Placement of Fault Current Limiters in Power Systems by HFLS Sorting and HIGA Optimization Approach

Hong-Tzer Yang, Wen-Jun Tang, Connie Wang, Piotr Lubicki and Steve Wang

***Abstract*-- As the number of new power plants and the scale of transmission systems sustainably grow, the probability of exceeding the short circuit rating of circuit breakers (CBs) increases, a fact which leads the system's security and stability to a big issue. Fault Current Limiter (FCL), as one of the solutions to current surge attenuation, attracts a lot of attention from utilities. To make the best use of FCL, the placements must be optimally determined along with the most suitable FCL parameters settings. This paper proposes a method combining Herarchical Fuzzy Logic System (HFLS) method for pre-sorting the feasible solutions and Hashing-Integrated Generic Algorithm (HIGA) as an optimization tool to find the best solution in the reduced search space. To verify the proposed approach as an effective means for placement of the FCLs, the proposed method is implemented through Matlab and DigSILENT and tested in a practical power system. The numerical results show that the proposed method may achieve a better solution in less time with fewer placements of FCLs, thus reducing the cost, while maintaining comparable system security.**

***Keywords*: Fault Current Limiter (FCL), Short-circuit Current, Voltage Stability, Search Space Screening, Hierarchical Fuzzy Logic Control, Generic Algorithm, FCL Placement Optimization**

I. INTRODUCTION

With the constant increase in power demand, power system has been facing the challenges of security and reliability [1][2]. Distributed Energy Resources (DERs) and Independent Power plants (IPPs) are applied to solve energy shortages. As a result, the occurrence rate and magnitude of fault current greatly increase [3]. The fault current may thus exceed the CB interruption capacity, leading to fail of CB operation and even cascading incidents, like blackouts [4].

Accordingly, many researches have been focused on this problem. The most direct solution is to upgrade all devices in the system, which in most cases is not economically feasible. Alternatively, power network reconfigurations have been suggested to eliminate overload or fault cases by changing the topology through sectionalizing switches [5][6]. Although no additional devices are needed with this method [7], the control in real-time is obviously problematic [8]. The current-limiting reactor application is another possible solution, which prevents CBs from over capacity current; however, it simultaneously consumes energy in normal operation.

With nearly zero power loss and smaller voltage drop during normal state, as well as a short delay time to introduce high reactance into the circuit, when a fault occurs [9], FCLs are one of the more attractive solutions to current surge attenuation. In the early stages, power electronics structure was widely used in FCLs. With the progress of material technology, superconductor has been integrated in FCLs. Superconductor has the electrical specification that the resistance value is nearly zero, when operating under a fixed scope of temperature and critical current density; on the contrary, the resistance increases immediately, as subject to a fault [10][11]. In addition, the application of FCL does not change the topology of an existing network [12] or impact other power devices [13]. Taken together, these characteristics make FCL an ideal candidate for solving existing high fault-current problems [14].

The placements of FCLs have been discussed in several studies. Most of studies have focused on specific locations, such as double-bus parallel, point of common coupling (PCC), transformer's neutral line or a smart grid in small areas [15]-[18], with a few considering overall system planning [19][20]. The objective function to minimize the number of FCLs installed and their shunt reactors' values has been employed with respect to the whole-system FCL placement optimization [21]. However, advantages of FCL are not fully taken for the objective function employed.

The planning of FCL installation is always a concern in large power systems. However, optimization of the FCLs placement becomes very difficult with so many candidates in the large power system. The computations needed for the power flow and fault current estimation in the systems consume much time. Besides, some locations and areas to install FCLs may have much less impact on the fault current than the other. The computing time of these candidates with less impact is thus meaningless, and so a sorting tool is, therefore, required.

Teng and Lu recommend a sensitivity factor for sorting candidates [21]. The sensitiveness of each candidate location is considered by the fault current reduction, when its fault impedance value is changed. They suggest that the more sensitive a candidate location is, the higher the installation potential. Accordingly, this method saves time of the optimization algorithm by reducing the search space;

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nevertheless, it still requires considerable time via the trial-error assessment.

The fuzzy logic system (FLS) has been widely used to solve the multi-objective problems [22]. When managing more than two input control variables, a collection of low-dimensional systems is needed. Instead of using a high-dimensional system that may cause fuzzy rule explosion, a hierarchical fuzzy logic system (HFLS) [23][24] employs the low-dimensional control systems based on different rules whose number is the same as the hierarchy number to increase the accuracy of results. HFLS is thus a good alternative deal with the multiple-variable systems.

Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Colony System (ACS) and Artificial Immune System (AIS) are classified as Population-Based Intelligent Search (PIS) algorithms [25]. PIS has been used by numerous studies as an optimization algorithm, and has been shown to have promise in many applications. Among such studies, GA has been employed in the research focusing on optimal placement of different system devices [26], such as FCLs [21], fault indicators [27], and capacitors [8][28][29], etc.

In this paper, the GA-based approach is used with the fitness function considering more aspects, including the FCL functions of voltage variation restraining. Based on the proposed new measuring sensitivity factors, HFLS is firstly presented in sorting the potential installation locations of FCL. Considered are not only the over-current buses, but also the source buses of the fault current. The optimization further employs the HIGA [32] method to eliminate the computing time of any repetitive solutions under evaluation. To verify the proposed approach for the optimization of FCL placement, the method is analyzed and tested through Matlab and DigSILENT in a practical power system.

II. Circuit Breaker Interruption capacity

Before discussing FCL placement optimization, definition of fault current and CB interruption capacity is clarified first.

A. Characteristics of Fault Current

When the short circuit current is calculated, the power system is assumed to be a Thevenin equivalent circuit (Fig. 1), consisting of an AC source and series R-L. The expression for a KVL circuit equation is derived as the function below.

$$\frac{Ldi}{dt} + Ri(t) = \sqrt{2}V\sin(\varpi t + \alpha) \qquad t \geq 0 \tag{1}$$

The solution becomes

$$i(t) = i_{ac}(t) + i_{dc}(t)$$
$$= \frac{\sqrt{2}V}{Z}\left[\sin(\varpi t + \alpha - \theta) - \sin(\alpha - \theta)e^{\frac{-t}{T}}\right] \tag{2}$$

where

$$i_{ac} = \frac{\sqrt{2}V}{Z}\sin(\varpi t + \alpha - \theta) \tag{3}$$

$$i_{dc} = -\frac{\sqrt{2}V}{Z}\sin(\alpha - \theta)e^{\frac{-t}{T}} \tag{4}$$

$$Z = \sqrt{R^2 + (\varpi L)^2} = \sqrt{R^2 + X^2} \tag{5}$$

$$\theta = \tan^{-1}\frac{\varpi L}{R} = \tan^{-1}\frac{X}{R} \tag{6}$$

$$T = \frac{L}{R} = \frac{X}{\varpi R} = \frac{X}{2\pi f R} \tag{7}$$

The total fault current, also called the asymmetrical fault current, is shown in Fig. 2, and is divided into ac in (3) and dc components in (4). The ac fault current named as the symmetrical or steady-state fault current is sinusoidal, while the dc element decays by time constant T, as given in (7). From the expressions presented above, each component is affected by the factors α and orsd mponent is sions presented e according to the diverse fault instants (as illustrated in Table I).

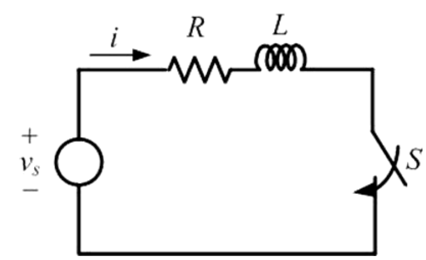

Fig. 1. Current in a series R-L circuit with ac voltage source

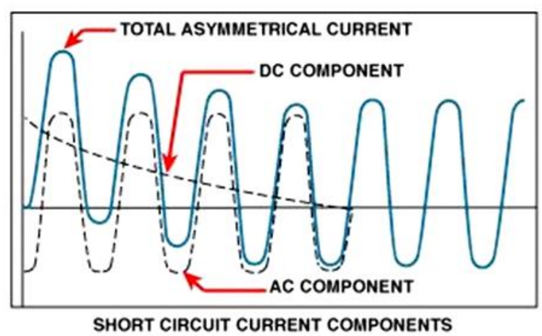

Fig. 2. Total Fault Current

TABLE I
Different Fault Current Values

Fault Occurrence	Short Circuit Value
$\alpha - \theta = 0°$	$i = \frac{V_m}{\lvert Z \rvert}\sin\varpi t$ $i_{rms} = \frac{1}{\sqrt{2}}\frac{V_m}{\lvert Z \rvert} = I_{ac}$
$\alpha - \theta = -90°$	$i = \frac{V_m}{\lvert Z \rvert}(e^{\frac{R}{L}t} - \cos\omega t)$ $i_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2(\varpi t)d\varpi t}$ $= I_{ac} \times \sqrt{1 + (\sqrt{2}e^{-\frac{R}{L}t})^2}$
$\alpha - \theta \neq 0° or -90°$	$i_{(0°)rms} \leq i_{rms} \leq i_{(-90°)rms}$

B. Circuit Breaker Interruption Capacity

According to ANSI IEEE Std. C37.04-1999 [31], the standard rating structure for AC high-voltage circuit breakers rated on a symmetrical current basis is taken as a reference. The required symmetrical and asymmetrical interrupting capabilities are described. The abilities are related with one-half cycle relay time, or sometimes a permissible tripping delay time is employed instead.

The highest value of the symmetrical component of the poly-phase or phase-to-phase short circuit currents in rms amperes determines the rated short-circuit current of a CB. In line with this value, the CB should normally close, latch, and interrupt. The relationship between rated short-circuit current and other necessary capabilities can be found in detail in ANSI IEEE Std. C37.04-1999.

The highest fault current value of the symmetrical component in rms amperes is taken into consideration at the specific operating voltage. And usually, this capability is equal to K times the rated short-circuit current. The K value of a modern CB is defined as 1.0, while older CBs require K to be more than 1.0. The asymmetrical interrupting capability is designed based on the value of the total short-circuit current rms amperes at the separation time of the primary arcing contact. The parting time is defined as one-half of a cycle or some other operating time particular to the breaker, like 1.0, 1.5, 2.5 or 3.5 cycles for rated interrupting time of 2, 3, 5, or 8 cycles, respectively.

The rated interrupting current standard used by Taiwan Power Company (TPC), in Taiwan, is the ANSI IEEE Std. C37.04-1979, which uses three-phase to ground faults to simulate the maximum fault current. The functions to determine the asymmetric fault current are used to estimate whether the CB interruption capacities are sufficient (as shown in (8) and (9)) :

$$K = \frac{D}{S} = \frac{\sqrt{1 + (\sqrt{2}e^{-\frac{t}{\tau}})^2}}{S} = \frac{\sqrt{1 + (\sqrt{2}e^{-\frac{377 \times t}{X/R}})^2}}{S} \tag{8}$$

$$i_{as} = K \times i_{sy} \tag{9}$$

where

K Multiplying Factor
D DC Effect Multiplier
S Asymmetric Capabilities (1.1/1.2/1.3 for CBs with 5/3/2 cycles)
t Parting Time
i_{as} Asymmetrical Fault Current
i_{ds} Symmetrical Fault Current

III. The Proposed FCL Placement Optimization Method

The proposed optimization method mainly comprises two parts, the HFLS for pre-sorting the solutions and HIGA for subsequent optimization in the reduced search space. The solution flowchart of the proposed method is presented in Fig. 4. As mentioned, the system uses DigSILENT and Matlab as two simulation tools, with DigSILENT for power flow analysis as well as fault current calculation (yellow squares), and Matlab for HFLS and HIGA (red squares). The connection between these two programs is based on the .csv file. From the flow chart, we can see that not only HFLS but also HIGA are all on account of the data obtained from DigSILENT, which include the values of current, voltage, shunt reactors, and generators.

A. HFLS Sorting Method

As shown in Fig. 5, the HFLS sorting process is divided into two levels. Mendel's Type-1 fuzzy system is used here with the addition of a new set of membership functions to ensure flexibility. The first two inputs go through the first-level fuzzy system; then, the output of the first-level is operated in the higher-level fuzzy system with the second-stage input. Either the components or the evaluating variables are independent from each other.

Aiming to completely appraise the sensitivity of each bus, the proposed method employs the hierarchies representing the probability of one bus being the fault current resource, the bus with over-capacity CB or both roles. The peak-current data for the bus are then used to define the sensitivity indices of Max Contribution Current (MCC) when a fault occurs on the connected bus, Generator Connected Number (GCN) as the number of connected generators to the bus, and Max Fault Current (MFC) as the fault current calculated based on (9).

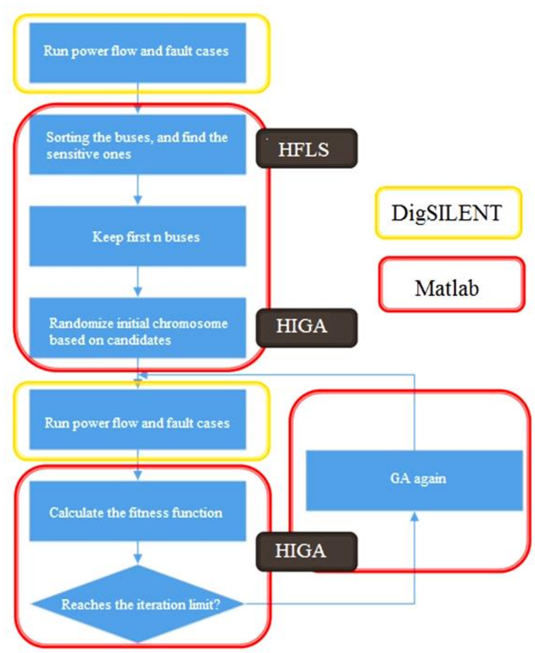

Fig. 4. Placement Optimization Method Flowchart

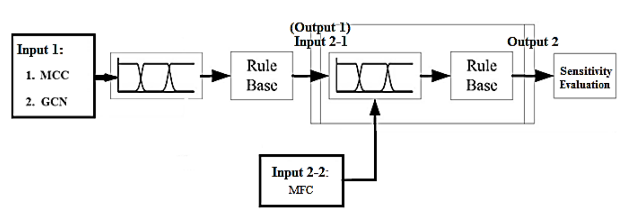

Fig. 5. HFLS Sorting Structure

MCC and GCN are the evaluation indices of the first stage (Input 1). Through the membership functions and rule base, the output is achieved mathematically as the inputs of the second stage along with MFC (as shown in Fig. 5). Illustrated in Fig. 6 are the membership functions of HFLS sorting. The x-axis range of MCC and MFC is changeable and refers to the virtual fault current of the under-planning systems. The rule base used in the paper is given in TABLE II and Fig. 7. To defuzzify the data, Center of Maximum (CoM) method is employed as shown in (10).

$$x_{final} = \frac{x_1 u_1 + x_2 u_2 + \cdots + x_n u_n}{u_1 + u_2 + \cdots + u_n} \tag{10}$$

where

x_n Typical numerical value for the scaled membership function n

u_n The degree of membership at scaled membership function n

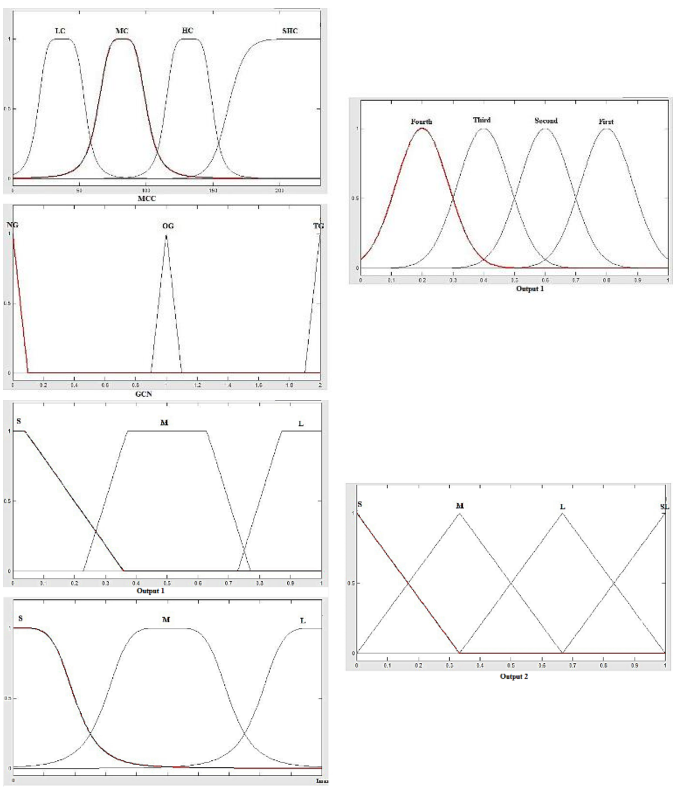

Fig. 6. Membership Functions of HFLS Sorting

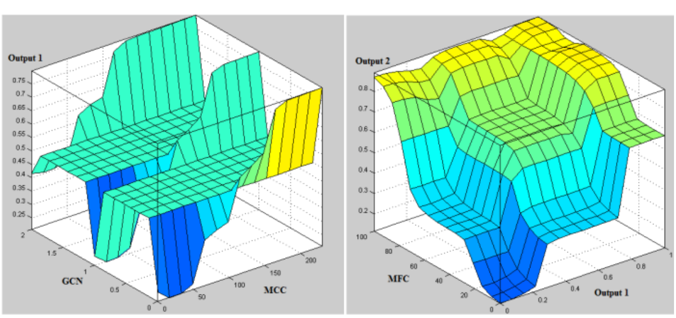

Fig. 7. Rule Base Surface of HFLS Sorting

TABLE II
HFLS RULE BASE
(a) FIRST STAGE

		MCC			
		LC	MC	HC	SHC
GCN	NG	Fourth	Third	Second	First
	OG	Third	Second	Second	First
	TG	Second	Second	First	First

(b) SECOND STAGE

		MFC		
		S	M	L
OUPUT1	S	S	S	L
	M	S	M	L
	L	M	L	L

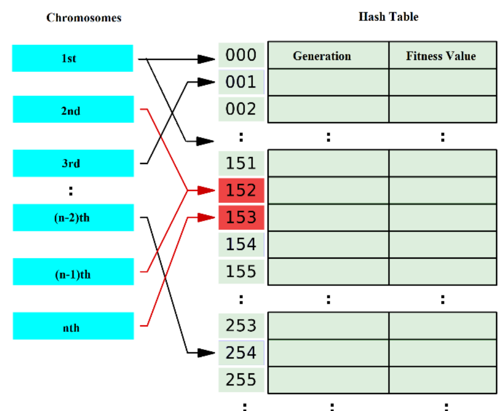

Fig. 8. Hash Table

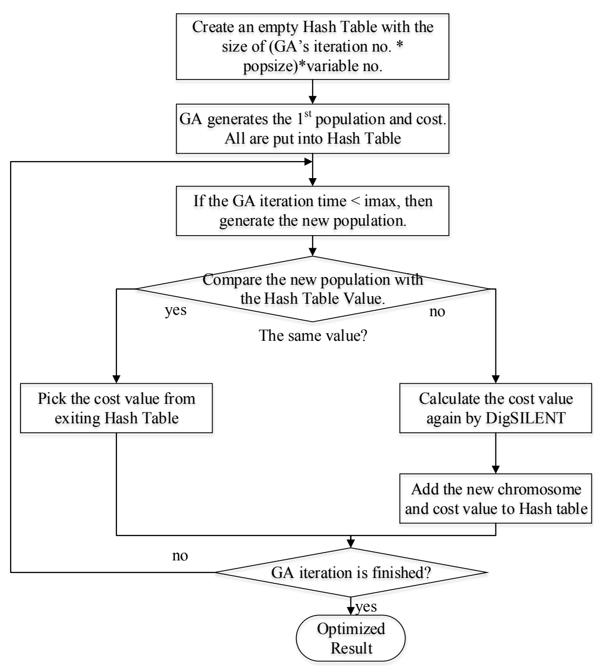

Fig. 9. HIGA Flowchart

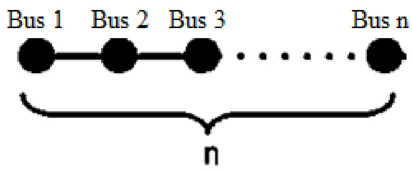

Fig. 10. Chromosome Structure

Sensitivity indices in the first-stage have an unbalanced evaluation mechanism, emphasizing that MCC should have more weight. For example, if a bus data has a Super High Current (SHC)-level MCC with no generator connected (NG), the output is the value more likely to be approached first. Then, in the second-stage, MFC acts in the leading role. The higher the value the MFC has, the more it influences the final output. Once the final output is determined, the sensitivity sorting of buses is completed. With above results, the first *m* buses are chosen for the following GA optimization step.

B. HIGA for Optimization

The traditional structure of the GA has the disadvantage that the same chromosome/solution may be generated more than once. A repetitive fitness value is thus calculated again; however, it costs computation time and decreases the efficiency, especially when applied in a large system or dealing with large quantities of data. To eliminate this problem, integrating hashing technique with the GA is proposed to solve the problem. Apart from the normal GA, HIGA employs a hash table to save the chromosome and its fitness value [32]. As shown in Fig. 8, the first chromosome is generated and saved in the hash table with its fitness value. Each chromosome is compared with the saved components in the hash table. Therefore, when the same chromosome appears a second time, the fitness value is obtained immediately, as marked in red in the figure. The HIGA flowchart is shown in Fig. 9, and the details of each step are listed as follows:

A hash table is initialed with a size whose length is the same as the iteration number multiplied by population size and width as a variable number plus one. The last row contains the fitness value of each population column.

1 The first GA population is generated, and the cost is then calculated. Population and results are input to the hash table.
2 The existing population is listed by the fitness value in descending order. The next generation is created based on the crossover or mutation mechanism and rate.
3 The new generation is compared with the existing chromosome in the hash table to check whether it is the same as the previous one.
   3.1 If the same, the fitness value is adopted directly without any further calculation.
   3.2 If different, the fitness value is calculated and then input to the hash table with its chromosome.
4 Stopping rule is checked.
   4.1 If max. iteration number is exceeded, the algorithm ends,
   4.2 If it is not exceeded, go back to Step 3.

Each variable has a fixed length binary number in the chromosome (as shown in Fig. 10). To simplify the optimization, every length refers to the FCL shunt reactor's value at the bus. However, if the value is zero, it denotes that there is no FCL installed.

The objective function is the key to an optimization algorithm. The proposed method is aimed at optimizing over-current-capacity systems with economic solutions. The problem is formulated as a multi-objective function in (11) with constraints that restrain the fault current within the CB interruption capacities. A penalty factor here is used for the constraint violation.

$$\min J = \sum_{i=1}^{N_B} Z_{i,FCL} + \varpi \times N + \alpha \times \Delta V \tag{11}$$

Subject to

$$Z_{i,FCL}^{\min} \le Z_{i,FCL} \le Z_{i,FCL}^{\max} i = 1 \cdots N_{FCL}$$

$$I_j^{SC} \le I_j^{SC,\max} j = 1 \cdots B_M$$

Where

$Z_{i,FCL}$ Shunt reactor's value of ith FCL

N The number of FCLs

ΔV Voltage variation at fault state

ω, α impact factor

IV. Case Studies

To verify the proposed approach for optimizing FCL placement, the method is implemented through Matlab and DigSILENT. The optimization method is programmed in Matlab with an interface developed to allow the power flow and fault analysis to be conducted in DigSILENT. The implemented approach is tested on the practical 83-bus power system of a large manufacturing factory in Taiwan to evaluate the quality of the achieved solution and the computational efficiency of the proposed approach (as shown in Fig. 11). The results from the proposed method are compared with those by using a Reference Method which employs MFC as space reduction index and HIGA as the following optimization algorithm. Based on the comparison, the advantages of the three-factor HFLS sorting can be demonstrated. The iteration time, population size, mutation rate and selection rate of HIGA are given to be 100, 16, 0.35 and 0.5, respectively.

There are 83 buses, 48 loads and 14 generators in this factory system, including three voltage levels (161kV, 33kV and 11.5kV). Due to the over-load problem and expansion of the factory, the fault current exceeds the exiting CB interruption capacities (50kA for 161kV and 40kA for 33/11.5 kV). The first 14 high fault currents can be found in Table III with their names before the FCL placement. To limit the over-capacity fault currents and leave a margin to ensure safety, the current limitation in constraint is given as 40kA. The optimization algorithm also employs the sorting results obtained from the sole index of MFC to perform the comparison.

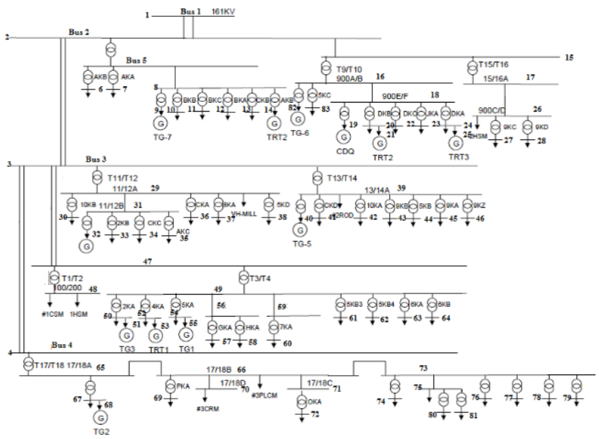

Fig. 11. Test System Topology

TABLE III
FIRST 14 HIGH FAULT CURRENTS BEFORE FCL PLACEMENT

Bus No.	Fault Current (kA)	Bus No.	Fault Current (kA)
Bus 82	95.537	Bus 3	32.221
Bus 24	69.310	Bus 51	31.708
Bus 17	62.720	Bus 32	30.594
Bus 16	53.805	Bus 50	28.500
Bus 5	35.699	Bus 12	27.981
Bus 32	33.783	Bus 2	27.363
Bus 1	32.221	Bus 67	26.776

TABLE IV
CANDIDATES OBTAINED FROM THE OPTIMIZATION METHODS

Proposed Method		**MFC with HIGA (Reference) Method**	
Bus No.	**Shunt Reactance (Ω)**	Bus No.	**Shunt Reactance (Ω)**
Bus 82	0	Bus 82	1.429
Bus 17	0	Bus 24	7.143
Bus 16	8.571	Bus 17	1.429
Bus 51	0	Bus 16	4.286
Bus 3	10	Bus 5	10

TABLE V
FIRST 10 HIGH FAULT CURRENTS

Proposed Method		**MFC with HIGA (Reference) Method**	
Bus No.	Fault Current (kA)	Bus No.	Fault Current (kA)
Bus 32	33.678	Bus 82	36.104
Bus 17	32.394	Bus 24	32.172
Bus 32	31.260	Bus 17	31.260
Bus 1	31.160	Bus 16	31.105
Bus 3	31.159	Bus 5	31.104
Bus 82	30.748	Bus 50	30.214
Bus 51	30.671	Bus 51	27.262
Bus 16	29.996	Bus 1	26.734
Bus 12	27.896	Bus 3	26.501
Bus 50	27.637	Bus 32	26.314

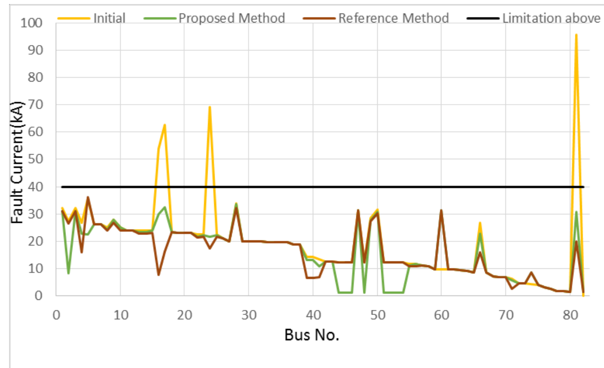

Fig. 12. Fault Current Comparison

Table IV shows the 5 candidates obtained from the proposed and the Reference Method, respectively. As can be seen, 5 FCLs are suggested by the Reference Method to be installed versus 2 FCLs done by the proposed method. Based on the candidates, the proposed algorithm optimizes the FCL placement and shunt reactors with zero meaning no FCL connected to that bus in TABLE IV. While the non-zero value indicates the FCL optimization location as well as its shunt reactance value.

To verify the advantages of proposed method, the fault currents are presented and compared by the Reference Method in Table V with the first 10 high fault currents after the optimization of FCL placement. Bounded by the interruption capacity of 40 kA, Fig. 12 further shows the fault currents comparisons of all the buses for the systems without FCL (initial), with the FCLs suggested by the proposed method, as well as with the FCLs by the Reference Method. It reveals in Fig. 12 that the proposed method does restrict the fault currents to the limitation with only two FCLs installed. In contrast, the referenced MFC integrated with HIGA method restrains fault currents to the limitation using five FCLs, which is obviously much less economical.

The effectiveness of the hash table is also demonstrated by the optimization with HIGA and normal GA referring to the same HFLS sorting candidates. It is noted that the computing time is decreased from 259 mins 7 secs to 180 mins 19 secs with the iteration number reduced from 1,600 to 1,459.

V. CONCLUSIONS

This paper has proposed an effective method based on HFLS sorting and HIGA optimization to obtain the best solution for the optimization problem of FCL placements and its shunt reactance values, especially for large power systems. HFLS renders the search for optimal candidates operational and effective, the results have been well verified in the case studies. The hash table has also been embedded in the GA to accelerate the optimization process with improved computing time demonstrated. The advantages of the proposed method are believed to be more apparent in application of the optimization approach in a large power system. Moreover, voltage variation is taken into account in the fitness function by using the significant function of FCL. Overall, the system security and reliability can thus be enhanced through the proposed method for optimal placement with less number of FCLs installed.

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