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Optimal Deployment of Fault Current Limiters for Fault Current Mitigation in Distribution Network

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ABSTRACT

Fault Current Limiters (FCLs) are used to suppress the fault current to a level that can be handled by the circuit breakers (CB). In medium voltage meshed Distribution Network (DN), the effectiveness of the FCL depends to a large extent, on the number, locations and parameters of the available FCLs. As such, this paper presents an Invasive Weed Optimization (IWO) based technique to determine the location of predefined number of FCLs and their parameters in order to constrain the fault currents to tolerable limit of the CBs' ratings. The number of candidate locations of the FCL in a distribution network is large, as such sensitivity analysis based on the fault currents is carried out first in to order to reduce the search space. The IWO is applied to solve an objective function based on the lines fault current and the impedance of the individual FCLs. The short-circuit fault current maximum allowable ratings of the CBs based on IEEE C37.04-2018, and the FCLs' impedances are used as the inequality constraints. To demonstrate its effectiveness, the developed FCL placement technique is developed in MATLAB simulation and applied on IEEE 14-bus, 30-bus, and 118-bus meshed systems. The performance of the proposed technique is validated by comparing the reduction in the fault currents on all the sensitive lines with those obtained using genetic-algorithm (GA). With the FCLs optimally deployed using IWO, the fault currents were reduced by 24.58%, 21.94% and 21.87% in the IEEE 14-, 30-, and 118-bus system respectively when compared with the GA.

Keywords— circuit breaker, distribution network, Invasive Weed Optimization, Fault current Limiter.

INTRODUCTION

Faults in Distribution Networks (DNs) are responsible for many forms of power quality issues ranging from blackout and severe overvoltage that can damage equipment. For instance, a single line-to-ground (SLG) faults count for around 70% of total faults in power DNs, even though three phase fault is more severe (Cardoso *et al*., 2022; Chantachiratham & Hongesombut, 2012). This is why the three-phase fault information is used to select and set phase relays while line-to-ground fault is used for ground relays (Chen *et al.*, 2021). Regardless of the type, fault leads to the injection of large abnormal current regarded as fault current. When fault occurs, the impedance of system suddenly becomes very low at effected point as a result of 5 to 15 times of rated current flow through the system. When this large fault current passes through the components, it creates excessive heat which can damage the equipment (Elmitwall *et al.*, 2016).

With the exponential growth of the grid connected Distributed Generation (DG), and over-stretched network facilities, power networks experience short-circuit faults repeatedly. In addition, the engagement of new energy suppliers, including independent and residential producers supplying to DNs directly have significantly increased the fault current levels of most networks. This led to overstressing the installed protection equipment and making necessary changes in the DNs (Farzinfar and Jazaeri, 2020; Fathi and Sadeh, 2020).

The conventional approaches used to curtail the devastating effect of the fault currents include the use of high-capacity circuit breakers (CBs), high impedance transformers, fuses, air-core reactors, and reconfiguration of the system such as splitting of power buses (Ghanbari *et al*., 2021). Many of these approaches have the disadvantage of tripping other additional breakers and disconnects, thereby bringing successive power outages that lower the reliability of the network (Ghanbari *et al.*, 2021). It would also cause potential instabilities in the power system, which in some cases may contribute to major cascading failures (Hu and Chiang, 2018). Even though the best solution is the replacement of the overstressed equipment, however it is not cost-effective alternative. As such, numerous solutions were devised to suppress the fault current and limit to it a level that can be handled by the CB (Behzadirafi, 2015).

Conventionally, adjustable arc suppression coils (ASCs) are automatically tuned to compensate the reactive component of the fault current by creating resonance with the distributed capacitor which is also known as the resonant grounding technique (Jain *et al*., 2016; Kothari and Nagrath, 2014). Over the years, the have been gradually improved to adequately compensate capacitive fault currents without putting

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much emphasis to compensate the active component (Jarrahi et al., 2019; Chantachiratham & Hongesombut, 2012). However, the magnitude of the fault current from its active portion is sufficient to overpower the CB and cause damage to the system. Fault Current Limiters (FCLs) are capable of compensating both active and reactive components of the fault current as they can be flexibly controlled to suppress the current. It is established that FCL device is faster and more cost effective than the ASCs (Sadeghi and Abasi, 2021; Khazali and Kalantar, 2014).

Moreover, FCL provides the essential protection to the network with fast action and short recovery times, low power loss, and the least negative effect on power quality and reliability (Kumar *et al*., 2020). It suppresses the fault current and hence reduces mechanical and thermal stress on the DN components. Various types of FCLs such as explosive limiters, solid state FCL, superconducting FCL, resistive, inductive, bridge, and resonance types have been studied and applied for fault currents suppression (Kong *et al.*, 2018). During the occurrence of a fault, an active FCL limit the fault current flow by exerting a high impedance, while under normal operating condition exhibiting a negligible impedance. In addition to fault current suppression, FCL can used for the enhancement of energy transmission, mitigation of voltage sag caused by a fault, and improving system stability, security and reliability (Wood, *et al.*, 2014).

In spite of the various applications of FCLs, its effectiveness largely depends on the location in the network, number and the parameters (impedance for instance) of the FCL. In DNs with radial structure, the placement of FCL is easy and straightforward, as it is generally installed next to the distribution substation (Pirouzi *et al.*, 2017; Farzinfar and Jazaeri, 2020). However, in meshed DNs, the FCL placement becomes much more complex. The complexity increases with the number of FCLs and the size of the DNs (Li *et al*., 2020). The difficulty can be attributed to the bidirectional flow of the fault currents which are not easily blocked by a single FCL, as against the unidirectional flow in the radial network (Pirouzi *et al.*, 2017; Sadeghi and Abasi, 2021).

Various approaches have been proposed for determining the optimal number, location and parameters of FCL in DNs, with different objectives. For instance, (Teng and Lu, 2018) applied genetic algorithm to determine optimum numbers and locations for FCL installed with the smallest FCL parameters to restrain short-circuit currents under CBs' interrupting ratings. Sensitivity factors of bus fault current reduction due to changes in the branch parameters are formulated and applied to choose the candidates for FCL installations. While in (Chantachiratham and Hongesombut, 2012), optimum numbers and locations for FCLs are determined in order to minimize the transmission loss and keep the bus voltages within their allowable limits. Particle Swarm Optimization (PSO) method is employed to search for the best location and parameter of FCLs to meet the specific requirements. Similarly, placement and sizing of the hybrid superconducting FCLs to restore the protection coordination of the DNs with the synchronous DGs is presented in (Sadeghi and Abasi, 2021). The aim is to reduce the size of the hybrid SFCLs and the total operation time of overcurrent relays for two primary and backup protection models in the fault conditions as much as possible. A crow search algorithm is utilized for the optimal solution of the problem. In (Yang, *et al.*, 2018), a two-stage optimization tool for the optimal placement of FCL is developed. The first stage of method combined a hierarchical fuzzy logic decision (HFLD) method and Hashing-integrated generic algorithm (HIGA). The HIGA is then further applied to determine the FCL initial shunt reactance of the candidate buses. Subsequently, PSO is then employed in the second stage for optimizing the FCL parameters in IEEE 30-bus system.
Furthermore, (Fathi and Sadeh, 2020) proposed a Genetic Algorithm (GA)-based method for finding optimal number, places and sizes of FCL to suppress fault currents in DN with Distributed Generations (DGs). In most of these studies, there are various constraints considered. These include constraining the fault current within maximum CB fault current ratings, relay setting parameters, minimum and maximum impedance of the FCL, among others (Teng and Lu, 2018).

Most of the aforementioned techniques suffer from drawback to another. These include constraints violation, convergence at local minima and computational complexity (Sadeghi and Abasi, 2021). Furthermore, some FCL placement techniques are restricted to radial network which quite straight forward. This study therefore, developed a technique for the optimal allocation of minimum number of FCLs in mesh DN and their parameters in order to minimize the fault currents to tolerable limit of the CBs' rating using an Invasive Weed Optimization (IWO) (Li *et al*., 2020). The IWO is chosen due to its effectiveness and robustness of the algorithm in solving mix-integer non-convex problems.

I. FORMULATION OF THE FCL PLACEMENT

The developed technique seeks to optimally determine the location of FCLs and their parameters in order to constrain the fault currents to tolerable limit of the CBs' ratings. As such, the objective function is formulated as a minimization problem;

$$\min\left\{\sum_{k=1}^{N_{FCL}} \mu Z_k^{FCL} + \sum_{j=1}^{N_{FCL}} \lambda\left(\frac{I_j^{fault}}{I_j^{fault} - I_j}\right)\right\} \tag{1}$$

Where Z_k^{FCL} is the impedance of kth FCL and N_{FCL} is the number of the FCLs. μ and λ are the weighting coefficients for trading off between the size of the FCLs and the fault currents, I_j^{fault}.

*A. **Invasive Weed Optimization Application***

The minimization of (1) is subject to the following constraints:

Fault current constraints: the fault current is constrained within the maximum allowable short-circuit current rating of the CBs, as

$$I\_l\text{\^{}}fault \leq I\_l\text{\^{}}CB \tag{2}$$

CL impedance constraints: for economic consideration, the impedance of the FCLs are constrained within certain minimum and maximum limits, $Z_k^{FCL\_min}$ and $Z_k^{FCL\_max}$ respectively, as shown in (3)

$$Z_k^{FCL\_min} \leq Z_k^{FCL} \leq Z_k^{FCL\_max} \tag{3}$$

To solve (1) subject to (2) and (3) as constraints, invasive weed optimization algorithm is applied.

*B. **Invasive Weed Optimization Application***

Due to its effectiveness and robustness of the algorithm in solving mix-integer non-convex problems, a population-based evolutionary Invasive Weed Optimization (IWO) is used to solve the sizing and placement of FLCs. In order to obtain the optimal solution faster, the IWO is presented with a certain portion or region of the search space. This certainly increases the likelihood of finding global optima faster rather than getting stuck in local optima. In addition, the reduction onal complexity.

Initially, fault analysis is carried out by inserting short circuit fault in various locations of the system at each time instant. Average fault current on each branch is computed. The branches are then ranked in the order of the fault current impact, ΔI_i defined in (4),

$$\Delta I_i = I_i^{fault} - I_i \tag{4}$$

The network branches are then arranged in the order of the ΔI_i and the most critical branches are selected. The IWO then optimized the FCLs based on the reduced space.

In the first instance, having defined the number of the FCL, n, the location, L_{FCL} and impedance, Z_k^{FCL} of the FCLs are generated randomly. Every string of the seeds represents a vector (population) constituting two equi-dimensional sub-vectors. The first sub-vector of the seed population is integer vector of FCL locations; L_1^{FCL}, L_2^{FCL}, …,L_n^{FCL} while the second is non-negative real valued vector representing their respective impedances; Z_1^{FCL}, Z_2^{FCL}, …, Z_n^{FCL} as schematically shown in Figure 1.

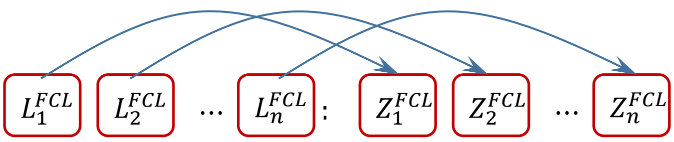

Figure 1: Representation of the IWO seeds of the developed FCL placement.

The seeds generated are then used to calculate the fitness values which are dispersed around the parent weed (Mehrabian and Lucas, 2006). The plant in the population is then allowed to produce seeds depending on its own fitness and the adaptability as well as the lowest and the highest fitness value of the plants in the colony. At each iteration, standard deviation is varied from an initial value of σ_{initial} to a final value of σ_{final}, using (5)

$$\sigma_{iter} = \left(\frac{iter_{max} - iter}{iter_{max}}\right)^n - \left(\sigma_{initial} - \sigma_{final}\right) + \sigma_{final} \quad (5)$$

Where, $iter_{max}$ is the maximum number of iterations, σ_{iter} is the present iteration standard deviation and n is the modulation index (Roozbeh *et al.,* 2014). The number of iterations is used as stopping criteria. Figure 2 shows the flowchart of the developed IWO-based FCL placement and sizing.

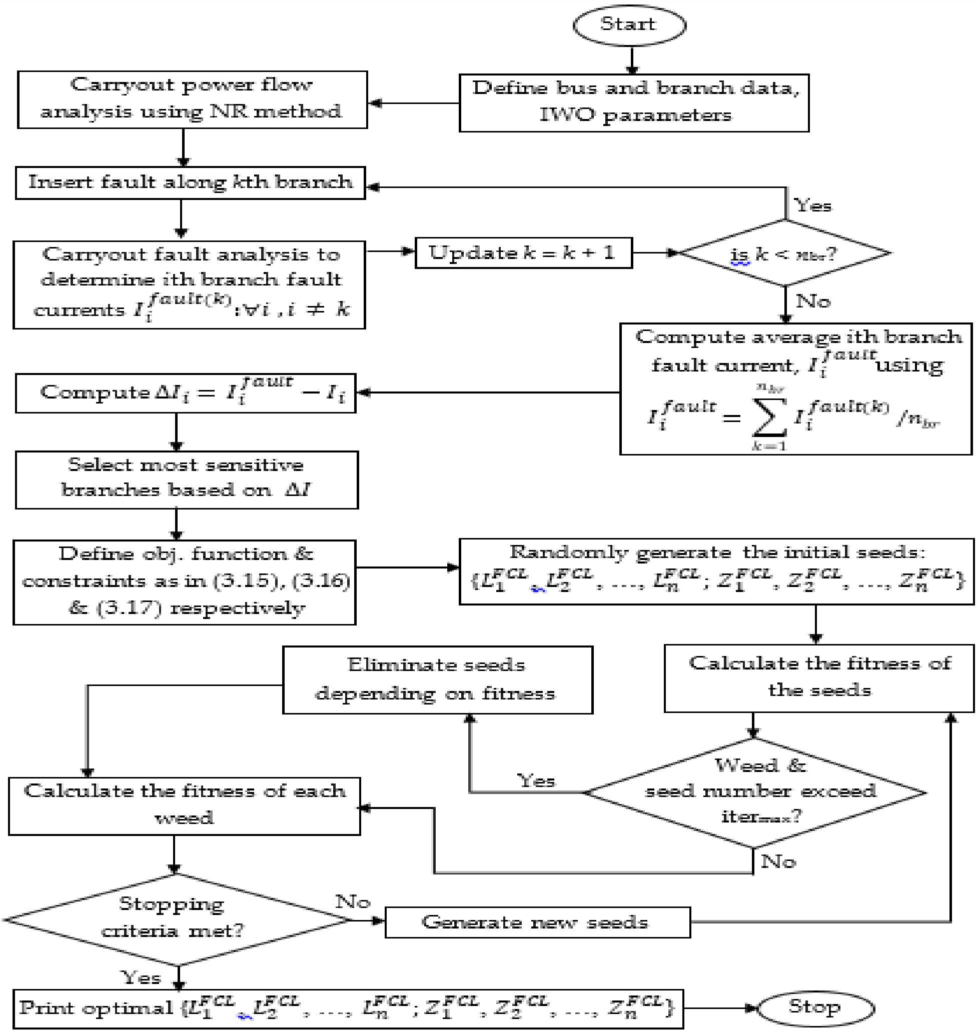

Figure 2: Flowchart of the developed FCL placement

After defining the network line and bus data, load flow and fault analysis is carried out to determine the normal and fault condition of the system. Fault impact (ΔI) is computed to get the most sensitive lines. The IWO then determine the optimal location and size of the FCLs based on the objective function in (1), subject to constraints defined in (2) and (3).

Due to its efficacy, IWO is applied for other engineering applications. For instance, in (Kaur, 2023), IWO is applied for optimal power flow in power system networks.

II. TEST SYSTEMS DESCRIPTIONS

The developed scheme is tested on IEEE 14-bus, 30-bus, and 118-bus systems. Among factors considered to choose these systems for this study are their sizes and network topologies.

The IEEE 14-Bus System is a well-known benchmark used in power systems analysis and research. The system consists of 14 buses (nodes) connected by 19 branches and includes various generators, loads, and branches. IEEE 14-Bus system has 5 synchronous generators, which represent power generation sources. Each generator is connected to a specific bus and contributes to the overall power supply of the network. Figure 3 shows the single line diagram of IEEE 14-bus system.

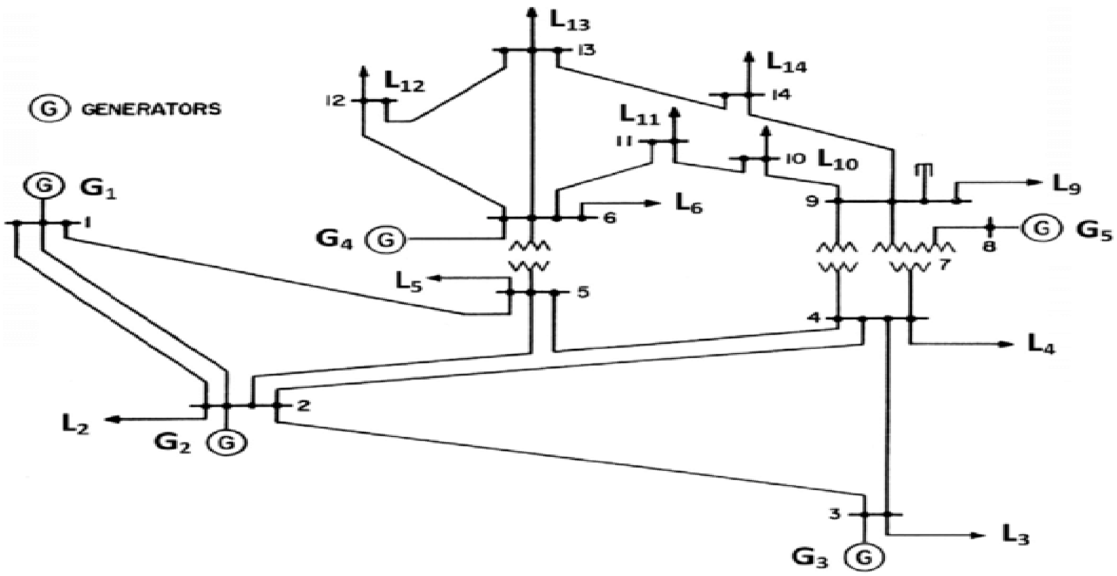

Figure 3: IEEE-14 Bus Single Line Diagram (Chen, 2003)

While the IEEE 30-Bus system consists of 30 buses connected by 41 branches. Figure 4 shows its single line diagram. In addition, the IEEE 118-bus is bigger than the previous two systems in terms of size (number of buses). The system has 118 buses, 118 branches, 54 thermal units and 91 load points. The line diagram of IEEE 118-bus system is shown in Figure 5.

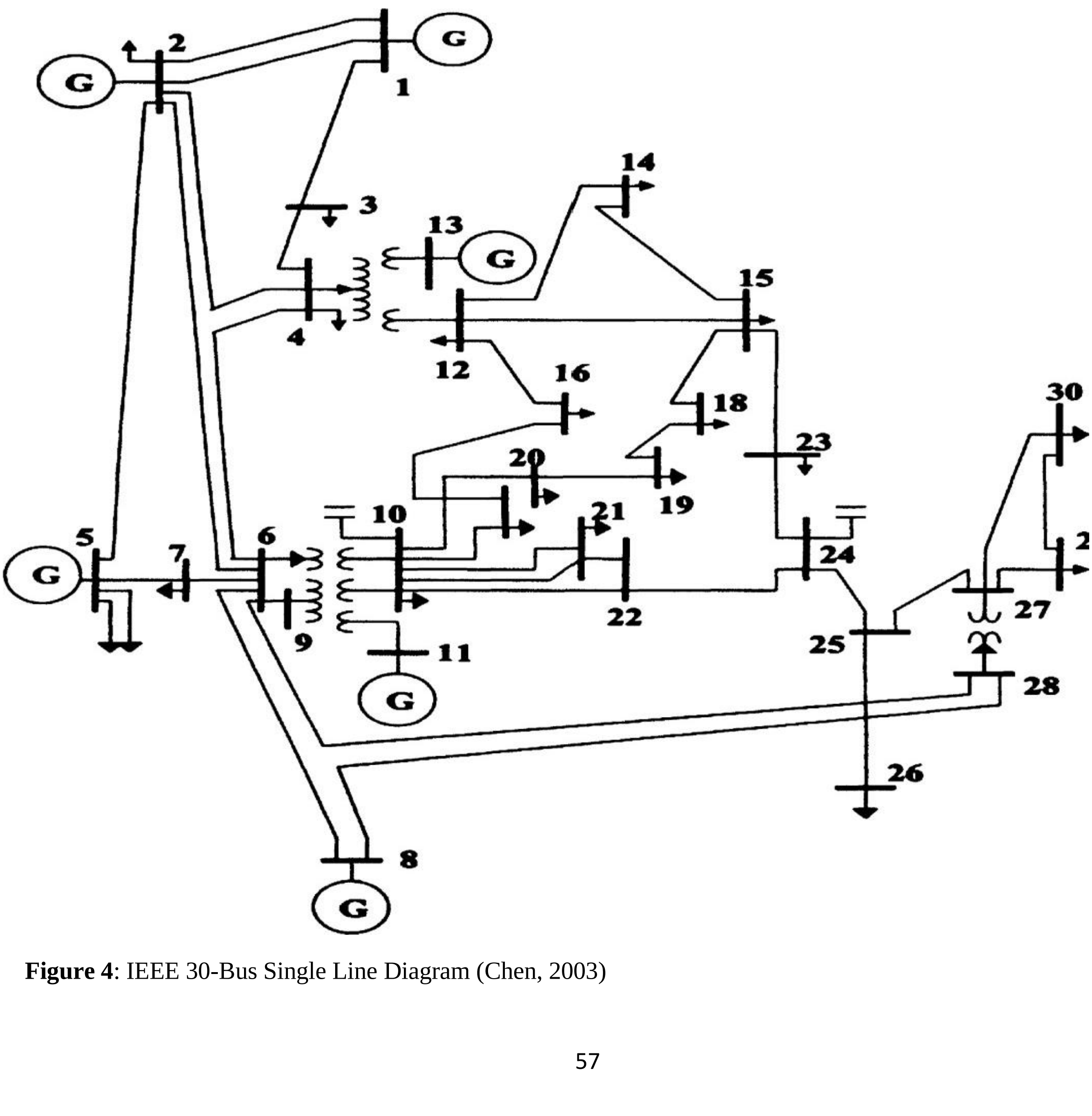

Figure 4: IEEE 30-Bus Single Line Diagram (Chen, 2003)

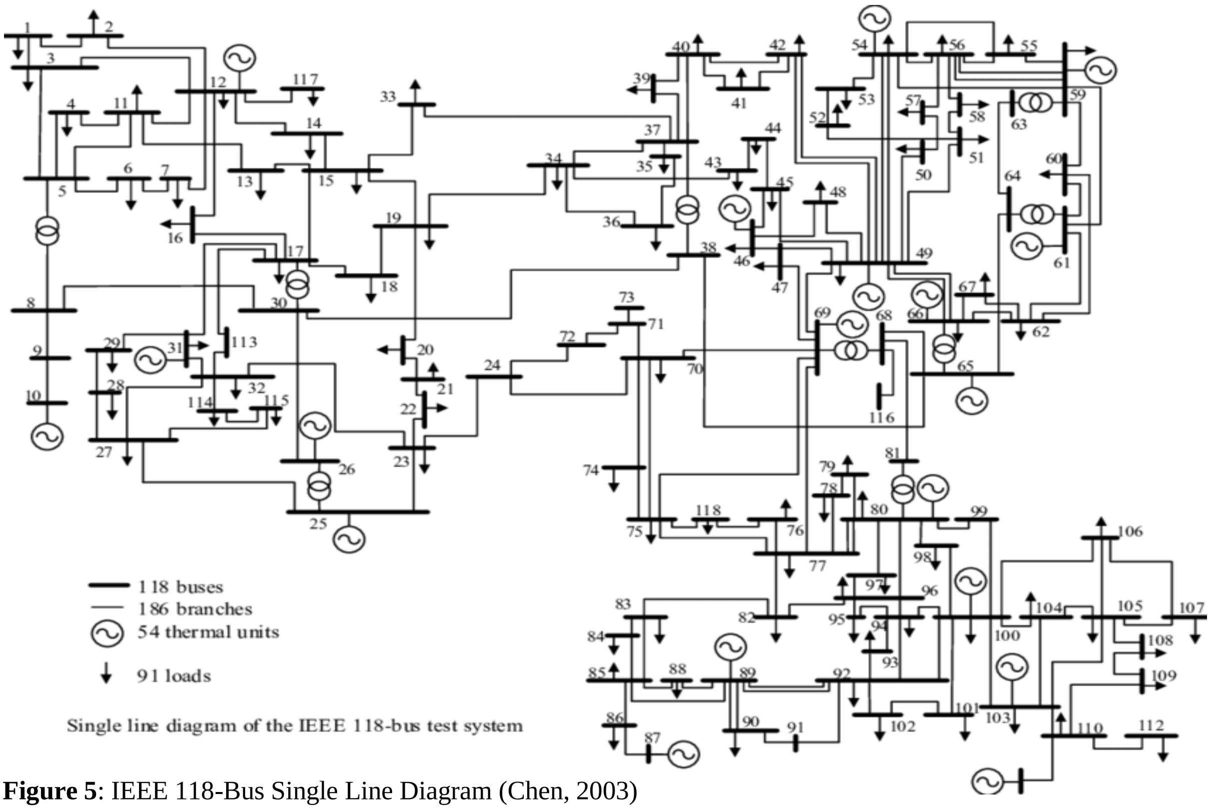

Figure 5: IEEE 118-Bus Single Line Diagram (Chen, 2003)

RESULTS AND DISCUSSION

This section presents the simulation results of the optimal placement of the FCLs in the medium voltage Distribution network using the IWO. The siting and sizing scheme of the FCL is developed in MATLAB simulation environment.

IEEE 14-bus System

In order to demonstrate the effectiveness of the developed technique on system with few number buses, the technique firstly applied on IEEE 14-bus system.

Power flow solution of the IEEE 14-bus is obtained prior to the fault and subsequently fault analysis is carried out. Table 1 shows the line currents with and without the occurrence of the fault.

Figure 6 shows the line current profile indicating the normal line currents and the fault currents along the 19 branches of the network. The fault current represents the average of the fault current when all the lines are subjected with a short circuit. The devastating impact of fault current can be observed considering the ratio of the line currents under normal to fault conditions.

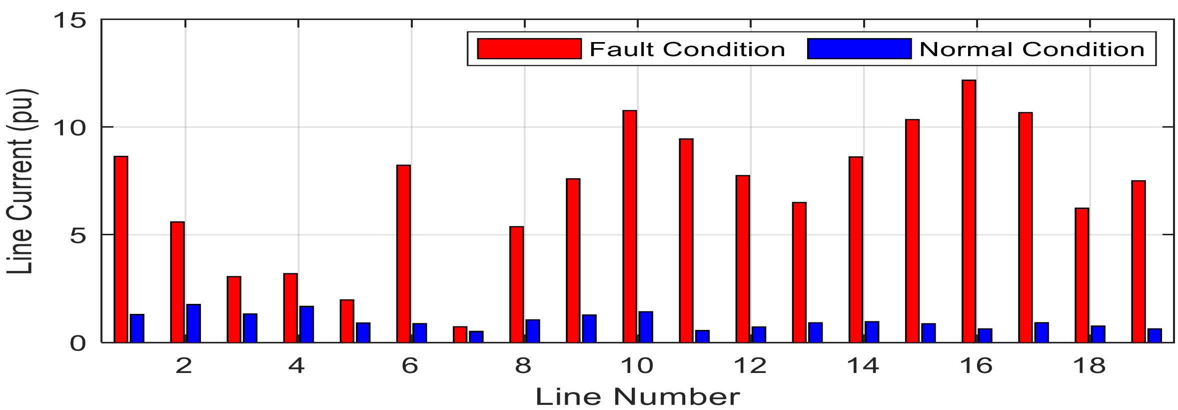

Figure 6: Line currents under normal and faulted conditions of IEEE 14-bus system

Table 1: Line currents of IEEE 14-bus under normal and fault conditions

Line Number	Normal Line currents (pu)	Average Fault currents (pu)	Fault current Impact, ΔI (pu)	CB ratings
1	1.2976	8.6375	7.3399	2.0952
2	1.7629	5.5956	3.8327	2.9258
3	1.3233	3.0559	1.7326	2.5466
4	1.6766	3.1945	1.5179	3.3532
5	0.9038	1.9749	1.0711	1.4076
6	0.8734	8.2293	7.3559	1.5468
7	0.5144	0.7265	0.2121	1.0288
8	1.0478	5.3745	4.3267	2.0956
9	1.2745	7.5976	6.3231	2.3490
10	1.4247	10.7647	9.3400	2.8494
11	0.5537	9.4496	8.8959	1.1074
12	0.7181	7.7470	7.0289	1.2362
13	0.9121	6.4972	5.5851	1.8242
14	0.9637	8.6148	7.6511	1.6274
15	0.8685	10.3459	9.4774	1.737
16	0.6288	12.1776	11.5488	1.157
17	0.9162	10.6714	9.7552	1.3324
18	0.7612	6.2342	5.4730	1.4524
19	0.6298	7.5060	6.8762	1.1596

In order to obtain the impact of the fault on the individual lines, the Fault Current Impact (FCI) is computed by subtracting the normal line current from the average fault current along the line. This differential shown in Figure 7, is the indicator of the devastating nature of the fault and the vulnerability of the line's CB to be overpowered.

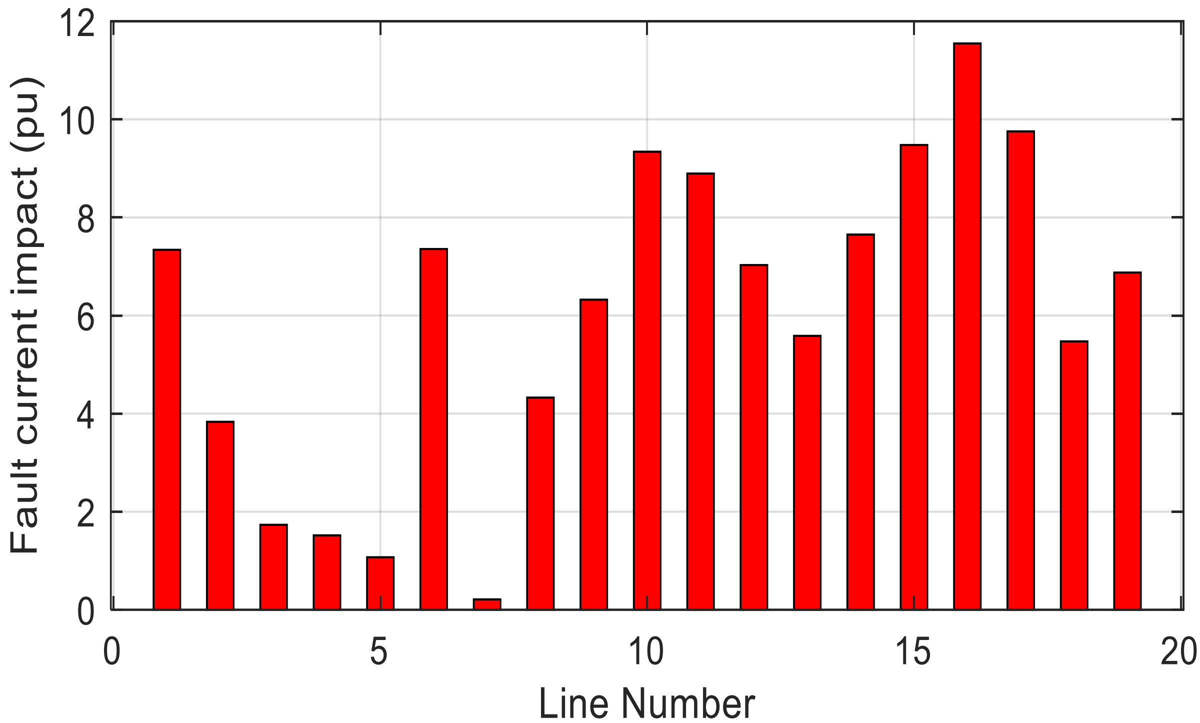

Figure 7: Fault Current Impact on IEEE 14-bus System

The branches of the network are arranged in descending order of the FCI as shown in Table 2. This is done in order to reduce the search space
.

Table 2: Sorted Fault current impact

Line Number	Fault current Impact (pu)
16	**11.5488**
17	**9.7552**
15	**9.4774**
10	**9.3400**
11	**8.8959**
14	7.6511
6	7.3559
1	7.3399
12	7.0289
19	6.8762
9	6.3231
13	5.5851
18	5.4730
8	4.3267
2	3.8327
3	1.7326
4	1.5179
5	1.0711
7	0.2121

It can be seen from Table 4.2 that lines 16, 17, 15, 10 and 11 with fault current impact of 11.5488, 9.7552, 9.4774, 9.3400 and 8.8959*pu* are the most critical lines and vulnerable to the impact of the fault. With the application of the IWO, the optimal location and size of the FCLs are determined as summarized in Table 3.

Table 3: Optimal Location and size (impedance) of FCLs in IEEE 14-bus system

Line Number	FCL size (pu)
16	0.8774
15	0.7455

Figure 8 shows the line currents with the IWO-optimized FCLs.

It is observed from the Figure 8 that all the line currents obtained after the placement of the FCLs are within the range can be handled by the CB, considering its ratings.

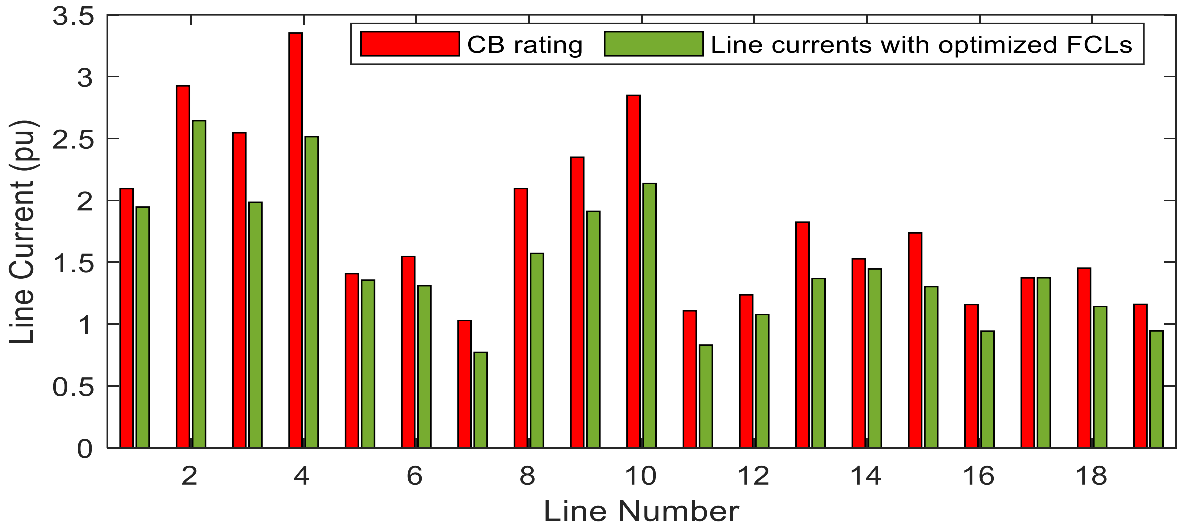

Figure 8: Line currents with the IWO-optimized FCLs on IEEE 14-bus System

In addition, the network average fault currents is reduced from 7.073pu obtained using GA to 5.335pu. This represents 24.58% reduction in the line fault current. Figure 9 shows the fault current obtained using GA and the IWO optimized FCLs.

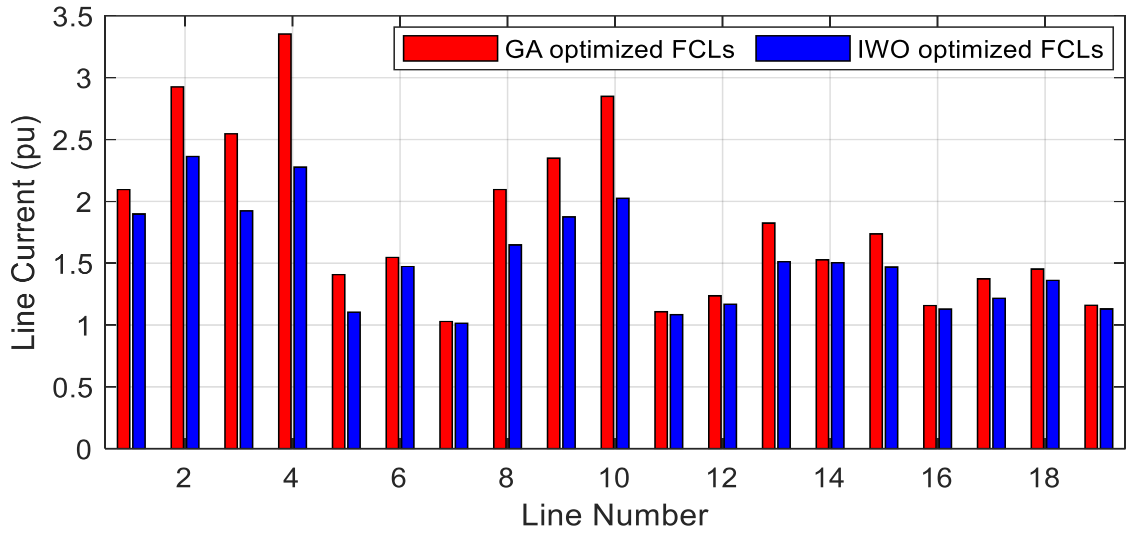

Figure 9: Fault currents with GA- and IWO-optimized FCL in IEEE 14-bus

A. IEEE 30-Bus System

To verify the effectiveness of the developed IWO-based placement of the FCLs on a relatively bigger network, the technique is applied on IEEE 30-bus system. Power flow solution of the IEEE 30-bus is also obtained prior to the fault and subsequently fault analysis is carried out.

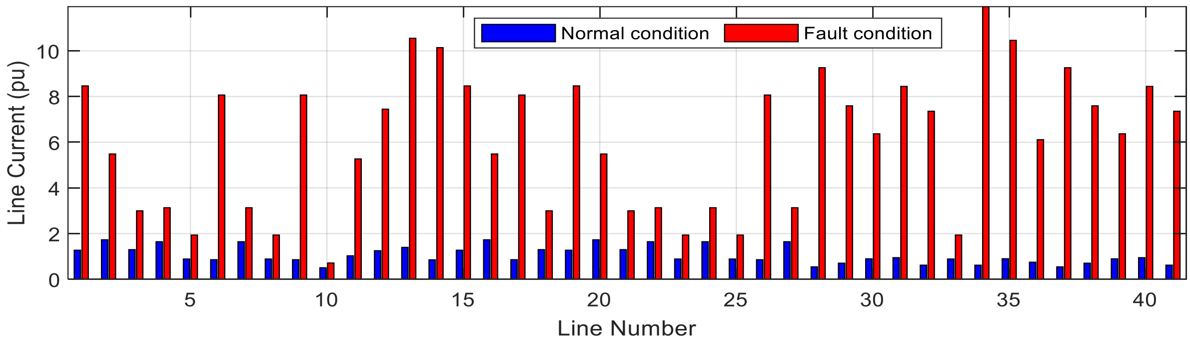

Figure 10: Line currents under normal and faulted conditions of IEEE 30-bus system

Figure 10 shows the line current profile indicating the normal line currents and the fault currents along the 41 branches of the network. The devastating impact of fault current can be observed considering the ratio of the line currents under normal to fault conditions.

As shown, it is noticed that the fault currents have significantly exceeded the interrupting capabilities of the CBs along all the branches. To determine the most critical branches, they are arranged in the order of the FCI (shown in Figure 11).

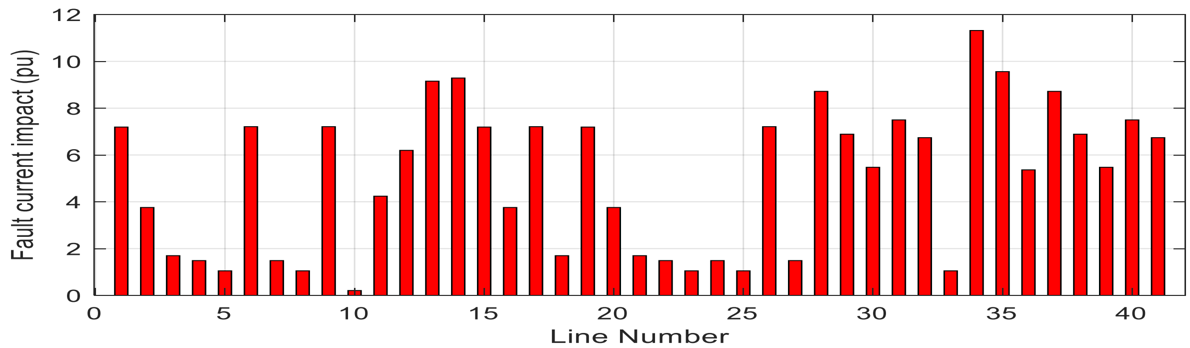

Figure 11: Fault Current Impact on IEEE 30-bus System

The 10 most critical branches are shown in Table 4.

Table 4: Most Critical Branches in IEEE 30-bus system

Line Number	Fault current Impact, ΔI (pu)
34	11.3178
35	9.56009
14	9.28785
13	9.1532
28	8.75983
37	8.71798
9	7.50875
31	7.49812
40	7.39808
6	7.20878

It can be seen from Table 4 that lines 34, 35 and 14 with fault current impact of 11.3178, 9.56009 and 9.28785*pu* respectively are the most critical lines and vulnerable to the impact of the fault. With the application of the IWO, the optimal location and size of the FCLs are determined as summarized in Table 5.

Table 5: Optimal Location and size (impedance) of FCLs in IEEE 14-bus system

Line Number	FCL size (pu)
34	0.8204
35	0.8545
28	0.7885

Figure 12 shows the line currents with the IWO-optimized FCLs.

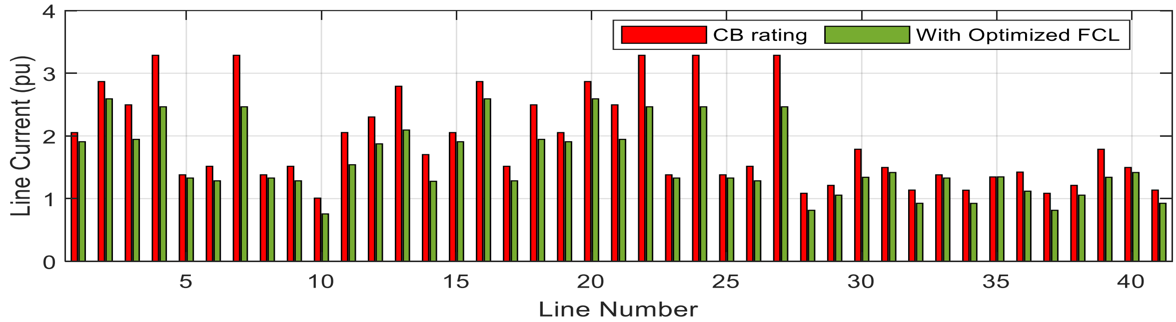

Figure 12: Line currents with the IWO-optimized FCLs on IEEE 30-bus System

It can be deduced from the Figure 12 that all the line currents obtained after the optimal placement of the FCLs are within the range can be handled by the respective CBs. In addition, the network average fault currents is reduced from 6.1554*pu* obtained using GA to 4.805*pu*. This represents 21.94% reduction in the line fault current. Figure 13 shows the fault current obtained using GA and the developed IWO optimized FCLs.

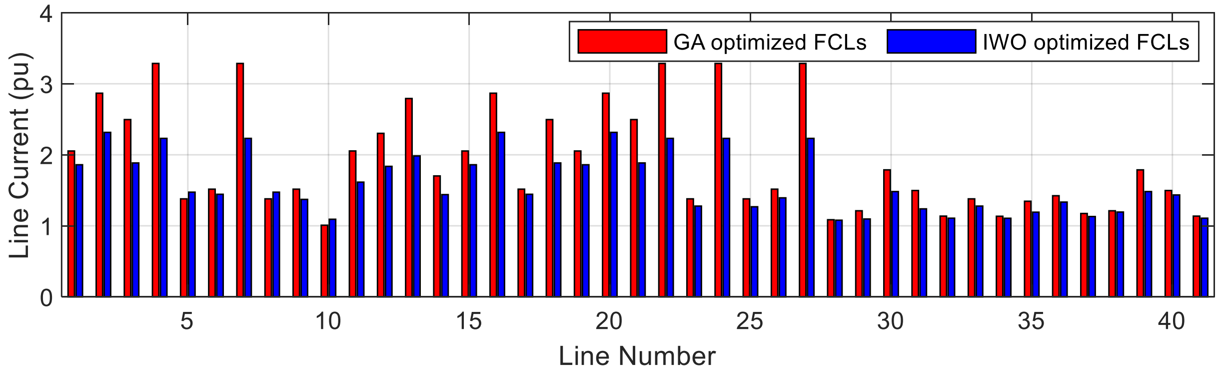

Figure 13: Fault currents with GA- and IWO-optimized FCL in IEEE 30-bus

B. *IEEE 118-bus System*

In order to demonstrate the effectiveness of the developed technique on a very large system, the technique is finally on applied on IEEE 118-bus system. Power flow solution of the IEEE 118-bus is obtained prior to the fault and subsequently fault analysis is carried out.

Figure 14 shows the line current profile indicating the normal line currents and the fault currents along the most critical branches of the network. The devastating impact of fault current can be observed considering the ratio of the line currents under normal to fault conditions.

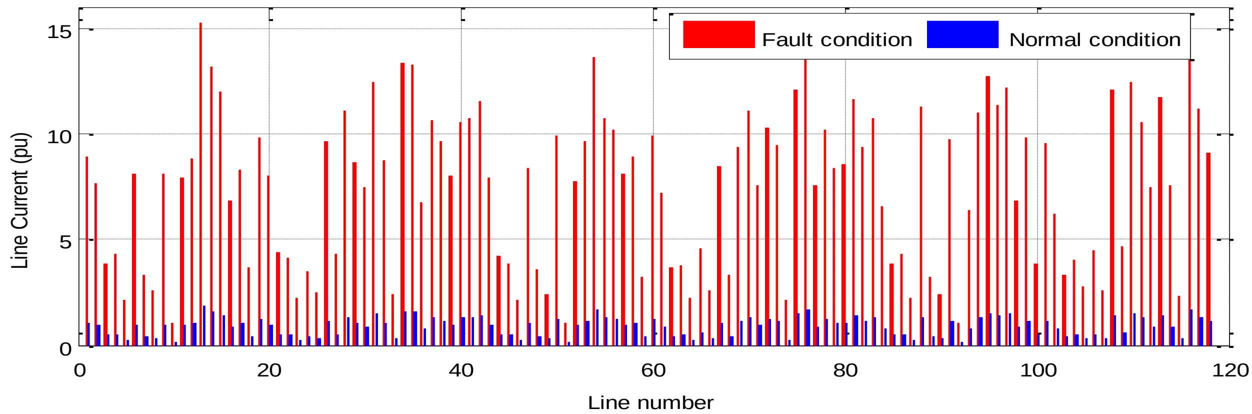

Figure 14: Line currents under normal and fault conditions of IEEE 118-bus system

Table 6: 20 most critical branches in IEEE 118-bus system

Line Number	Fault current impact (pu)
13	13.43874
116	12.3765
76	12.23086
54	11.99273
34	11.75275
35	11.64759
14	11.55466
95	11.16122
110	10.93083
31	10.89994
97	10.69913
75	10.61861
108	10.59221
15	10.55921
113	10.32874
81	10.2058
42	10.16919
96	10.0041
88	9.880904
117	9.80005

In order to obtain the impact of the fault on the individual lines, the Fault Current Impact (FCI) is computed as shown in Table 6. After sorting the FCIs, lines 13, 116, 76, 54 and 34 with FCIs 13.44, 12.38, 12.23, 11.99 and 11.75pu respective are found to be the most sensitive lines. Table 6 shows 20 most critical branches in the 118-bus system. It can be inferred even from the table that line 13 is the most vulnerable line of all the 186 lines in the system. With the reduced size of the search space, the IWO was able to determine the optimal location and size of the 7 FCLs as summarized in Table 7.

Table 7: Location and size of FCLs in IEEE 118-bus system

Optimal location (line number)	FCL size (pu)
13	0.9564
76	0.8766
34	0.9321
35	0.5455
110	0.8457
75	0.7485
113	0.9410

Figure 4.11 shows the line currents of the IEEE 118-bus with the IWO-optimized FCLs.

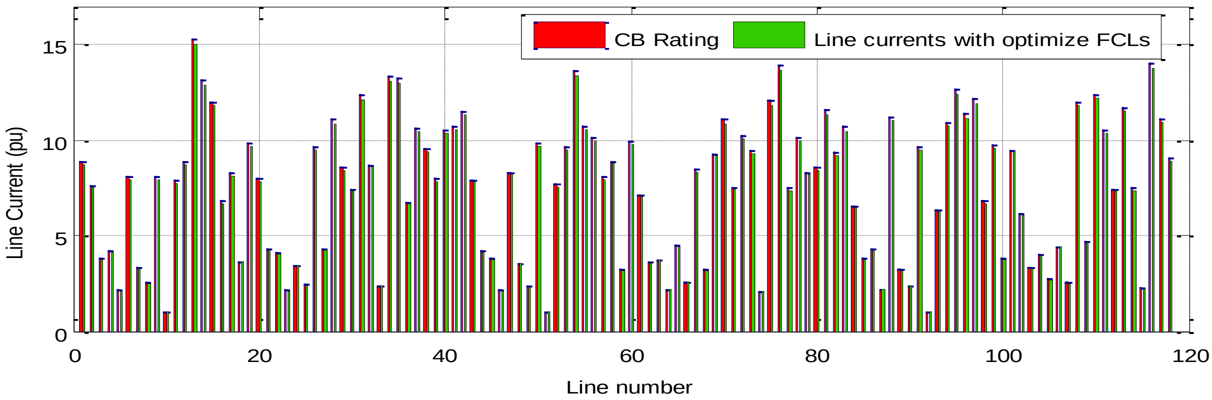

Figure 11: Line currents with the IWO-optimized FCLs on IEEE 118-bus System

It is observed from the Figure 4.11 that all the line currents obtained after the placement of the FCLs are within the range can be handled by the CB, considering its CB ratings. Moreover, the network average fault currents is reduced from 7.43pu obtained using GA to 5.805pu. This represents 21.87% reduction in the line fault current.

Conclusion

This paper presented an Invasive Weed Optimization (IWO) based technique to determine the optimal location and sizing of predefined number of Fault Current Limiters in medium voltage meshed distribution system. The need to determine the optimal location and size of the FCLs is to suppress the fault current to a level that can be handled by the CB. In addition, effective deployment of FCLs in power system can result in considerable saving in the investment of high-capacity CB. Impedance of the FCLs and the fault currents are considered as the objective function. The number of candidate locations of the FCL in a distribution network is large, as such sensitivity analysis based on the fault currents is carried out first in to order to reduce the search space. This involves carrying out fault current flow analysis on the original system and identifying the lines with highest fault currents. The IWO is applied to solve an objective function based on the lines fault current and the impedance of the individual FCLs. The short-circuit fault current maximum allowable ratings of the CBs based on IEEE C37.04-2018, and the FCLs' impedances are used as the inequality constraints.

To demonstrate its effectiveness, the developed FCL placement technique is developed in MATLAB simulation and applied on IEEE 14-bus, 30-bus, and 118-bus meshed systems. The performance of the proposed technique is validated by comparing the reduction in the fault currents on all the sensitive lines with those obtained using genetic-algorithm (GA). From the simulation, is found that the fault current is reduced from 7.073*pu* obtained using GA to 5.335*pu* by optimally placing the FCLs using the developed IWO IEEE 14-bus system. This represents 24.58% reduction in the line fault current. For the 30-bus network, the average fault currents is reduced from 6.1554*pu* to 4.805*pu* using the GA and IWO respectively, representing 21.94% reduction in the line fault current. Moreover, the network average fault currents is reduced from 7.430*pu* obtained using GA to 5.805*pu* when 7 FCLs are optimally sized and placed in the 118-bus system. This represents 21.87% reduction in the line fault current. It is concluded that the optimal sizing and siting of the FCLs in the networks has significantly reduced the fault currents to the level that can be handled by the respective CBs.

REFERENCES

Cardoso, M. L., Venturini, L. F., Baracy, Y. L., Ulisses, I. M. and Bremermann, L. E. (2022). Fault indicator placement optimization using the cross-entropy method and traffic simulation data. *Electric Power Systs Research*, 212: 1-12.

Chen G., Jiang D., Wu ., and Lu Z. (2003) "Simulation Study of Bridge Type Solid State Fault Current Limiter for High Voltage Power Network", IEEE, pp. 2521-2526, 2003.

Elmitwall, A., Gouda, E. and Eladawy, S. (2016). Restoring recloser-fuse coordination by optimal fault current limiters planning in DG-integrated distribution systems. *International Journal of Electrical Power & Energy Systems*, 77, 9-18.

Farzinfar, M. and Jazaeri, M. (2020). A novel methodology in optimal setting of directional fault current limiter and protection of the MG. *International Journal of Electrical Power Energy System*, 116(105564).

Fathi, M. and Sadeh, J. (2020). Optimal Placement and Sizing of FCLin Presence of Distributed Generation in Sub-transmission Networks. Beijing, China: IEEE.

Firouzi M., and Gharehpetian G. B. (2013) "Improving Fault Ride-Through Capability of Fixed-Speed Wind Turbine by Using Bridge-Type Fault Current Limiter", IEEE Trans. On Energy Conversion, TEC-00405-2012, pp.1-9,

Firouzi M., Gharehpetian G. B. and Mozafari B. (2015) "Bridge-type superconducting fault current limiter effect on distance relay characteristics", Science Direct, Electrical Power & Energy Systs 68: 115–122, Dec 2015.

Ghanbari, M., Gandomkar, M. and Nikoukar, J. (2021). Protection Coordination of Bidirectional Overcurrent Relays Using Developed Particle Swarm Optimization Approach Considering Distribution Generation Penetration and Fault Current Limiter Placement. IEEE Canadian Journal of Electrical and Computer Engineering, 44(2), 143 - 155.

Gonen T. (2005) Electric Power Transmission System Engineering, Analysis and Design, Crc Press Tayor and Francis Group.

Hongyang H, Zheng X. and Xi L., (2012). "Improving Performance of Multi-Infeed HVDC Systems Using Grid Dynamic Segmentation Technique Based on Fault Current Limiters", *IEEE Trans. On Power System*, vol. 27, no. 3, pp. 1664-1672, August 2012.

Hu, Y. and Jianxun, J. (2016), "Characteristic Analysis of a Fully Controlled Bridge Type Superconducting Fault Current Limiter," in *IEEE Transactions on Applied Superconductivity*,26(7):1-6, https://doi:10.1109/TASC.2016.2594950

Hu, Y. and Chiang, H.-D. (2018). Optimal Placement and Sizing for Fault Current Limiters: Multi-Objective Optimization Approach. Portland, OR, USA: IEEE Power & Energy Society General Meeting (PESGM), pp. 1-5.

J. Kozak, M. Majka, S. Kozak and T. Janowski, (2013) "Comparison of Inductive and Resistive SFCL," in *IEEE Transactions on Applied Superconductivity*, 23(3): 604-614, doi:10.1109/TASC.2012.2231714.

Kaur, M. and Narang, N. (2023), Optimal Power Flow Solution Using Space Transformational Invasive Weed Optimization Algorithm. *Iran J Sci Technol Trans Electr Eng* 47, 939–965. doi.org/10.1007/s40998-023-00592-y

Kothari, D. P. and Nagrath, I. J. (2014). Modern Power System Analysis. In Symmetrical Fault Analysis (pp. 327-367). Delhi, India: Tata McGraw Hill Education private Limited.

Kovalsky L., Yuan X., Tekletsadik K., Keri A., Bock J., and Breuer, F. (2005) "Applications of SupApplications of Superconducting Fault Current Limiters in Electric Power Transmission Systems," *IEEE Transactions On Applied Superconductivity*, 15(2): 2130-2133.

Kumar R., Choudhary R. and Vikas K. (2016) "High Voltage Fuse Blown Indicator with Voice Based Announcement System", *International Journal of Information Research and Review*, 03(05): 2358-2361.

Mehrabian, A. and Lucas, C. (2006), A novel numerical optimization algorithm inspired from weed colonization. Ecol. Inform. 1. 355–366.

Roozbeh, R.. Far, Vasile P. and Enrico, Z. (2015) "Invasive Weed Classification", *Neural Computing and Applications* 26 (05): 525–539,

Sadeghi, M. and Abasi, M. (2021). Optimal placement and sizing of hybrid superconducting fault current limiter for protection coordination restoration of the distribution networks in the presence of simultaneous distributed generation. *Electric Power Systems Research*, 201(107541), 1-10.

Saeid, Z., Khazali, A. H., Hashemi, S. M., Katebi, F. and Khalili, R. (2017). Fault Current Limiter Optimal Placement by Harmony Search Algorithm. Stockholm: CIRED 22nd Int'l Conference on Electricity Distribution.

Santamaria J. (2011) Analysis of Power Systems Under Faults Conditions, California State Uni., Sacramento, 2011.

Sushma Y. and Choudhary G. K., (2014) "Review on Fault Current Limiters*", International Journal of Engineering Research & Technology (IJERT*), 3(4): 1595-1603.

Teng, J.-H. and Lu, C.-N. (2018). Optimum Fault Current Limiter Placement. Kaohsiung, Taiwan: Int'l Conference on Intelligent Systems Applications to Power Systems.

Wood, A. J., Wollenberg, B. F. and Sheble, G. B. (2014). Power System Security. In Power Generation, Operation and Control (pp. 296 - 349). Michigan, USA: Wiley.

Wu X., Mutale J., Jenkins N. and Strbac G. (2005) "An investigation of Network Splitting for Fault Level Reduction," The Manchester Centre for Electrical Energy (MCEE), UMIST, January 2003.

Yu, P., Venkatesh, B., Yazdani, A. and Singh, B. N. (2016). Optimal Location and Sizing of Fault Current Limiters in Mesh Networks Using Iterative Mixed Integer Nonlinear Programming. *IEEE Transactions on Power Systems*, 31(6): 4776 - 4783.