Optimal Location Assignment and Design of Superconducting Fault Current Limiters Applied to Loop Power Systems

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***Abstract*—Short-circuit current is strongly related to the cost of apparatus and the efficient use of power transmissions. Therefore, the introduction of Superconducting Fault Current Limiters (SFCL's) becomes an effective way for suppressing such a high short-circuit current in loop power systems. Firstly, a method to obtain a smaller SFCL capacity by observing the SFCL behavior including sub-transient and transient effects during a short circuit is proposed. Secondly, we propose using a micro-genetic algorithm (micro-GA) combined with a hierarchical genetic algorithm (HGA) to simultaneously search for the optimal location and the smallest SFCL capacity. The efficiency of the proposed method is shown by numerical examples with a loop power system.**

***Index Terms*—Hierarchical genetic algorithm (HGA), loop power system, micro-genetic algorithm (micro-GA), Superconducting Fault Current Limiter (SFCL).**

I. Introduction

IN NEAR future, many Independent Power Producers (IPP's) will participate in power generations according to their own strategic contracts by deregulation. This has brought in its wake the problem of increased fault levels often exceeding the withstand capability of existing circuit breakers. One possible option to combat this circumstance is to adapt new technologies as high-temperature superconducting equipment. Among them, Superconducting Fault Current Limiters (SFCL's) are attractive because they bring benefits such as fast limiting such a high short-circuit current without sensors, no effects to the system during normal power system operation, etc. [1], [2]. Since short-circuit current is strongly related to the cost of apparatus and the efficient use of power transmissions, the reduction of high short-circuit current may bring to the considerable reduction of investment cost for high capacity circuit breakers and construction of new transmission lines.

Though such a fast circuit breaker nowadays can protect the equipment against its thermal limit, it cannot avoid the dynamic force from the high current which may cause a permanent fault in the power system when the current at the operation time of circuit breaker reaches the value much higher than the circuit breaker capacity. Based on this system protection concept, we may obtain a smaller SFCL capacity by including the sub-transient and transient phenomena of short-circuit current in the analysis.

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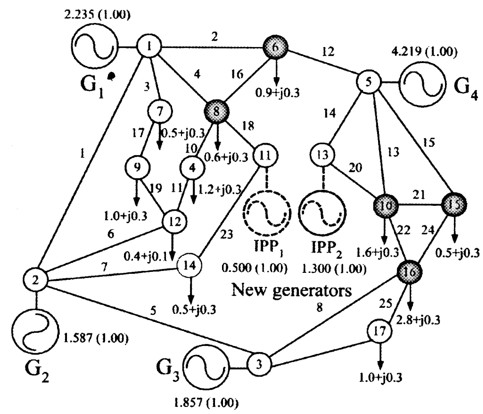

Fig. 1. Loop power system model.

For large-scale power system planning, it is important to develop a method that should be flexible to determine the suitable location and its economical design of SFCL. For this aim, we propose using a micro-genetic algorithm (micro-GA) combined with a hierarchical genetic algorithm (HGA) to simultaneously search for the optimal location and the smallest SFCL capacity. The flexibility in defining the required objective function with the proposed approach makes it possible to evaluate the requirement of SFCL's in power systems. The efficiency of the proposed method is shown by numerical examples.

II. Loop Power System and Short Circuit Current

A calculation of short-circuit current using a loop power system in Fig. 1 was carried out after new power generators of IPP_1 and IPP_2 were connected to the system. A three-phase to ground fault was applied one by one at every bus for 0.1 s period. It has been found that short-circuit currents at the buses as identified by the gray color exceed the maximum limit of circuit breakers which need to be kept at any bus under 21.5 pu, for example. Obviously, it is impossible to remove the fault by circuit breakers due to the large dynamic force from high short-circuit currents. Besides, the situation becomes much more difficult since the short-circuit currents can flow from many directions. Details of network parameters, machines, excitation systems and load flow are given in [3].

III. Superconducting Fault Current Limiter Model

Fig. 2 shows the model of SFCL used in this study. We modeled the SFCL by using ObjectStab library in Dymola based on

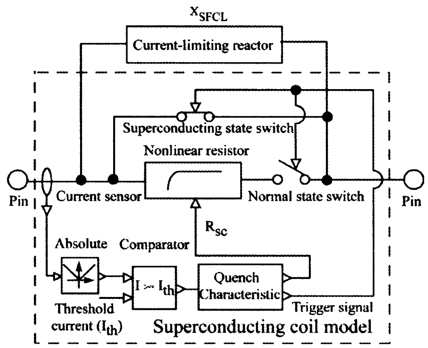

Fig. 2. SFCL model.

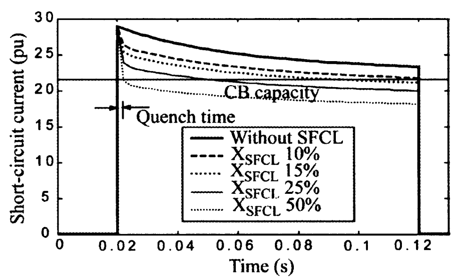

Fig. 3. Short-circuit currents including sub-transient and transient effects.

the quench characteristic of superconducting coil using the following dependence:

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

where R_m is the maximum resistance of superconducting coil at normal state ($R_m \approx 100\ \Omega$), T_{sc} is the time constant of transition from the superconducting to normal state which is assumed to be 1 ms as in [2].

It is analogous to the SFCL consisting of a reactor and a high-temperature superconducting coil made from compounds of ceramic oxides operating at 77 K, for each phase housed in a tank containing the liquid nitrogen.

IV. Small SFCL Capacity by Considering Sub-Transient and Transiet Phenomena of Short-Circuit Current

Fig. 3 shows the envelopes of the maximum values of the calculated short circuit-currents based on the power system in Fig. 1. In order to see how to obtain a smaller capacity of SFCL, one SFCL was placed at line no. 16 and a three-phase to ground fault was developed at bus 6. We varied the value of current-limiting reactance of SFCL X_{SFCL} from 10% to 50% of the maximum value 0.11 pu and observed the result as shown in Fig. 3. It is evident that the short-circuit currents decay with time according to sub-transient and transient time constants. The SFCL's with greater X_{SFCL} values of 25% and 50% absorb the short-circuit currents too much. Thus, the value of $X_{SFCL} =$ 15% is more economical from this point of view. It should be emphasized that if we don't consider the sub-transient and transient effects of short-circuit currents and consider only the peak current value, the greater value of X_{SFCL} will be obtained and it will cost more when introducing SFCL's in power systems.

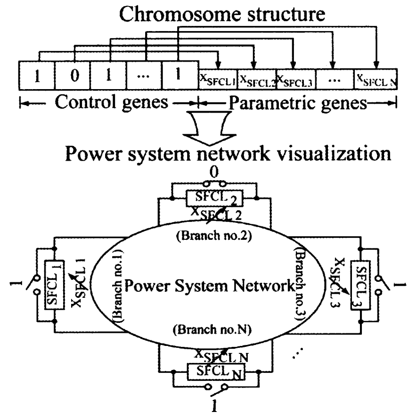

Fig. 4. HGA chromosome structure.

V. Proposed Technique

Genetic Algorithms (GAs), in comparison with other optimization techniques, bring benefits particularly because they can be used to solve all sorts of problems even if there is little prior knowledge of the problem being solved. Unfortunately, in the problem of choosing the suitable location and the smallest required capacity of SFCL, very often, power structures are modified in the optimization process. The search space is much large and random walk or enumeration should not be profitable. It has been verified in our previous research that the combined method of a micro-GA and HGA is efficient from the viewpoints of speed improvement and limitlessness of system structure varying [4]. Therefore, a similar approach is applied to solve the problem in this paper.

A. Hierarchical Genetic Algorithm and Micro-Genetic Algorithm

The implementation of the proposed GA used HGA concept and a micro-GA with real-valued encoding chromosome. Fig. 4 illustrates the HGA chromosome representation for this problem. With this configuration, we can explain how to translate in genetic codes as followings. The control genes are analogous to SFCL locations. The control gene signified by "0" at the corresponding site, is not being activated meaning that SFCL at the corresponding location will be bypassed through the control switch during the simulation. Parametric genes are analogous to reactance values of current-limiting elements of each SFCL which are related to the SFCL capacity. Using this HGA chromosome representation, locations and SFCL capacities can be simultaneously optimized.

The combination of possible SFCL locations which can be estimated from the control genes of HGA chromosome becomes very huge, for example, if the number of branches is 25 which is the sum of all branches of power system in Fig. 1, the possible combination is $\sum_{i=1}^{25} {}_{25}C_i$, where i is the number of installed SFCL. Therefore, it is important to improve the GA performance and time efficiency of algorithm. Fig. 5 shows the algorithm flowchart of a micro-GA used in this study for accelerating the GA calculation time. The idea of a micro-GA is to find the optimum as quick as possible without improving any average performance. It can be done by using a very small size

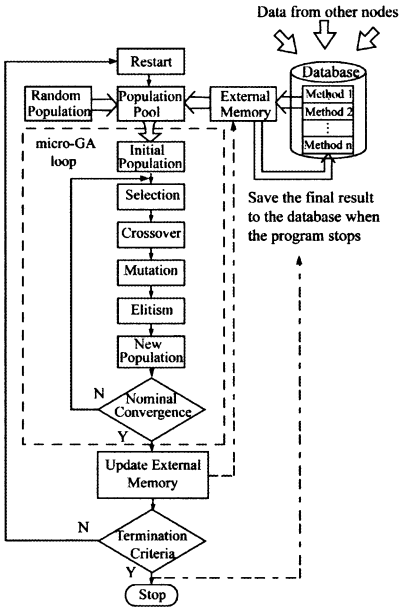

Fig. 5. Micro-GA flowchart.

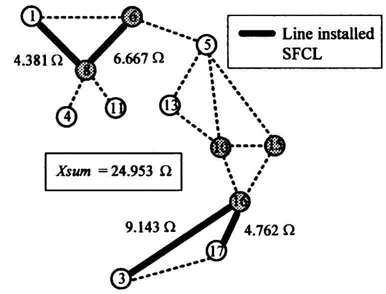

Fig. 6. Optimal SFCL configuration.

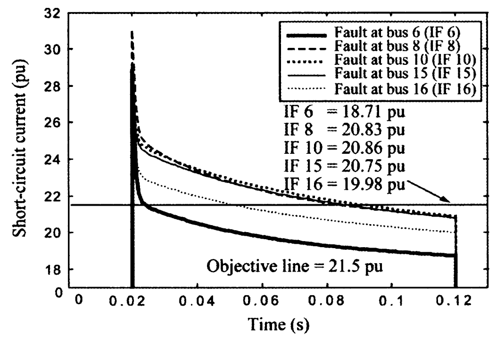

Fig. 7. Short-circuit currents after installing SFCL's.

of population, usually not more than 10, and using a reinitialization process to keep enough diversity in the population. The GA operators inside the micro-GA loop are similar to those in basic GAs. The technical aspect in details of a micro-GA is extensively discussed in our previous paper [4].

B. Formulation of the Problem

The most important step for the evolutionary search is how to define the fitness, which is related with the objective function and the constraints of the problem. Our objective for the economical use concentrates on the prospective saving by reducing the numbers of installed SFCL's and reducing their required minimum reatances. The problem can be formulated as the following optimization problem

$$\min J = Xsum + (N \times k) + \sum_{i=1}^{5} w_i \tag{2}$$

where $i = 1, 2, 3, 4, 5$ corresponding to the fault at bus 6, 8, 10, 15, 16 respectively, $Xsum$ is the sum of all current-limiting reactances which is related to total SFCL capacity, where $Xsum = \sum_{j=1}^{N} X_{SFCL_i}$, N is the number of the active SFCL determined by the control genes of HGA chromosome structure, k is a weighting value for trading off between number and capacity of SFCL, w_i is a penalty value for fault limitation, where $w_i = 1$ if $I_{F_i} < I_{CB}$ else 10^8, subject to $X_{SFCL_i}^{\min} \leq X_{SFCL_i} \leq X_{SFCL_i}^{\max}$.

The proposed objective function is useful because up to now no costs for SFCL are known. This equation can be used to trade off between the number and capacity of SFCL. By using (2), first the objective line I_{CB}, the weighting value k for trading off between number and capacity of SFCL are determined. These values are arbitrarily adjusted depending on the purpose of designers.

We employed the proposed GA to solve this optimization problem by setting the objective line I_{CB} to be 21.5 pu, weighting value k to be 20, X_{SFCL} in range 0 to 20 Ohms of each SFCL. SFCL's were installed in all branches, thus the bit-length of control genes was 25. The results presented in this paper have been obtained by the GA settings 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.

VI. Result and Discussion

The loop power system in Fig. 1 was used to show the effectiveness of the proposed method. First, the threshold currents of each SFCL were set based on the criterion that SFCL must not operate by normal current and must operate against the fault current. In this study, the limitation characteristic of SFCL is expected to be active when the current is greater than 3 to 3.5 times of normal current. Fig. 6 shows the final result of the optimal SFCL configuration obtained by the proposed GA. It can be seen that we need to install SFCL's in 4 lines and the minimum required for current-limiting reactance is 24.953 Ohms. Fig. 7 shows the maximum envelopes of short-circuit currents after we installed SFCL's as in Fig. 6. Obviously, all the currents of problem buses at the operation time of circuit breakers are under the predetermined objective line. All SFCL's successfully absorbed the excess fault currents. Next, the performance of installed SFCL's with the above configuration was examined. From the results in Fig. 8, the following points are clarified: 1) SFCL 1–8 and 6–8 are operated for protecting the fault at bus 6 and 8 and SFCL 3–16 and 16–17 are operated for protecting the fault at bus 10, 15 and 16, 2) it can be seen that the maximum thermal energy of SFCL 1–8, 6–8, 3–16 and 16–17 are determined by the fault at bus 8, 6, 16 and 16 with the maximum thermal energy 1.2, 1.8, 1.8 and 0.45 MJ respectively, 3)

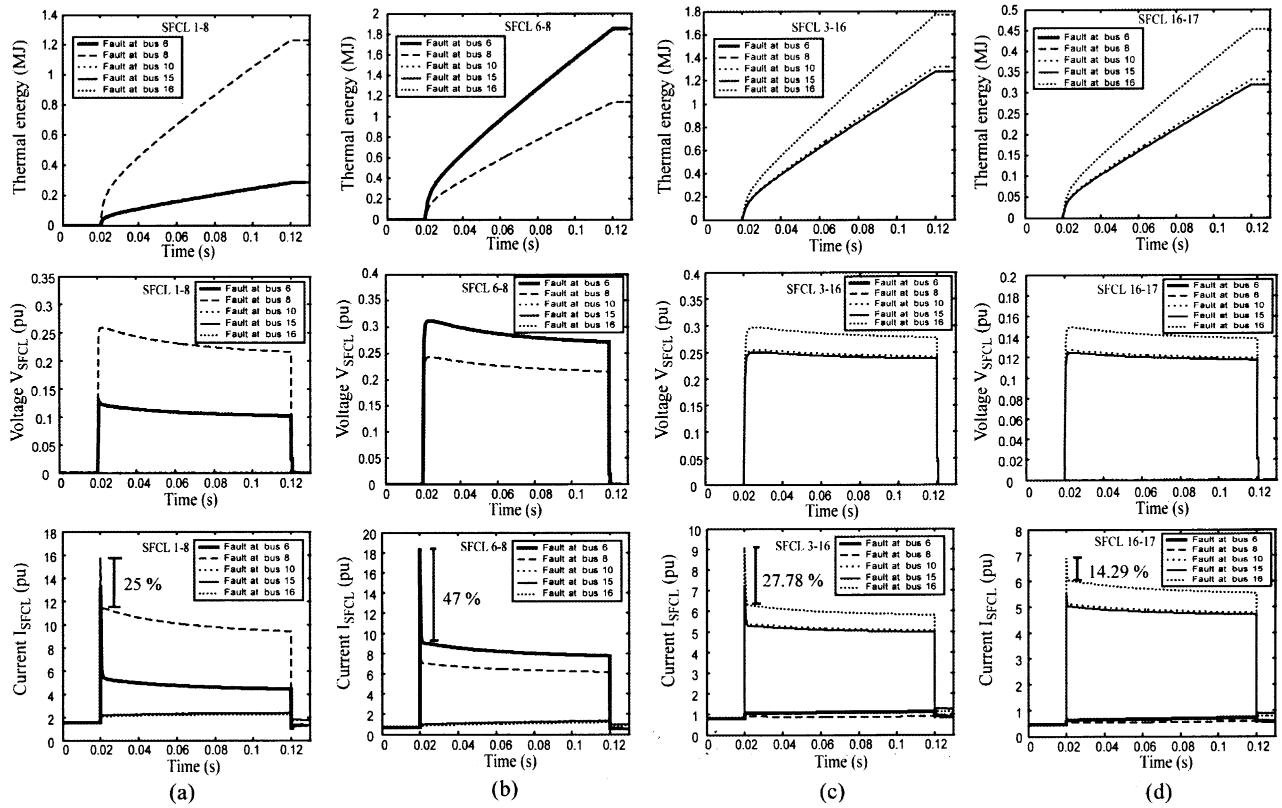

Fig. 8. Performance of installed SFCL's: Thermal energy can be observed only in the active SFCL which the fault current reaches the value higher than the threshold current of SFCL, (a) SFCL 1–8 is active for faults at bus 6 and 8 (b) SFCL 6–8 is active for faults at bus 6 and 8, (c) SFCL 3-16 is active for faults at bus 10, 15 and 16, (d) SFCL 16–17 is active for faults at bus 10, 15 and 16.

the voltages dropped at each SFCL and the percentage of current limiting from the transient peak currents of each SFCL are shown in the last two rows.

VII. Conclusions

SFCL is an emerging novel technology and brings benefits for limiting a high short-circuit current in power systems. In this paper, first a method to obtain a smaller SFCL capacity by including the sub-transient and transient effects of fault currents was explained by a numerical example. Then, a method to determine suitable location and design the smallest capacity of SFCL simultaneously in a loop power system using a combined method of a micro-GA and HGA was proposed. The efficiency of the proposed method is shown by numerical examples.

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