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Research Article

AN ELITIST GRAVITATIONAL SEARCH ALGORITHM BASED APPROACH FOR OPTIMAL PLACEMENT OF FAULT CURRENT LIMITERS IN POWER SYSTEMS

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ABSTRACT

Power system is getting complex due to a boost in the number of new power plants and the expansion of the transmission system in order to meet the growing for electricity. This scenario results in a large number of short circuits in the system, which may exceed the rating of existing circuit breakers (CBs) and may severely destroy system equipment. Installing fault current limiters (FCLs) into the power system is one of the most cost-effective ways to degrade fault current levels. This paper presents a method to specify the optimal numbers and locations for FCLs placement in terms of installing the smallest FCL parameters to restrain short-circuit currents below the interrupting currents of circuit breakers, to minimize transmission loss. Due to a lack of genetic, PSO and other optimization algorithms, an Elitist Gravitational Search Algorithm (EGSA) for more accurate and better results is used. This algorithm is employed to search for the location and parameter of FCLs to meet the specific requirements. The proposed method is applied to the IEEE 30-bus test system. Simulation results indicated the adequacy and precision of the proposed method.
Keywords: Fault Current Limiter (FCL), Elitist Gravitational Search Algorithm (EGSA), Optimal Placement, Circuit Breaker (CB).

1. INTRODUCTION

Growing electricity demand and using the distributed generations (DGs) cause the network providers to confront with a rise in grid loads. In consequence, power system equipment must be adapted with increasing the fault current levels [1]. By expanding and developing the electricity networks, the value of the fault current inchmeal develops. By increasing the fault current, network switches lose the capability of breaking this power. So, to break such current, it is obligatory to use circuit breakers (CBs) with higher breaking capacity. This inflicts vast costs on the system. After fault identification, to have considerable technically and economically saving,

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the fault current can obviously be confined by a method. This is conceivable by installing fault current limiters (FCLs) [2].

An FCL is an equipment having an insignificant impedance in a normal condition which is able to switch to a high impedance state if the current exceeds a given threshold value due to a fault. This device is capable to withstand the increase in short circuit power of the network to barricade other equi pment being damaged [3]. Because of these characteristics, the FCL will be an essential component for future smart grids. The installation of the FCLs on the power systems brings about the following advantages:

• Authorizes a high level of networks interconnection thus making possible a flexible link between producers, distribution operators, and consumers which is required in the modern electric market.

• Meliorates power quality by cutting down the voltage drop during a short circuit.

• Allows a higher power (voltage) quality by reducing interruptions, dips, harmonics, and flickers.

• Avoids using extra-size of components and avoids replacing the new protection equipment in case of network development [4].

Depending on the location of installation, FCLs could provide lots of advantages noted before but, their advantages appreciably depend on the number, location, and impedance of the FCLs [5]. Researchers have been proposed different objective functions for this purpose.

In [6], an iterative mixed integer nonlinear programming (IMINLP) algorithm was proposed to define the best location and size of FCL. In the paper, the total installation costs, including a fixed cost of installation and the incremental cost of impedance, is minimized by proposing an objective function.

A Genetic Algorithm (GA)-based FCL allocation was suggested in [7]. So the location and size of the FCLs are specified by minimizing the cost of the protection system.

A Harmony Search Algorithm (HSA) was employed to determine the location and impedance of FCL in power system which has fault currents exceeding the permissive amount of protective equipment while using the least amount of impedance [8].

A PSO-based method has been proposed in [9] that its objective functions are reliability, power loss, and economical use of FCLs.

Also, the PSO algorithm was utilized for optimal location and sizing of FCLs. The sizing optimization problem is formulated as a nonlinear programming problem in which the main objective is to minimize variations in fault current levels because of installation of DGs [10].

In [11], a search space reduction technique and GA was used to diagnose the optimal number and locations for FCL placement.

Enhancing the transient stability of power system is one of the objective functions that was noteworthy for researchers [12].

In [13], a solution to select the optimal location of the FCLs was suggested, which the sensitivity analysis of the angular separation of the rotors of synchronous machines was presented.

Authors in [14] have been incorporated transient stability as an objective function and explained the effects of fault type on the optimal location of FCL. In [15], a protective objective function has been used to locate and size the FCLs in the power system. In the paper, a method was proposed that consider the uncertainties of the DGs and the operating time of directional overcurrent relays.

In [16], the optimal location of FCLs was employed, in which the sensitivity analysis of power changes and power losses were calculated. In case of the fault occurrence, the FCL's resistive value is large and connected in series with a transmission line.

A two-stage optimization approach for optimal placement of FCLs was proposed in [17]. In stage I, the authors suggest a fuzzy logic based method for the reduction of search space for FCL placement and after that, GA is used to inspect the location of FCL. In stage II, PSO is employed to recognize the parameters of FCL. The weakness of this article, the two-stage optimization is, which increases the time taken to run the optimization algorithm.

In this paper, an Elitist Gravitational Search Algorithm (EGSA) for optimal placement of FCLs is employed that simulation results demonstrate the efficiency and accuracy of the proposed method compared to other algorithms. Also, in this algorithm, the optimal solution can be achieved in a less time and number of repetitions.

2. CIRCUIT BREAKER INTERRUPTION CAPACITY

Before presenting the proposed optimal placement of FCL, characteristics of fault current and interruption capacity of CB are briefly propounded [18].

2.1. Characteristics of Fault Current

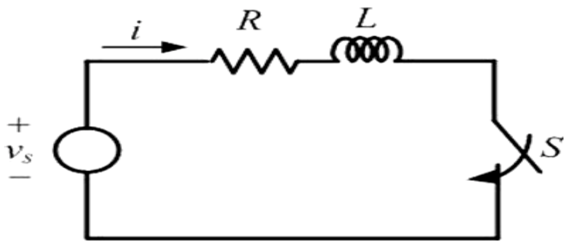

Figure 1. Current in a series R-L circuit with ac voltage source

To compute the short circuit current, the power system Thevenin equivalent circuit should be achieved (Figure 1). The Thevenin equivalent circuit consists of an AC source in series of R-L impedance. The KVL equations of Figure 1 is as follows:

$$L\frac{di}{dt} + Ri(t) = \sqrt{2}V\sin(\omega t + \alpha) \quad t \geq 0 \tag{1}$$

The solution becomes:

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

Where:

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

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

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

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

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

The total fault current (i(t)), the asymmetrical fault current, is shown in Figure 2. Pursuant to (3) and (4), it is divided into ac and dc components. The ac fault current named as the symmetrical or steady-state fault current is sinusoidal, while the dc statement decays by the time constant T, as given in (7). From the expressions presented above, each component is affected by the factors α and other components are sinusoidal terms introduced according to the diverse fault instants (as illustrated in Table 1).

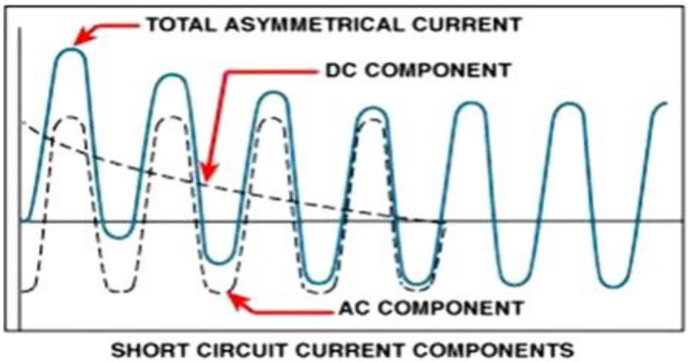

Figure 2. Total Fault Current

Table 1. Different Fault Current Values

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

In according to ANSI IEEE Std. C37.04-1999 [19], the standard rating structure for ac high voltage CBs rated on a symmetrical current basis is considered as the reference. The needed symmetrical and asymmetrical interruption capabilities are relied on one-half of the cycle relay time, and sometimes, an admissible tripping delay time is utilized instead. The peak value of the symmetrical component of the phase-to-phase short-circuits currents in rms specifies the rated short-circuit capacity of a CB. This value specifies the current at which the CB should normally closed and open. Routinely, the capacity of CB is adjusted to be equal to K times the rated short-circuit current. The K value of a modern CB is defined as 1.0, while that of former CBs exceeds 1.0. The asymmetrical interruption capability is allocated pursuant to the rms value of the total short-circuit current in amperes at the instant of the primary arcing contact separation. The rated interrupting current standard employed 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 specify the asymmetric fault current are used to estimate whether the CB interruption capacities are satisfactory (as shown in (8) and (9)):

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

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

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_{sy}: symmetrical fault current

3. GRAVITATIONAL SEARCH ALGORITHM

Evolutionary algorithms can unravel many optimization problems [20]. Some algorithms result in a better solution for some problems. Hence, evolutionary algorithms are still popular among researchers [21]. In [22], an optimization method named Gravitational Search Algorithm (GSA) is proposed. In this algorithm, an optimization approach based on the law of gravity was introduced [23]. The agents of this algorithm are supposed as objects and their performance are measured by their weights. All of these objects absorb each other using the gravity force. This force causes a global motion of all the objects toward the larger ones. Large objects correspond to the eligible solutions. Also, the large objects have slower velocities rather than small ones, which guarantees the efficiency of the algorithm.

3.1. Law of Gravity & Motion

In GSA, every object has four specifications; location, inertial weight, active gravitational weight, and inactive gravitational weight. The location of the objects is a point in the search space which is a solution of the problem. The weight of gravitational and inertial objects is determined based on their fitness value. In other words, every object is a representation of a solution and the algorithm is conducted by tuning the gravitational and inertial weight parameters. Corresponding to the algorithm, all the objects are expected to be attracted by the heavier object. This object expresses the optimal solution in the search space.

The system is presumed as a set of "n" objects and the location of these objects is a point of the search space that is the solution to be obtained. The location of the i^{th} object is calculated using (10):

$$V_i = Xi = \left(X_i^1. \dots . X_i^d. \dots . X_i^n\right); \quad \text{for } i = 1.2. \dots . N \tag{10}$$

The location of the dimension "d" of the i^{th} object is represented by X_i^d. At the time "t", the force originated from object "j" and affected the object "i" is calculated using equation (11):

$$F_{ij}^d = G(t)\frac{M_{aj}(t) \times M_{pi}(t)}{R_{ij}(t)+\varepsilon}(X_j^d(t) - X_i^d(t)) \tag{11}$$

In (11), the parameters M_{aj} and M_{pi} are respectively the active and inactive gravitational weights corresponding to the j^{th} and i^{th} objects. G(t) is the gravity constant at time t and R_{ij} is the Euclidian distance (norm 2) between i^{th} and j^{th} objects; the parameter "ε" is a very small positive number.

$$R_{ij}(t) = \left\| X_i(t). X_j(t) \right\|^2 \tag{12}$$

To preserve the stochastic characteristic of the proposed algorithm, it is assumed that total forces from i^{th} object to the j^{th} object equals the sum of random of forces, affecting it.

$$f_i^d(t) = \sum_{j=1.j\neq i}^{n} rand_j \times F_{ij}^d(t) \tag{13}$$

In (13), $rand_j$ is a random number with a uniform distribution in the range [0, 1]. Based on the Newton law of Motion, the acceleration of the i^{th} object in the j^{th} dimension at time t is represented by $a_i^d(t)$ and inertial weight of the i^{th} object is represented by M_i.

$$a_i^d(t) = \frac{f_i^d(t)}{M_{ii}(t)} \tag{14}$$

The velocity of any object equals as follows:

$$V_i^d(t+1) = rand_i \times V_i^d(t) + a_i^d(t) \tag{15}$$

Hereupon, the location of each object is calculated as follows:

$$X_i^d(t+1) = X_i^d(t) + V_i^d(t+1) \tag{16}$$

The parameter $rand_i$ is the uniform random variable in the range [0, 1]. This random variable makes the search space to be random.

3.2. Gravity constant "G"

At the onset, the gravity constant "G" starts with an initial value (G_0) and decreases over times. Because of the gravity decrement phenomenon, the actual value of the gravity constant depends on the genuine age of the earth. The gravity constant is represented in equation (17). Based on (17), the gravity constant is a function of the initial value G_0 and the time t, and is represented in (18):

$$G(t) = G(t_0) \times \left(\frac{t}{t_0}\right)^B \tag{17}$$

$$G(t) = G(G_0. t) \tag{18}$$

G_0 is the value of the gravitational constant at the first cosmic quantum-interval of time of "t_0". The "G" constant is used to control the accuracy of the search algorithm and β is an attenuation factor and is commonly a constant. The inertial and gravitational weights could be updated using (20).

$$Ma_i = Mp_i = M_{ii} = M_i = Z\ ; \ \ for\ i = 1.2. \dots . N \tag{19}$$

$$Z(t) = \frac{(Fit_i(t) - Worst(t))}{(best(t) - Worst(t))} \tag{20}$$

In (20), $Fit_i(t)$ is the fitness of the i^{th} object at time t. In minimization problems, one may use equations (21), (22) to calculate the best and worst fitness value, respectively.

$$best(t) = \min fit_j(t) \qquad j \in \{1.2. \dots . N\} \tag{21}$$

$$Worst(t) = \max fit_j(t) \qquad j \in \{1.2. \dots . N\} \tag{22}$$

In maximization problems, equations (21) and (22) may be used to calculate the worst and best fitness value, respectively.

3.3. Elitist Gravitational Search Algorithm (EGSA)

In [24], an advantageous optimization method was introduced to solve the optimization problems. In most of the problems, one way to make a compromise between the exploration and exploitation is reduction the number of the agents, with time, according to (13). Therefore, only an adjust of larger objects that impress the other ones, would be taken into account. In order to avoid from the local optimal traps, after several iterations, the exploration should be less used and the exploitation should become more important and used. In order to attain this goal which is to the enhancement of the searchability, object selection influence should be used. To do this, only the "K" superior objects of the population, have the capability of affecting the other objects. In other words, in every iteration of the algorithm, any individual object is impressed by a force which is the consequence of the forces originated from the individual "K" superior objects. Therefore, the (13) is modified as (23).

$$f_i^d(t) = \sum_{j\in K_{best}, j\neq i} rand_j F_{ij}^d(t) \tag{23}$$

In (23), "K_{best}" is the "K" superior objects of the population that have the best fitness and heavier weight. The "K_{best}" is a function of time which begins with the K_0 as the initial value and decreases with time. This decrement is linear and eventually, there is just one agent, affecting the others. The aforesaid method somehow reduces the required mathematics.

3.4. Methodology

The approach for placement and sizing of FCL has two phases. In phase I, search space is decreased and the possible location of FCL is chosen; and in phase II, by using EGSA, the optimal sizing of FCLs are calculated. The procedure of phase I start with load flow and short-circuit analysis. For this goal, the system is simulated and load flow is calculated. After that, a short-circuit analysis should be done by considering a wide range of faults at different locations of the system.

The capacity of CBs should be specified; it is considered about 10 times more than nominal current and the value determined from the load flow stage. The contribution of this paper is that the proposed method can be adapted on any system. At first, the differences of line currents in fault conditions and the CB rated current is calculated (ΔI) and the number of times that the line fault current exceeds the CB rated current is specified (N_f). By considering ΔI and N_f, a probability matrix is formed.

After realizing the numbers and locations of FCLs in the test system, EGSA is applied for determining the parameter of FCLs. The objective function of EGSA is:

$$fitness = w \times \sum_{i=1}^{Nf} Z_{FCL} + \sum_{i=1}^{Nf} \Delta I \tag{24}$$

In (24), "w" is a weight factor that is used to balance the two terms of the fitness function.

3.5. Simulation and Results

To assess the proposed approach for the optimal FCL placement problem, the approach is applied to the IEEE 30-bus system (Figure 3). The network consists of 30 buses and 41 lines. The nominal current of the lines calculated from load flow is shown in Figure 4. The FCL reduces the fault current at the first cycle in fault conditions. By knowing that fact the probability matrix should be calculated and the value of maximum (PROB) of aforesaid matrix is stated.

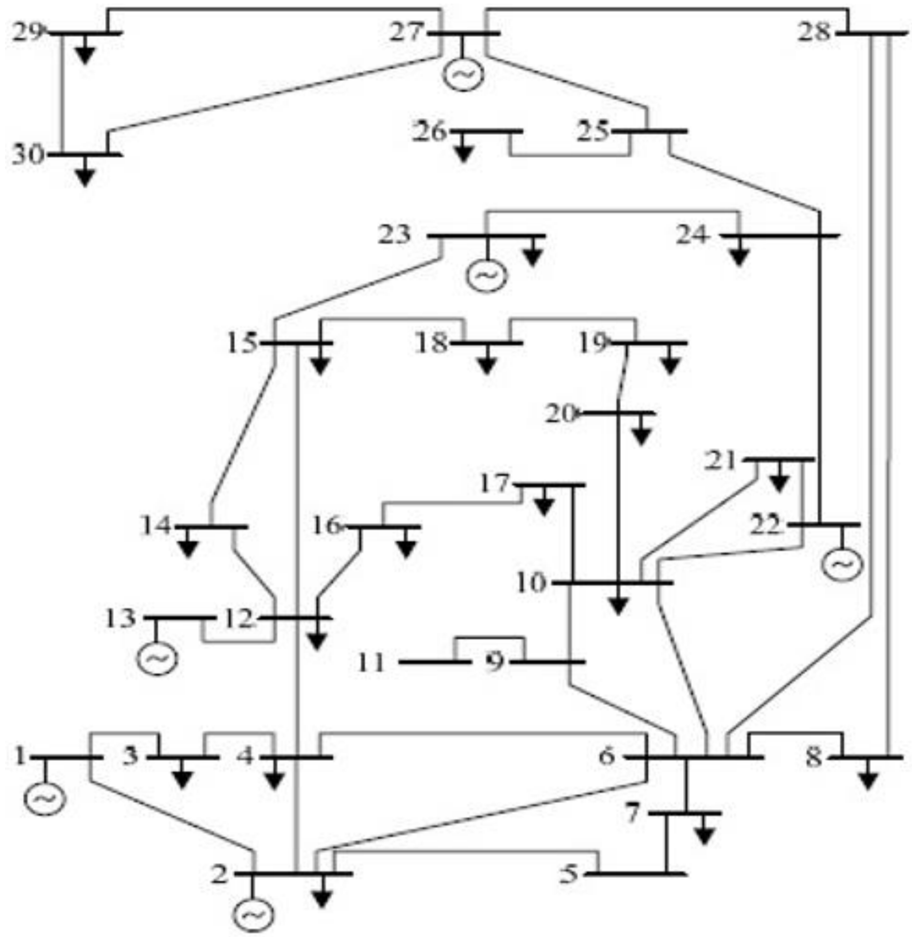

Figure 3. IEEE 30-bus test system

The results of the proposed method for IEEE 30-bus system are indicated in Table 2. From this Table, it is obvious that lines 1, 2 and 9 are the possible locations for FCL. For these lines, the ΔI are above the adaptive threshold and N_f are much more than the other lines. It means that these lines are a candidate for higher short circuit levels and the probability of high fault currents are much more for them. The results of phase II of the proposed method is shown in Table 3. Table 2 shows the optimized parameter of FCLs. The optimal impedance values obtained from EGSA are more accurate than the GA and PSO algorithms value. Figure 5 shows the fitness value variations of EGSA iterations. The EGSA algorithm has some advantages with regard to the PSO algorithm as follows: In the PSO algorithm, the directions of the movements are only calculated by the usage of P_{best} and G_{best}. Whereas in EGSA, the movements are calculated by means of all forces obtained by all other agents. Another advantage of the EGSA with respect to the PSO is in PSO, updating is performed without considering the quality of the solutions, and the fitness values are not momentous in the updating procedure while in GSA the force is proportional to the fitness value and so the agents see the search space around themselves in the influence of force [22]. GA has many problems in comparison with EGSA and one of the main problems is premature convergence due to a loss of population diversity at a suboptimal point [22].

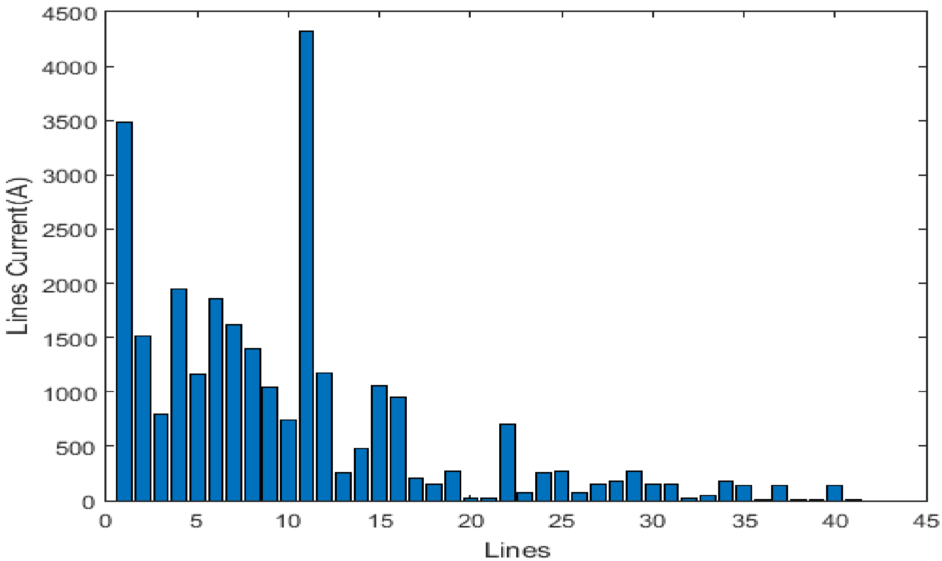

Figure 4. The nominal lines currents of IEEE 30-bus system.

Table 2. Results of the proposed method for IEEE 30-bus system

line	I_f	ΔI	PROB	line	I_f	ΔI	PROB	line	I_f	ΔI	PROB
1	16	5.622	0.358	12	0	0	0	23	0	0	0
2	11	1.984	0.205	13	0	0	0	24	1	0.0006	0.0005
3	0	0	0	14	0	0	0	25	0	0	0
4	3	0.097	0.029	15	0	0	0	26	7	0.461	0.061
5	1	0.001	0.001	16	0	0	0	27	6	0.350	0.052
6	3	0.093	0.029	17	0	0	0	28	5	0.266	0.048
7	3	0.090	0.028	18	0	0	0	29	4	0.192	0.043
8	0	0	0	19	0	0	0	30	3	0.143	0.043
9	8	0.596	0.067	20	2	0.0776	0.034	31	2	0.094	0.042
10	0	0	0	21	0	0	0	32	1	0.048	0.043
11	0	0	0	22	0	0	0	33	0	0	0

Table 3. Optimized impedances for FCLs for IEEE 30-bus system

Line	Impedances for FCL (pu)
1	0.341
2	0.167
9	0.092

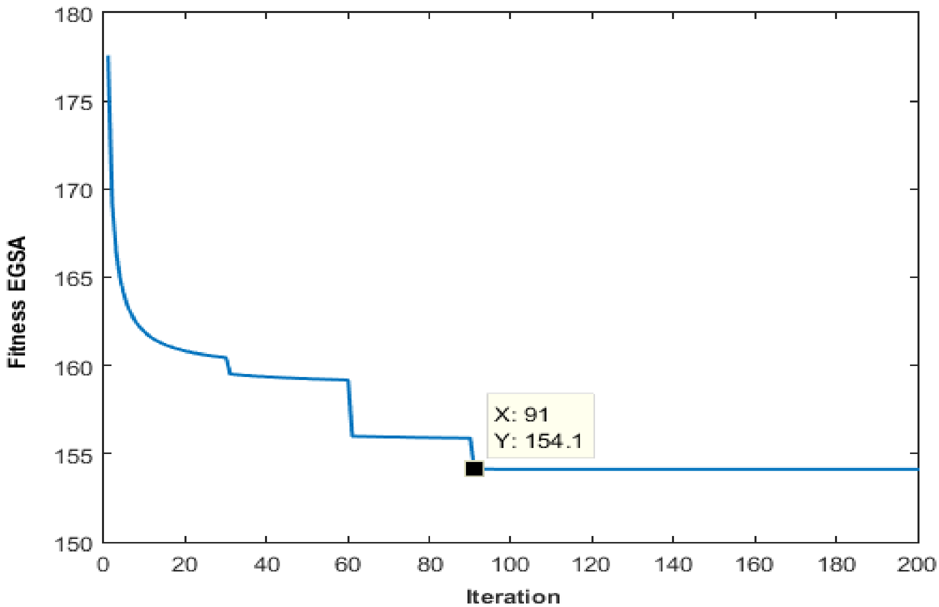

Figure 5. Fitness value variations of EGSA iterations.

Also, according to Figure 6, GA and PSO algorithms have converged after 113 and 106 iterations, respectively. While EGSA has converged after 91 iterations; which is indicative of the rapidity and ability of this algorithm. Fault current flowing through the CBs in the presence and absence of FCLs with different algorithms are shown in Figure 7. Because of EGSA capability, the fault current values flowing through the CBs in the presence of FCL is more accurate than the other algorithms, which is indicative of the accuracy of the EGSA algorithm. It is noticeable that the fault currents flowing through the CBs for a network with FCLs that utilizes EGSA are in the range of CB capacity for interrupting the faulty lines. Also, it is so clear that FCLs limit the current so that the network could stay stable and continue its task and operation.

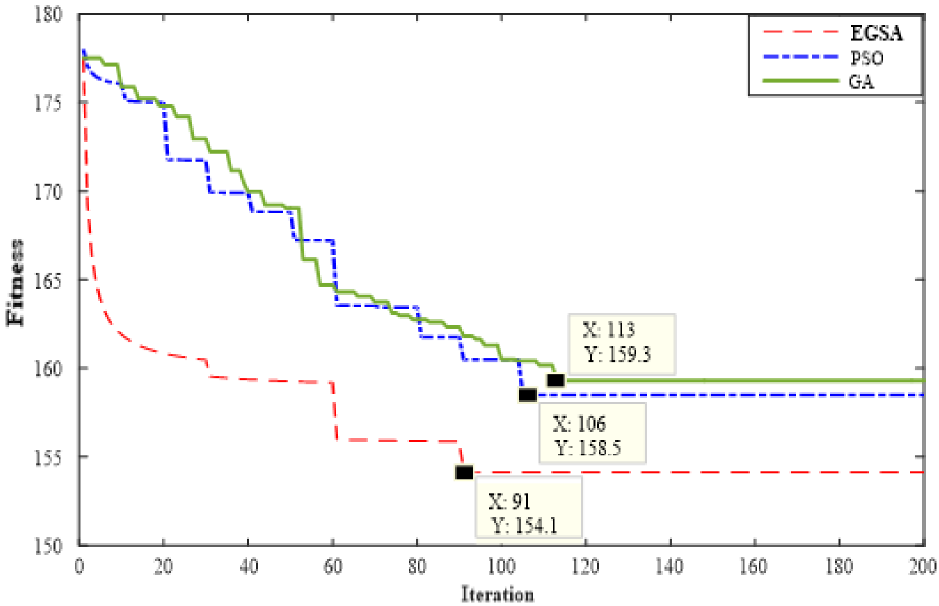

Figure 6. Fitness value variations of EGSA iterations.

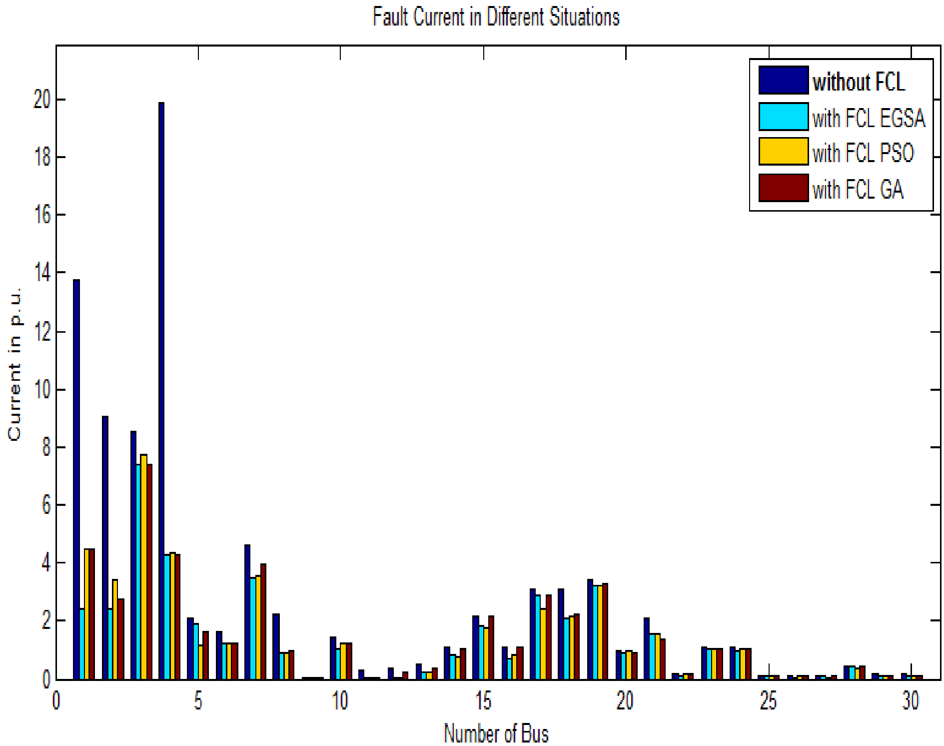

Figure 7. Fault current flowing through the CBs of IEEE 30-bus system with different algorithms.

5. CONCLUSIONS

In this paper, a novel FCL sizing and placement scheme is presented. The FCLs are placed with the goal to restrict the fault currents at buses and the fault currents flowing through lines caused by faults at other buses. In this paper to the optimization problem is determines in order to minimize the used impedance while satisfying the defined constraints. The proposed method is implemented in the 30 bus IEEE system and EGSA is employed to solve the optimization problem. The results demonstrate that the fault currents are suppressed to the admissible levels using the least impedance. Also, the results show that the values obtained from EGSA are more accurate and more reliable.

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