Allocation of FCLs in Transmission Networks with High Penetration of DGs: A Two-Stage Approach

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2021 International Conference on Smart Energy Systems and Technologies (SEST) | 978-1-7281-7660-4/21/$31.00 ©2021 IEEE | DOI: 10.1109/SEST50973.2021.9543340

***Abstract*—Fault current limiters (FCLs) are getting high-degree of attention since they can properly overcome the transient conditions of modern power systems. FCLs have the ability to limit the short-circuit currents before reaching to its maximum value so that they can be cut off by the available switches. In fact, FCLs show negligible resistance in the normal operation, but their resistance suddenly increases with a short-circuit and prevents it from rising. The technical and economic benefits of FCLs in power systems depend on their number, locations and optimal structural parameters. In this paper, a two-stage approach is proposed for determining the number, location and impedance of FCLs in the transmission network with high penetration of distributed generations (DGs). The suggested algorithm determines the number and locations of FCLs in the first step using a sensitivity based technique and the value of FCL impedance is chosen in the second step utilizing an optimization objective function. The improved grey wolf optimizer (IGWO) is developed to solve the optimization problem which its main objective is reducing the short-circuit level of the network. The proposed approach is assessed on the IEEE-30 bus transmission network considering the effects of different kind of DGs. The results shown that FCLs can significantly reduce the short-circuit level of the network along with other advantages.**

***Index Terms*—Fault Current Limiters, Transmission Network, Distributed Generation, Short-Circuit Level, Two-Stage**

I. Introduction

A. Motivation and Aim

In recent years, growing attention has been paid to devices that are capable of limiting high short-circuit currents. This issue has become more important with the integration of distributed generation (DGs) sources in modern power systems. When the short-circuit level of the network increases, the rating of circuit-breakers (CBs) may be exceeded and the faults might not be isolated from the system. So, safe and stable operation of the network would definitely need some new devices to manage these harsh transient conditions. The use of fault current limiters (FCLs) has always been suggested as a useful alternative to decrease short-circuit levels along with other benefits [1], [2]. The FCLs can efficiently improve different aspects the power networks, however, they should be allocated and sized optimally to propose their profits [3]–[5]. Motivated from this issue, a novel approach for placement and sizing of FCLs is proposed in this paper.

B. Literature Review

Numerous reports have been published on the introduction of new structures of FCLs as well as their appropriate location, number and size in the network, which shows the importance of their application in modern power networks. In [2], the optimal location of FCLs has been determined to minimize the objective function based on economical perspectives, reliability and power losses. Authors of [3] provides optimal FCL placement to improve system stability. In [4], the objective functions of reliability and reduction of short circuit level are considered as the objectives of the optimization algorithm. An optimal allocation method for reducing short-circuit currents and mitigating voltage sag is proposed in [5]. The authors in [6] developed an algorithm built on iterative mixed integer nonlinear programming to allocate FCLs in a small network as its computation procedure is complex for bigger systems. The cost minimization of protection system incorporated with FCLs economic perspective are the objective functions of [7] which is solved by genetic algorithm.

A multi-objective approach using particle swarm optimization (PSO) is suggested in [8] considering the power loss, reliability of the network and FCL impact on economic conditions. The harmony search optimization technique is developed in [9] to locate and size the FCLs. Authors of [10] proposed a search space reduction technique with genetic algorithm to allocate FCLs. The probabilistic behavior of power system and reduction of short-circuit level with optimally allocated FCLs are the main goals of [11]. The multi-objective firework algorithm for solving the objective functions of reliability, cost and short-circuit level for systems with FCLs is proposed in [12]. The authors of [13] developed a method to optimally allocate DGs and FCLs in smart grids. In this paper, FCLs to lessen the fault current value in various locations of the system to a bearable level for CBs. A Pareto optimization problem along with sensitivity analysis based approach is proposed in [14] to find the location and size the resistive based FCLs in active distribution networks. The system reliability is the single objective of [15] for identification the optimal location of FCLs. The optimal power flow with fault current constraints

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resulted from FCLs are studied in [16]. A combined problem of coordination between overcurrent relays and FCL allocation is solved in [17] using the cuckoo search optimization algorithm and linear programming.

A brief review on the literature indicates that the focus is more on finding the location and size of FCLs in traditional power networks and there are few studies that consider the effects of DGs. In other words, the gap in existing reports is that they did not deliberate the important impacts of DGs on the fault current as well as the FCL allocation problem. So, this issue is studied in the paper to fill the gap.

C. Contributions and Organization

In this paper, a two-stage approach is proposed for optimal allocation of FCLs in transmission networks with high penetration of DGs. The number, location and impedance of FCLs have been determined in the suggested technique. In the first step, a probability matrix is built to identify the number and location of FCLs considering the effects of different kind of DGs. This matrix is based on the number and value of exceeding from high tolerable CB fault current. The second step is dedicated to finding the optimal value of FCL impedance considering minimization of the short-circuit level. The optimization problem in the second step has been solved using the Improved Grey Wolf Optimizer (IGWO). The approach has been tested on IEEE-30 bus transmission network with presence of different kind of DGs and the results show that the suggested technique reduce the fault current level efficiently with high degree of performance.

To summarize the contributions of the proposed approach, the following items can be considered:

- Proposing a novel two-stage approach for allocation of FCLs with low computational burden and high accuracy.
- Considering the impacts of highly penetrated DGs.
- Proposing IGWO to solve the proposed objective function.

II. Proposed Technique

The proposed method consists of two steps to optimally allocate the FCLs. In the first step, the number and location of FCLs are determined. In the second step, the optimal FCL impedance value is selected. Fig. 1 shows the general structure of the proposed method.

A. First Stage:Number and Location of FCLs

The first step of the proposed method is to locate the FCL using a probability matrix. Since the FCLs can reduce the short circuit level of the network by entering an impedance in the event of a fault, the FCL selection options will be related to the same issue. The maximum short-circuit current that can be tolerated by a CB has a certain rating which is 7 to 10 times of the rated network current. So, FCLs should limit the fault current to a value that can be cut-off by CBs. The stages for this step are as follows:

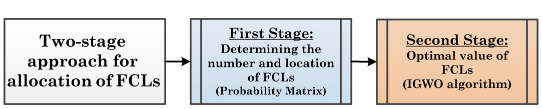

Fig. 1. Overall structure of proposed method

- *Step 1-1: Load-flow analysis in normal condition*

The first stage is to find the results of a load-flow in the studied system. In this paper, well-known Newton-Raphson load flow approach is utilized for this purpose. This approach is a powerful method that can be used in both radial and mesh networks. Also, it is much faster than traditional algorithms which converge to optimum results with less operations. This stage results in finding the normal currents of each line that will be consumed in next stages.

- *Step 1-2: Short-circuit analysis*

In the second stage, the short circuit analysis of the network is performed to identify the current of lines in all fault modes on different network buses. For this purpose, three-phase short-circuit without resistance (simulating the worst case of a fault) is simulated in all buses, and the current passing through the lines is calculated using Newton-Raphson load flow in all test cases. For example, in a standard 30-bus network, a three-phase short circuit without resistance is simulated in all 30 bus networks and the current through all lines is calculated in each mode.

- *Step 1-3: Finding the probability matrix*

In the final stage of the first step, a probability matrix is defined to find the optimal location of FCLs. The candidates for FCL installation location is chosen by analyzing the results of proposed probability matrix.

According to results in stages 1 and 2, the normal and fault current of each line are known in each test case. This current for each line and in each case may be more or less than the current in normal network mode. If the fault current is greater than the normal one for a line in each state, an index is defined accordingly. This index for each line is developed in such a way that the difference between the fault current and the normal current in each state is calculated and added together for all cases. The mathematical relation is as follows:

$$.\Delta I_N=\sum_{i=1}^{M} I_{\text{fault },i}-I_{\text{normal },i} \quad \left(\text{if } I_{\text{fault }} \geq I_{\text{normal }}\right) \tag{1}$$

In 1, the symbol N indicates number of the line in the studied system and symbol M specifies the total number of conditions in which the fault current is more than the normal current for each line. Also, symbol i stands for the condition number in which fault current is more than the normal current and I_{fault} and $I_{Inormal}$ show the fault and normal current for each condition. For example, in the 30-bus network, it is possible that the fault current may be 10 times higher than the normal current in 30 fault case studies in different network buses, so the value of Min the above relation is 10. In other words, this index is the summation of 10 different values.

Now that the index ΔIN has been identified, an accurate feature is need to find the number and locations of FCL. If the fault current is higher than the normal current, two conditions are possible, whether this current is more or less than the maximum breakable current of the CB. If it is less than the CB cut-off rating, it can be detected and cut off and will not cause a problem for the system. But if the current is more than the CB rating, it will cause damage. As a result, an index must be defined to make it more important. This indicator, called Nf, specifies the number of times the line current increases in each fault state of the maximum current cut by the CB. The maximum cut-off current of each CB in this paper is selected as 7.5 times the normal current [8].

$$N_f = \text{ number of fault current exceeds the CB rated current} \tag{2}$$

After determining the two indices ΔIN and N_f for each line, the sensitive matrix (SM) of the FCL installation candidates is formed in the system. The values of this matrix consist of a combination of two indicators introduced in (1) (in the normalized condition) and (2). These two indices are multiplied so that for each line, both indices will be considered. The reason for this multiplication is to determine the effect of the second index on the first index. The SM is a row or column matrix that, if considered a column, has N rows and 1 column. The relation of SM is specified as follows:

$$SM = \begin{bmatrix} N_{f1} \times \Delta I_1 \\ . \\ . \\ . \\ N_{f_N} \times \Delta I_N \end{bmatrix} \tag{3}$$

Once the SM is identified, the FCL installation location must be decided according to the values of its components. For this purpose, the elements of this matrix are sorted from high to low. The highest value among the orders in the SM indicates the most suitable line for FCL installation. The choice of the number of FCLs will be according to the conditions of the network and its designers.

- *Flowchart of the first stage*

Fig. 2 shows the flowchart of the first step of the proposed method. As shown in this figure, the first stage is to find the results for the load flow in normal condition of the network. The second stage, involves the short circuit analysis of the network in which the current of branches in all fault conditions is identified. The next stage is to calculate the index ΔIN and then in the fourth stage, the N_f index is computed. In the final stage, SM is formed and sorted from large to low values. The number of lines that have the highest value in the components of this matrix are determined as the FCL installation candidates. The number of FCL installations allowed in different networks is based on the available costs and the network operator's decision. Of course, this number is usually specified in different reports [9]–[12].

B. Second Stage: Impedance Value of FCLs

After identifying the candidate locations for FCL installation, in the second step of the proposed method, the proposed approach seeks to find the optimal impedance value of the

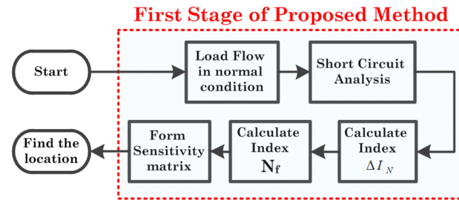

Fig. 2. First stage of proposed FCL allocation method

selected FCLs. It must be noted that the ultimate goal of this step is to reduce the short-circuit level of the entire network. So, optimization techniques must be utilized to achieve this aim. The stages for this step are as follows:

- *Step 2-1: Proposing the objective function*

With gathering the results of the last step, this step starts with proposing the novel objective function. In this paper, the suggested objective function tries to find the optimal impedance value of each installed FCL so that the short-circuit level is significantly reduced. This reduction actually means that all CBs are able to cut off fault current in all possible fault scenarios. To do so, the index ΔIN can be utilized to form the objective function. Also, it is clear that the lower FCL impedance results in lower cost. Based on these facts, the proposed objective function defined as follows:

$$\begin{aligned} & OF = w \times \sum_{i=1}^{N_f} Z_{FCL} + \sum_{i=1}^{N_f} \Delta I_N \\ & I_{f,i} \le I_{f,i}^{CB} \\ & Z_{FCL}^{\min} \le Z_{FCL} \le Z_{FCL}^{\max} \end{aligned} \tag{4}$$

In (4), w is the weighting factor used to balance the two terms used in the objective function. Also, Z_{FCL} indicates FCL impedance in the selected locations. Where $I_{f,i}$ is the short_circuit current magnitude and should be lower than the breaking capacity of CB in i^{th} bus of the network and $Z_{FCL}^{\min}$ and $Z_{FCL}^{\max}$ are the minimum and maximum impedance of FCLs, respectively. The other symbols used are also already defined. The purpose of this paper is to minimize the objective function using IGWO algorithm. For this purpose, IGWO algorithm must find the best answer of proposed objective function in the problem search space.

- *Step 2-2: IGWO algorithm implementation*

The GWO algorithm is a well-known optimization algorithm that is originally proposed in 2014 [18]. This algorithm shows promising results in solving different optimization problems. However, the accuracy and performance of the algorithm might be decreased because of its low exploration diversity. To resolve this problem, different solutions can be suggested. In this paper, a novel improvement of GWO is proposed as follows.

A common challenge in all optimization techniques is to find the global minimum. This issue can be resolved by fine-tuning of parameters α and A in the original GWO algorithm. These parameters can be balanced to find the global minimum with a fast convergence. In the original algorithm, the transition between exploration and exploitation phases is created by the adaptive values of α and A. To do so, half of the iterations dedicates to exploration ($|A| = 1$) and the other half are utilized for exploitation ($|A| > 1$). In general, high exploration in search space can result in low local optima stagnation probability. Different approaches can be offered to improve the exploration rate. The key point in this issue is related to proposing an algorithm than have the ability to make a balance between exploration and exploitation phases. In original GWO, value of α decreases linearly from 2 to 0 using the update equation as follows:

$$a = 2\left(1 - \frac{t}{T}\right) \tag{5}$$

where T indicates the maximum number of iterations and t is the current iteration. To rectify the problems associated with the Eq. (5), a novel approach using the exponential function is suggested to have a decay of α over the course of iterations:

This improvement in exponential decay function can balance the numbers of iterations used for exploration and exploitation between 70% and 30%, respectively. Application of IGWO can overlook the impact of right balance between exploration and exploitation phases to guarantee an accurate approximation of global optimum. Moreover, proposed IGWO have the ability to make the convergence faster for real time applications. The pseudo code of MGWO is given in Algorithm I.

- *Step 2-3: Analyzing the network with FCLs*

In final stage of the proposed approach, the network is analyzed in the presence of FCLs with the optimal values selected by the IGWO. The allocated FCLs did not affect the system in normal condition. However, they impact the system in fault conditions as limiting the fault current to bearable values of CBs. To find this impact, a short-circuit analysis is done by simulating different fault scenarios all over the network.

Algorithm 1 Pseudo Code of Proposed IGWO

Initialize the search agent (grey wolf) population

$$Xi(i = 1, 2, \dots n)$$

Initialize α, A, and C
Calculate the fitness of each search agent
X_α =the best (or dominating) search agent
X_β =the second best search agent
X_δ =the third best search agent

while $t <$ Maximum number of iterations **do**
  foreach search agent **do**
    update the position of the current search agent
  end for
  update α
  update A and C
  calculate the fitness of all search agents
  update $X_\alpha, X_\beta,$ and X_δ
  $t = t = 1$
end while
Return X_α
End

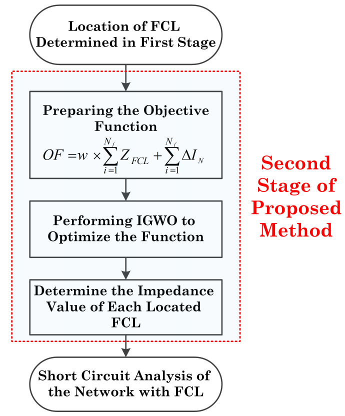

Fig. 3. Second stage of proposed FCL allocation method

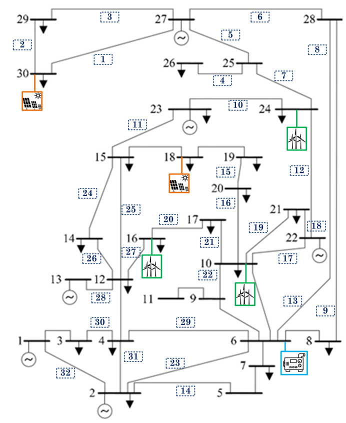

Fig. 4. Single line diagram of modified IEEE 30-bus system

- *Flowchart of the second stage*

Fig. 3 shows the flowchart of the second step of the proposed method. As shown in this figure, the second stage begins with the results of the first step. Then, the proposed objective function introduced in Eq. (4) along with constraints are prepared. In the second stage, the IGWO optimization algorithm is implemented to minimize the proposed objective function which results in optimal selection of the impedance for each located FCL in the network. At final stage, the network is analyzed in the presence of FCL with the optimal values selected by the IGWO algorithm. This analysis includes network short-circuit analysis.

III. Simulation And Results

The developed FCL allocation framework is assessed on modified IEEE 30-bus and the results are given in the following. The system and the proposed approach is modeled and coded in MATLAB software. Also, to show the superiority of proposed IGWO, a comparative study is presented. The results clearly show that the proposed algorithm is able to find and size the FCLs to reduce the short-circuit level significantly.

A. The Simulated System

The simulated system is a modified version of IEEE 30-bus transmission network which has different kind of DGs. This network originally has 6 generators, 32 transmission lines and 20 bus which its basic information is given in the [9]. To assess the impact of DGs, three wind farms, two solar farms and one diesel based generator are added to the system. The voltage level of the system is 132 kV and 33 kV which its single line diagram is shown in Fig. 4. The simulation details of DGs are brought from [5]–[14].

B. The Results

As mentioned in last section, the proposed method starts with finding out the results of a load flow in the simulated system. To do so, the Newton-Raphson approach is applied on the network and normal current of each branch is determined in normal condition. Fig. 5 shows the currents of each branch in the network. As can be seen, the current of lines 1, 2 and 4 is higher than other lines. The highest current is related to line 1 with a value of more than 450 A. In the second stage, the short-circuit analysis on the studied system is performed. To do so, the worst case scenario which is three-phase fault without resistance in all bus is simulated. In this case, 30 different fault scenarios are considered and the current passing each branch in each scenario is gathered. For example, Fig. 6 shows the current of all lines for a three-phase fault applied to bus 3. This line is chosen because it has the worst case of the 30 possible states based on observations. For instance, the fault current in line 4 is about 20 p.u. which is much bigger than CB tolerable rating. Also, it is seen that fault current in lines 1 to 4 is greater than CB maximum rating. As a result, this will add a number to the N_f index for these four lines. But in

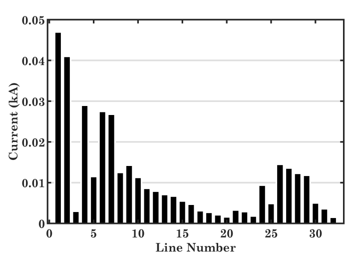

Fig. 5. The current of lines in normal condition

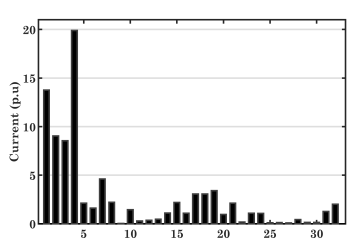

Fig. 6. The current of lines in bus 3 fault without FCL

Table. I. Results of proposed method for first step

Line	N_f	ΔI_N	SM	Line	N_f	ΔI_N	SM
1	16	5.622	83.95	**17**	1	0.892	0.892
2	11	1.984	21.82	**18**	0	0.749	0
3	1	0.327	0.327	**19**	0	0.806	0
4	3	0.97	2.91	**20**	2	0.776	1.55
5	1	0.23	0.23	**21**	1	0.823	0.823
6	3	0.93	3.79	**22**	1	0.929	0.929
7	7	0.90	2.7	**23**	0	0.659	0
8	0	0.548	0	**24**	1	0.942	0.942
9	8	0.596	4.76	**25**	1	0.269	0.269
10	0	0.412	0	**26**	7	0.461	3.22
11	0	0.367	0	**27**	6	0.352	2.12
12	0	0.742	0	**28**	5	0.289	1.44
13	0	0.643	0	**29**	4	0.192	0.768
14	0	0.384	0	**30**	3	0.529	1.58
15	1	0.698	0.698	**31**	1	0.912	0.912
16	0	0.571	0	32	2	0.487	0.974

Table. II. Results of proposed method for second step

Number of selected line	FCL impedance (pu)
1	0.546
2	0.267
9	0.147

other lines, this current is less than the breakers and does not cause a problem. Another observation of this state is that the current of line 9 is lower than the normal state of the network (in this case the current of line is 0.013 kA). In other lines, the current is increased which is effective in calculating the index ΔIN.

The next stage is to find the suitable location of FCL using SM. As described, this matrix is built on proposed indices ΔIN and N_f for each line. The Table II presents the results of calculated indices ΔIN, N_f and SM for the studied system. From this table, it is seen that the N_f index is zero for some lines and ultimately, SM results are zero, too. So, these lines would not affect short-circuit level of the system.

The values of SM for lines 1, 2 and 9 are higher than others. So, these lines are selected as candidates for FCL installation. The first step of proposed method ends with selecting these lines as FCL possible locations.

Knowing the FCL optimal locations, the proposed objective function is defined for each of lines and solved using IGWO. The weighting factors in objective function are selected in a way that the two terms of function are in balance, which are 0.15, 0.12 and 0.2 for lines 1, 2 and 9, respectively. After executing the objective function for the three candidate lines, the values in Table III are obtained. These values represent the impedance of each FCL in terms of network per unit. After selecting the values in Table 3, the network will be analyzed in the presence of these FCLs.

Fig. 7 shows the current of all lines in the fault mode in bus 3 with the presence of optimal allocated FCLs in comparison with system without FCLs. In this figure, it can be seen that the maximum recorded fault current is less than the maximum rating of CB. As a result, this current will be cut off by CB and the network will be protected against short-circuits. Moreover, it can also be seen that the short circuit level is significantly

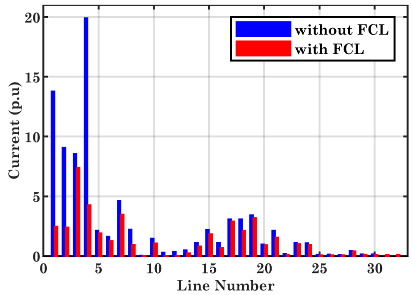

Fig. 7. The current of lines in bus 3 fault with and without FCL

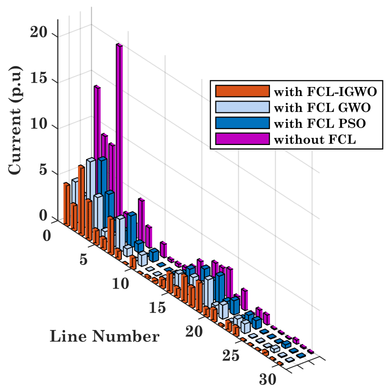

Fig. 8. The comparative study

reduced and the fault current in all lines is under the ratings of CBs.

This result indicates the accuracy of the proposed method that even in the worst case, the presence of FCL could be effective. The interesting point in this case is the reduction of short circuit current in line 4 that is decreased less than 2 pu. This significant reduction indicates the appropriate positions of the proposed FCLs.

C. Comparative Study

The proposed method is compared with two other optimization algorithms named GWO and PSO. This study is done to validate the performance of proposed framework. To do so, all of steps of proposed method is the same, however the optimization algorithm is replaced by two other mentioned algorithms. The same results of fault in bus 3 is presented for these techniques in Fig. 8. It is clear from this figure that the method is more reliable than the other two methods.

IV. Conclusions

In this paper, an efficient approach for allocation of FCLs in DG penetrated power system is recommended. Considering the obtained results, it can be stated that the FCLs significantly reduces the current passing through the lines. As a result, the probability of irreparable damage to the network is reduced to an acceptable level, and all network CBs will have the ability to cut off the fault current in the event of the worst fault conditions. This result is important because power grids are expanding abundantly, thus increasing the network short circuit level. Using FCL in the proper position with optimal impedance allows power network operators to easily extend the system without any concern.

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