.4+j0.1	0.64+j0.16	0.16+j0.04
14	0.5+j0.3	0.75+j0.45	0.25+j0.15
15	0.5+j0.3	0.75+j0.45	0.25+j0.15
16	2.8+j0.3	4.48+j0.45	1.40+j0.15
17	1.0+j0.3	1.60+j0.48	0.40+j0.18

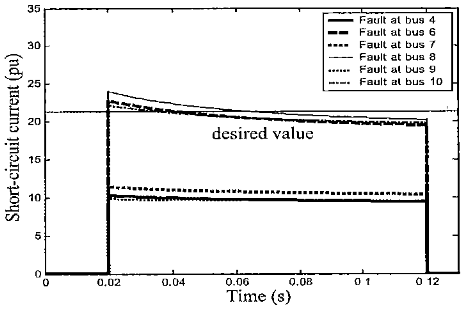


Fig. 2. Short-circuit currents at bus 4, 6, 7, 8, 9 and 10 before installing IPPs and new loads

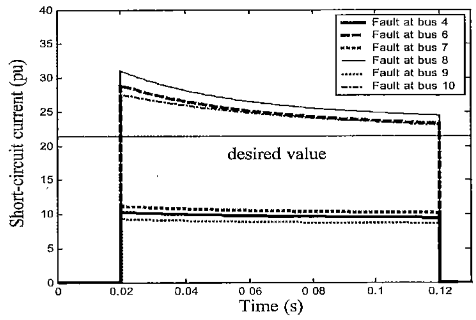


Fig. 4. Short-circuit currents at bus 4, 6, 7, 8, 9 and 10 after installing IPPs and new loads

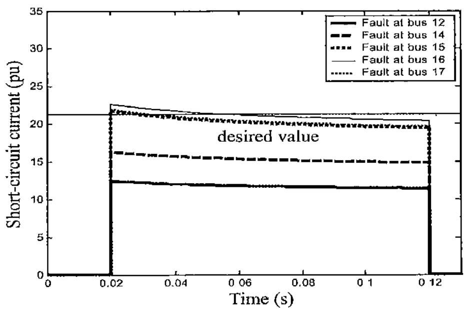


Fig. 3. Short-circuit currents at bus 12, 14, 15, 16 and 17 before installing IPPs and new loads

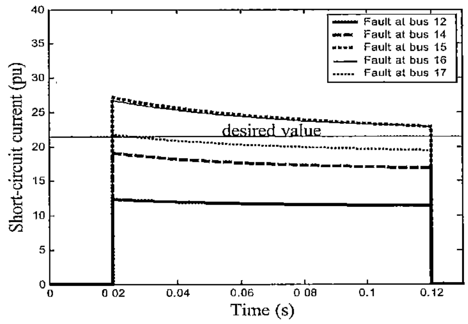


Fig. 5. Short-circuit currents at bus 12, 14, 15, 16 and 17 after installing IPPs and new loads

respectively. An increasing number of participants both generators and loads will lead to the widespread increasing of short-circuit currents, which may be higher than the circuit breaker ability to interrupt the short-circuit currents, in a loop power system. The complete replacement of existing circuit breakers with very high capacity ones would be infeasible because proper circuit breakers could not be mass products, besides the high purchasing, the difficulties in finding spare parts and high installation costs of the new circuit breakers. There is yet another solution using a bus separating method. This method seems to be a practical one, however, it is not only the high expense to rebuild or upgrade each substation, bus also a lot of difficulty issues such as coordination in the protection scheme for loop systems and construction time. Thus, the present work aims at an alternative solution concerning the use of SFCLs in a proper combination and the use of an optimization tool to assign the suitable location and to select the suitable circuit parameters of SFCLs, i.e. the resistance of the superconducting coil and the reactance of the current-limiting inductor, in order to limit the short-circuit currents in the most economical way.

As a matter of fact, during the fault period by large short-circuit currents, energy is transferred to the zones of electrical contacts. One may encounter severe wielding phenomena which may be able to put the apparatus out of use or the effects of strong dynamic force due to the large short-circuit currents which may cause a permanent fault in the power system if the short-circuit current reaches the value much higher than the circuit breaker capacity since the contacts cannot be opened. Therefore, in this study, the authors pay attention to the amount of short-circuit currents which must be lower than the withstand capability of the circuit breaker at the time when fault can be cleared.

The problem of increased level of short-circuit currents can be seen in the following example. Here, the short-circuit currents at all buses need to be kept under 21.5 pu which is the desired level of the short-circuit current for the design purpose. When a three-phase to ground fault is applied to each bus for 100 ms period, the short-circuit current is evaluated for each condition. Fig. 2 and Fig. 3 illustrate the result of short-circuit current calculations at nominal condition in case of no IPPs and new loads in the system. It was found that the short-circuit currents were lower than the desired level of the short-circuit current meaning that the circuit breaker can be operated without failures. After new power generators of IPP_1 and IPP_2 and new loads were connected to the system, the results in Fig. 4 and Fig. 5 show that short-circuit currents at bus 6, bus 8, bus 10, bus 15 and bus 16 as indicated by the gray color in Fig. 1 exceeded the maximum limit of desired level. The situation becomes much more difficult since the short-circuit currents can flow from many directions.

3. Modeling of S/N Transition-type Superconducting Fault Current Limiter

3.1 Basic Structure Fig. 6 shows the basic structure and impedance characteristic of the S/N transition-type superconducting fault current limiter used in this paper. The SFCL consists of a non-inductive superconducting coil for each phase housed in a tank containing the coolant such as the liquid helium for low-temperature superconductors or the liquid nitrogen for high-temperature superconductors and a current-limiting inductor. In this study, a current-limiting

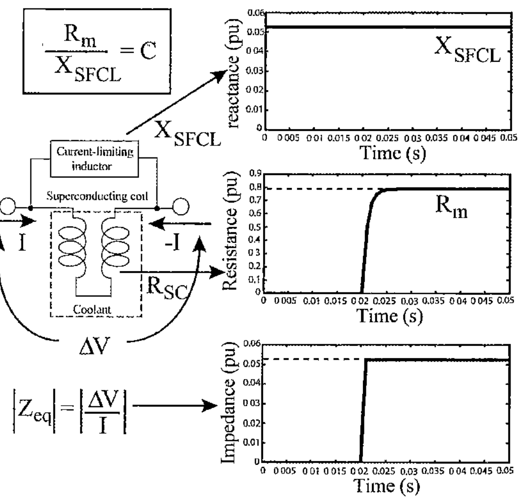


Fig. 6. Basic structure and impedance characteristic of the S/N transition-type SFCL

inductor is used because of less energy is wasted and less ambient temperature cooling is required. At the normal operation, the line current flows through the superconducting coil. In the event of a fault occurring, there is a sharp change from the superconducting state to the normal state. As a result, the fault current can be limited by a current-limiting inductor. The ratio of the maximum resistance of the superconducting coil to the reactance of the current-limiting inductor R_m/X_{SFCL} is kept constant and large enough to prevent the current flowing through the superconducting coil during the fault period. It can be seen from the characteristic impedance in Fig. 6 that the maximum equivalent impedance of the S/N transition-type SFCL is limited by the maximum value of the reactance of the current-limiting inductor.

3.2 S/N Transition-type SFCL Model by ObjectStab in Dymola In this paper, the authors modeled the S/N transition-type SFCL by using ObjecStab library in Dymola [7] [8]. Some benefits of using this tool which simplify the modeling of detailed characteristics of the S/N transition-type SFCL are as follows (1) it supports non-causal modeling meaning that the model terminals do not necessary have to be assigned an input or output role making it easy to model either series or parallel components in power systems, (2) the library has an open structure and all models can be accessed and modified, (3) all models can be exported for use in Matlab/Simulink, then a full set of Matlab tools can be used and also possible for using genetic algorithms, and (4) the calculation accuracy of this tool has been proved to be a comparative one as in commercial programs such as EuroStag and SimPow.

Fig. 7 shows the model of S/N transition-type SFCL used in this study. It consists of a superconducting coil and a current-limiting inductor model. The superconducting coil is here supposed to be non-inductive. The S/N transition characteristic of superconducting coil is explained by

$$R_{sc}(t) = R_m(1 - \exp(-t/T_{sc}) \cdots\cdots\cdots\cdots\cdots (1)$$

where R_m is the maximum resistance of superconducting

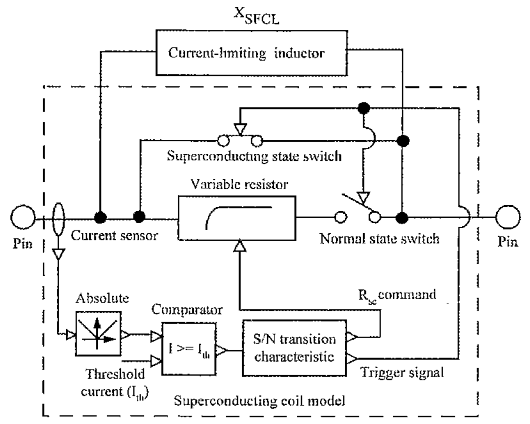


Fig. 7. S/N transition-type SFCL model in ObjectStab

coil at normal state, T_{SC} is the transition time constant from the superconducting state to normal state. In general, this transition state time constant is assumed to be 1 to 5 ms. However, in this paper, the time constant is assumed to be 1 ms based on the data in Ref. (5). Under normal operation, ac current passes through the superconducting state switch. Upon the incidence of a fault, as the fault current raises above a threshold current which is the critical current of the superconducting coil, the increase in fault current causes the S/N transition of the superconducting coil. At this point, superconducting state switch opens and normal state switch closes, the resistance of S/N transition characteristic is calculated by Eq. (1) and the variable resistance component contributes the physical resistance according to the R_{sc} command.

4. Obtaining Smaller Circuit Parameters of SFCL by Considering Sub-transient and Transient Phenomena of Short-circuit Current

It is true that there are some constraints between the maximum resistance of the superconducting coil R_m and the reactance of the current-limiting inductor X_{SFCL} which imply that trading of sharing energy in the superconducting coil and saving in superconductor material of the superconducting wire should be designed. Since the information of cooling cost and superconductor material cost is still obscured, in this study, for the sake of simplification, the authors fixed the R_m/X_{SFCL} ratio.

In this paper, the current-limiting element of SFCLs is inductive and the resistance of the superconducting coil is varied dependent on the R_m/X_{SFCL} ratio. It should be noted that because the R_m/X_{SFCL} ratio is kept constant; as one parameter increases or decreases, another parameter increases or decreases as well. Then, the problem can be simplified by adjusting one parameter. Though the general idea suggests that the value of R_m should be large in order to prevent the short-circuit current flowing into the superconducting coil during the fault, setting R_m with a too large value should not be economical. Because the equivalent impedance of the SFCL is limited by the maximum impedance value of the current-limiting inductor, once the R_m/X_{SFCL} ratio is

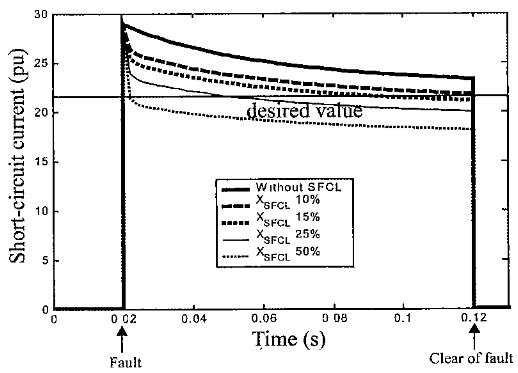


Fig. 8. short-circuit currents when varying circuit parameters of S/N transition-type SFCL

fixed, the evaluation of smaller R_m by adjusting smaller X_{SFCL} can be done easily. Because the value of R_m is directly related to the length of the superconducting wire, this implies that the reduction of R_m can save high expense for superconductor material.

In order to see how smaller circuit parameters R_m and X_{SFCL} of SFCL can be obtained, one SFCL is placed at the line no.16 and a three-phase to ground fault for fault period of 0.10 s is developed at bus 6. The R_m/X_{SFCL} ratio is fixed at 15. The desired level of short-circuit current which can be the maximum capability of the circuit breaker is set to be 21.5 pu. The network is simulated and results are obtained for different values of SFCLs to assess the impedance effects of SFCLs to the short-circuit currents. The values of X_{SFCL} are changed between 10% to 50% of the maximum value 0.105 pu and the result is plotted in Fig. 8. Observation on the short-circuit currents shows that they decay with time according to the sub-transient and transient time constants. As stated earlier, the authors pay attention to the amount of short-circuit currents at the time when fault can be cleared by the circuit breaker. Though the short-circuit current at the beginning of fault may be still higher than the desired level, but at the time, the circuit breaker cannot open the contact because it is faster than the time that circuit breaker can be responded. From the result, at the time 0.12 s, the SFCLs with greater X_{SFCL} values of 25% and 50% exceedingly absorb the short-circuit currents because the short-circuit currents are much lower than the desired level. Thus the value of $X_{SFCL} = 15\%$ which is closet to the desired level is more economical from this point of view.

It has been shown in Ref. (9) that the impedance effects of SFCLs to the sub-transient and transient time constants can be evaluated analytically with a radial and simple power system. However, in large and mesh power systems, the calculation is not easy and more complex. Therefore, there is no better way to study this effect than to perform it through simulations. In summary of this remark and by way of emphasis, the authors note that a limitation of the short-circuit current when sub-transient and transient effects are wholly taken into account may enable the use of smaller circuit parameters of SFCLs and cheaper equipment with a lower short-circuit capability.

5. Proposed Genetic Algorithm

5.1 Genetic Algorithm in Overview In genetic algorithms (GA's), candidate solutions to a problem are analogous to individuals in a population where each individual is simplified to a chromosome that codes the variables of the problem. A population of individuals is maintained within search space for GA's. Each represents a possible solution to a given problem. The initial population can be a random collection of bizarre individuals. The individuals will interact and breed to form future generations called offspring. The key concept is that the stronger individuals will reproduce more often than weaker individuals. Presumably, the population will get a collective of the stronger as generations pass and the weaker individuals will die out. An optimal solution can be found and represented by the final winner in the competitive environment. GA's use three basic operators containing reproduction, crossover and mutation to generate successive populations. Because the evolution of better solutions by the proposed GA evaluates from how good or bad the solution is, not depending on how to solve or get those solutions directly, the designers has a great deal of freedom to modify the objective function to make it suitable for a given problem without modifying the main algorithm.

5.2 Formulation of Optimization Problem
With the genetic search, the evaluation process is performed by an objective function as a measure of the system performance. The goal of GA based optimization of this problem is to find a minimum number of required SFCLs and to select the possible smallest circuit parameters of SFCLs that are more economical while keeping the short-circuit currents of all buses under the desired level for every considered operating condition. The problem can be formulated as the following optimization equation

$$\min J = \max\left(\sum_{i=1}^{N} X_{SFCL_i} + \sum_{i=1}^{N} R_{m_i} + (N \times k) + \sum_{j=1}^{M} w_j\right)_p \quad \cdots\cdots\cdots\cdots (2)$$

subject to

$$X_{SFCL_i}^{min} \leq X_{SFCL_i} \leq X_{SFCL_i}^{max}$$

where N is the number of active SFCLs which is determined by the number of "1" in the control genes of HGA chromosome structure

M is the number of considered bus faults

X_{SFCL_i} is the reactance of i^{th} fault current-limiting inductor

R_{m_i} is the resistance of i^{th} superconducting coil subject to

$R_{m_i} = C \cdot X_{SFCL_i}$, if $R_{m_i} > R_{m_{\max}}$ then $R_{m_i} = R_{m_{\max}}$

p is the number of considered operating conditions

k is a weighting value for trading off between the number of required SFCLs and the summation of circuit parameters of SFCLs

w_j is a penalty value of fault limitations, where $w_j = 1$ if $I_{Fi} < I_{CB}$ else $w_j = 10^8$ where I_{Fi} is the fault current at i^{th} bus and I_{CB} is a desired level of the short-circuit current which can be the maximum capability of the circuit breaker

The proposed objective function is useful because up to now the cost information of SFCLs is obscured. There is little information to guide whether or not installing SFCLs with small circuit parameters in many locations is cheaper than installing ones with big circuit parameters in fewer locations. The proposed objective function is very flexible because it can be traded-off between the number of required SFCLs and the summation of circuit parameters of SFCLs depending on which one is more crucial in the viewpoint of designers. By using Eq. (2), first the objective line I_{CB} (a desired current level), the weighting value k for trading off between the number of required SFCLs and the summation of SFCL circuit parameters are determined. These values are arbitrarily adjusted depending on the purposes of designers.

5.3 Hierarchical Genetic Algorithm (HGA)

To apply GA, first it is necessary to code the potential solution of the problem as an individual. In this paper, the concept of HGA will be applied.

The essence of the HGA is its ability to code the system parameters in a hierarchical structure. The arrangement of gene structures can be set in a multi-level fashion consisting of one-level control genes and second-level parametric genes [10] [11]. In order to reduce the number of optimized parameters, only X_{SFCL_i} can be chosen to be a parametric part because the R_{m_i}/X_{SFCL_i} ratio is kept constant. R_{m_i} specifications are satisfied automatically by the constant ratio and constraint actions as explained in section 5.2. Thus, the overall HGA chromosome structure can be constructed as in Fig. 9. With this configuration, the control genes are analogous to the SFCL locations. The control gene signified as "0" at the corresponding site, is not being activated meaning that the SFCL at the corresponding location will be bypassed through the control switch during the simulation. Parametric genes are analogous to the reactance values of SFCLs. Using the HGA concept, locations and reactance values of SFCLs (including the resistances of superconducting coils as they are respected to the R_{m_i}/X_{SFCL_i} ratio) can be simultaneously optimized.

There is no better way to understand how HGA chromosome structure works than to go through a demonstration example. In this paper, a chromosome is coded by integer values. The way of changing the integer part to the real part of a given problem is using Eq. (3)

$$A_i = \underline{A} + I_{Ai} \times (\bar{A} - \underline{A})/(number\ of\ step) \cdots (3)$$

where A_i is a real value of the decoded parameter, I_{Ai} is an integer value from the chromosome. $\underline{A}$ and $\bar{A}$ are upper and lower bound of each parameter in real values respectively.

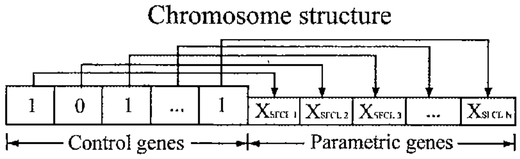


Fig. 9. HGA chromosome structure

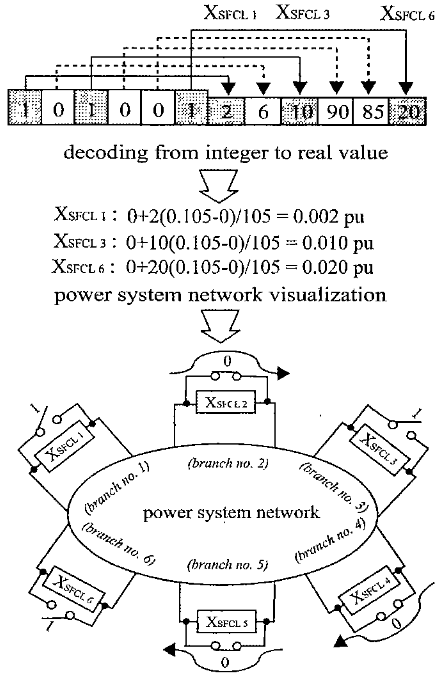


Fig. 10. Chromosome representation of an introduction of SFCLs into power systems

If the number of the branch candidate is determined to be 6 and the value of each limiting reactance of SFCL is between 0 and 0.105 pu with *number of step* of 105, which is equal to the incremental step size of 0.001. The chromosome representation of an introduction of SFCLs into power systems can be shown in Fig. 10. It can be seen that only three SFCLs ($SFCL_1$, $SFCL_3$ and $SFCL_6$) as indicated by the gray color will be active and will be participate into the power system simulation. By this way, SFCL configuration can be changed from one system to the others.

In general problem, SFCL configuration is always modified in the optimization process and the number of considered cases is huge. For example, in this study, the combination of SFCL groups can be estimated by the control genes of HGA chromosome as

$$S = \sum_{i=1}^{n} (i+1) \times {}_nC_i \cdots\cdots\cdots\cdots (4)$$

With $n = 14$, which is the number of branch candidates associated with the problem buses that short-circuit currents exceed the desired level (indicated by the gray color in Fig. 1), the possible cases of SFCL groups that are installed within 14 branches are 131,071 cases. Obviously, the search space is much large and random walk or enumeration should not be profitable or even basic GA's simulated case by case is not suitable. It can be

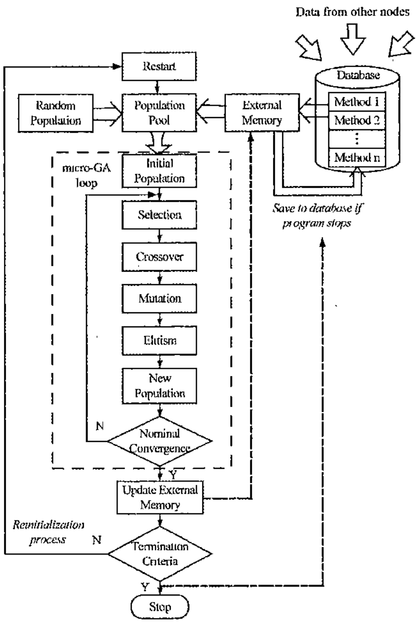


Fig. 11. Micro-GA algorithm flowchart

seen that using HGA, it provides the capability in which the optimized location can be independently and automatically obtained. This is undoubtedly due to the HGA's ability to solve the problem in a simultaneous fashion. Nevertheless, to reduce the calculation time, the branches connected to the problem buses as candidates based on the guideline in Ref. (6) are chosen to be considered in this study. In fact, the proposed method is not restricted to such cases, other branch candidates may be freely added into the control genes, if necessary, and the proposed method can be used without modifying the optimization algorithm.

5.4 Micro-genetic Algorithm The aim of a micro-GA is to find the optimum as quickly as possible without improving any average performance. It can be done by using a very small size, usually not more than 10, of population in the procedure and using a reinitialization process to keep enough diversity in the population. The point is that, when applying GA's to large-scale problems, most of the time is consumed for calculating the objective index. If the population size can be reduced without effecting the convergence capability of GA's, the total spending time will be decreased considerably. Fig. 11 illustrates the algorithm flowchart of a micro-GA used in this study for accelerating the GA calculation time. The technical aspect in details of a micro-GA is extensively discussed and explained in details in Ref. (11) (12).

The authors employed the HGA chromosome structure and a micro-GA to solve this optimization problem. The results presented in this paper have been obtained with the population size of 5 and maximum generation of 60. The computation time is strictly related to the number of times that the objective function is evaluated, for one evaluation being necessary about 2 seconds.

5.5 GA operators

5.5.1 Crossover (Recombination) Crossover operators are used to generate new solutions by taking information from previous solutions. When uniform crossover is used with integer or real-valued chromosome, it is usually referred to as *"discrete recombination"*. Discrete recombination can be used with any kind of variables (binary, integer, real or symbol). It performs an exchange of variable values between the individuals. Let $x = [x_1, \cdots, x_n]$ and $y = [y_1, \cdots, y_n]$ be the parent strings. Then the offspring can be generated according to:

$$z_i = x_i \cdot a_i + y_i \cdot (1 - a_i) \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where $i = 1, 2, \cdots$, no. of variables
z_i is a variable after recombination
$a_i \in \{0, 1\}$ uniform at random

To illustrate how discrete recombination works, consider the following two chromosomes with 12 variables. In this example, the first six variables correspond to the control genes and the others correspond to the parametric genes.

Individual 1: 0 0 1 1 0 1 2 6 10 90 85 20
Individual 2: 1 1 0 0 1 0 88 23 10 5 12 45

For each variable the parent who contributes its variable to the offspring is chosen randomly with probability 0.5. The internal masks determining which parent produces the offspring are assumed to be:

Mask 1: 0 1 0 0 1 0 1 0 1 1 0 0
Mask 2: 1 0 1 0 1 1 0 1 1 1 1 1

1 means this part is produced by parent 1

0 means this part is produced by parent 2

After recombination the offspring are created as:

offspring 1: 1 0 0 0 0 0 2 23 10 90 12 45
offspring 2: 0 1 1 0 0 1 88 6 10 90 85 20

5.5.2 Mutation The concept of using mutation is to recover good genetic material that may be lost through the acting of selection and crossover. Mutation of integer or real variables mean that randomly created values are added to the variables with a low probability. The new value is computed according to

$$z_i = x_i + s_i \cdot r_i \cdot a_i \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

where $i = 1, 2, \cdots$, no. of variables
x_i is a variable before mutation
z_i is a variable after mutation
$s_i \in \{-1, +1\}$ uniform at random
$r_i = r\cdot$ search interval, r: mutation range (0.1 for standard)
$a_i = 2^{-u \cdot k}, u \in [0, 1]$ uniform at random
k: mutation precision

The above algorithm means, probability of small step-sizes is greater than that of bigger steps. Thus most of mutated individuals will be generated near the individual before mutation. Parameter k defines the minimal step-size. The mutation steps are created inside the area $[r, r \cdot 2^{-k}]$. To illustrate how mutation works, consider two chromosomes with 12 variables. In this example, the first six variables correspond to the control genes and the others correspond to the parametric genes.

individual 1: 1 0 0 0 0 0 2 23 10 90 12 45
individual 2: 0 1 1 0 0 1 88 6 10 90 85 20

The internal masks determining which variable to be mutated and its sign for adding are assumed to be:

Mask 1: 0 1 0 0 0 0 0 0 0 0 0 0
mask 2: 0 0 0 0 0 0 0 0 0 0 −1 1

If the mutation steps can be calculated as:

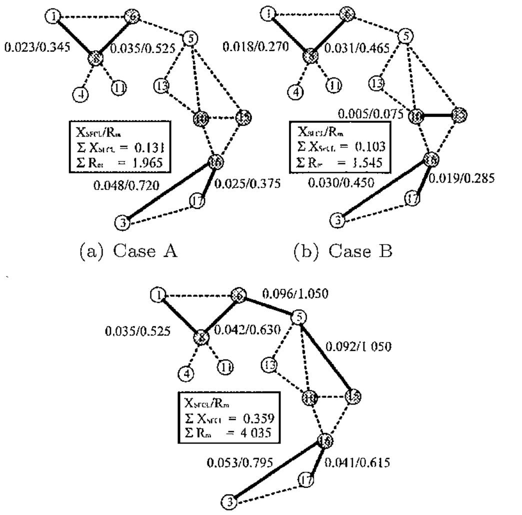
mutation step 1: 0 1 0 0 0 0 0 0 0 0 0 0
mutation step 2: 0 0 0 0 0 0 0 0 0 0 11 1

Thus after mutation, the new chromosome becomes:

individual 1: 1 1 0 0 0 0 2 23 10 90 12 45
individual 2: 0 1 1 0 0 1 88 6 10 90 74 21

6. Simulation Results

A loop power system in Fig. 1 using three widely different loading conditions in Table 3 was used in the study. To demonstrate the idea of the proposed method and to simplify the study, in this paper, the authors have studied an example to find the most effective solution on improvement of the short-circuit current limitation during three-phase to ground fault. A three-phase to ground fault was applied to each bus at t = 0.02 s for 100 ms period. The objective line was set at 21.5 pu. The 14 branches connected to bus 6, bus 8, bus 10, bus 15 and bus 16 were chosen as candidates because those branches connected to the buses that the short-circuit currents exceeded the maximum limit of 21.5 pu. The bound of each X_{SFCL} was set between 0 and 0.105 pu. The R_m/X_{SFCL} ratio was kept constant at 15 and $R_{m_{\max}}$ was 1.05 pu. The threshold currents of each SFCL were set based on the criteria that SFCL must not operate by normal currents and must operate against the fault currents. The proposed method is flexible from the viewpoint of its easiness in modifying the objective function to make it suitable for a given problem without modifying the main algorithm of the GA. In order to see the flexibility of the proposed method, the constructed test system was simulated for three different cases by varying the weighting value k in Eq. (2). By this way, the objective function is changed for three different cases. Because there is little information to guide whether or not installing SFCLs with small circuit parameters in many locations is cheaper than installing ones with big circuit parameters in fewer locations, it is a need of a method that can be traded-off between the number of required SFCLs and the summation of circuit parameters of SFCLs depending on which one is more crucial in the viewpoint of designers. Case A and Case B are used to demonstrate two different purposes for minimizing the number of required SFCLs and for minimizing the circuit parameters of SFCLs. Case A and Case B are employed the same objective function in Eq. (2) but different in weighting values. However, Eq. (2) can be easily modified by including some other constraints, if



(a) Case A (b) Case B (c) Case C

Fig. 12. SFCL configurations by the proposed GA

necessary. Case C is an example when the designer desires to add a new constraint.

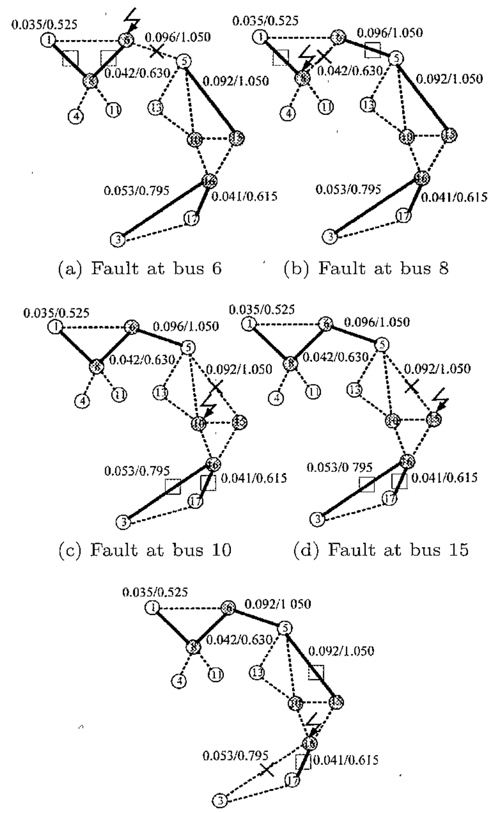
(1) Case A: k = 40 (Minimize the number of required SFCLs) In this case the number of required SFCLs installed in a system is considered to have high degree of importance. After setting the objective function, the GA algorithm as shown in Fig. 11 is used to solve the solution. The best SFCL configuration obtained by the proposed method based on this case is shown in Fig. 12(a).

(2) Case B: k = 0.1 (Minimize the circuit parameters of SFCLs) In this case the circuit parameters of SFCLs justified by the summation of reactances of current-limiting inductors and resistances of superconducting coils are considered to have high degree of importance. After setting the objective function, the GA algorithm as shown in Fig. 11 is used to solve the solution. The best SFCL configuration obtained by the proposed method based on this case is shown in Fig. 12(b).

(3) Case C: k = 20 (Add new constraint) In this case, the importance of the number of required SFCLs and the circuit parameters of SFCLs are traded off equally. This case is considered to show the flexibility of the purposed method when a constraint is added into the optimization. Here, the authors are assumed the constraint that one SFCL with the biggest circuit parameters near the fault location does not operate. Though this case is uncommon and rare, but it is possible if the designers think of the systems with higher reliability. To understand how the objective function of the proposed GA can be modified when the constraint is considered, consider the following example control gene part which is a part taken from the full HGA chromosome.

Branch no:	2	12	16	4	10	18	13	20	21	22	15	24	8	25
	0	1	1	1	0	0	0	0	0	0	0	0	1	1

From the above control genes, the number of "1" in the control genes demonstrates the branch number that SFCL is installed. In this example, five SFCLs will be connected in the system according to the corresponding


(a) Fault at bus 6 (b) Fault at bus 8

(c) Fault at bus 10 (d) Fault at bus 15

(e) Fault at bus 16

Fig. 13. Example accident patterns for case C

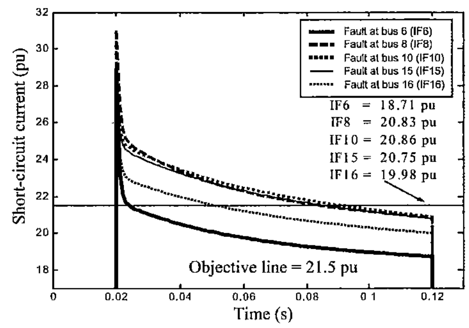


Fig. 14. Full operation for case A

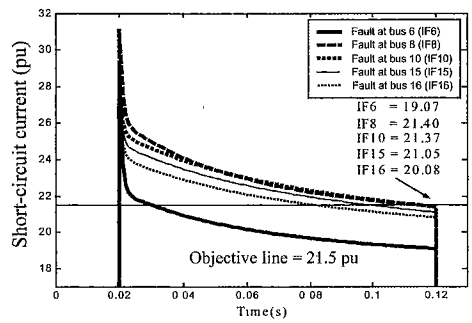


Fig. 15. Full operation for case B

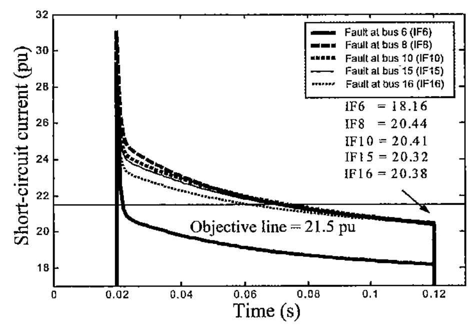


Fig. 16. Full operation for case C

branch number. When the constraint that one of five SFCLs does not operate is considered, the possible scenarios can be made by using the following steps.

Step 1: Generate the scenario list by changing "1" for one position to "0" until it fulfills the number of possible scenarios. Based on the above example control genes, the scenario list can be generated as follows:

0 0 1 1 0 0 0 0 0 0 0 0 1 1: Scenario 1
0 1 0 1 0 0 0 0 0 0 0 0 1 1: Scenario 2
0 1 1 0 0 0 0 0 0 0 0 0 1 1: Scenario 3
0 1 1 1 0 0 0 0 0 0 0 0 0 1: Scenario 4
0 1 1 1 0 0 0 0 0 0 0 0 1 0: Scenario 5

Step 2: For i^{th} scenario, Eq. (2) is used to evaluate the index ϕ_i. With the setting of weighting value k and the number of scenario q where q depends on the number of "1" in the control genes which are randomly generated in the HGA chromosome and can be varied from generation to generation, the objective function in Eq. (2) is modified to Eq. (7) by adding the constraint that one SFCL does not operate.

$$\min J = \max(\phi)_q \quad \cdots\cdots\cdots\cdots\cdots (7)$$

After modifying the objective function based on the above steps, the GA algorithm as shown in Fig. 11 is used to solve the solution. The best SFCL configuration obtained by the proposed method based on this case is shown in Fig. 12(c).

Comparing to result of case A and case B, in case B, as the weighting value k decreases, the summation of reactances of current-limiting inductors and resistances of superconducting coils decrease as well. However, it was found that the additional SFCL had to be installed at the line 10–15.

Fig. 13 illustrates some accident patterns of case C. In this figure, the symbol marked by "×" means the SFCL that does not operate which is not associated during a fault and the symbol marked by "□" means the active SFCL which is associated during a fault. Fig. 14 to Fig. 16 illustrate dynamic responses of the short-circuit currents under the heavy load condition of case A, case B and case C respectively. For case C, the plot of short-circuit currents as shown in Fig.16 corresponds to the accident patterns in Fig. 13. It should be noted that all the currents at t = 0.12 s which is the time that the circuit breaker can be responded are under the predetermined objective line. From the above results, the following points are clarified:

(1) Line 1–8, 6–8, 3–16, and 16–17 are expected to be important lines to be installed SFCLs in order to reduce large short-circuit currents, because they always appear in the solutions.

(2) When one SFCL with the biggest circuit parameters near the fault does not operate, the SFCL configuration in case A and case B cannot limit the fault currents. It is obvious from the SFCL configuration in case C that the SFCL at line 5–6 performs as a backup SFCL for protecting the fault at bus 6 and 8. Similarly, the SFCL at line 5–15 performs as a backup SFCL for protecting the fault at bus 10, 15, and 16.

(3) The proposed method is flexible. The algorithm can be used even if the situation in the optimization has been changed. It should be noted that any situations can be freely added into the optimization depending on the purposes of designers.

7. Conclusions

The use of SFCLs is an emerging novel technology and brings benefits for limiting such a large short-circuit current in power systems. In this paper, the authors proposed an idea to obtain the use of smaller circuit parameters of SFCLs by wholly taking sub-transient and transient effects into account in the limitation of short-circuit currents. Then, a method to allocate suitable location and to select the smallest circuit parameters of SFCLs using a combined method of HGA and a micro-GA was proposed and was applied to solve a problem of increased fault level in an example loop power system. The efficiency, effectiveness and flexibility of the proposed method were shown by numerical examples.

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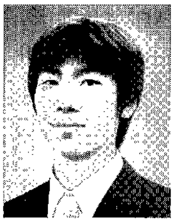

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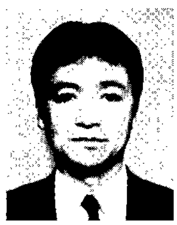

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