



New Computational Method for Optimal Allocation of Fault Current Limiters in Power Systems

M. Ghotbi-Maleki* and R. Mohammadi Chabanloo*(C.A.)

Abstract: Expansion of power system causes short-circuit currents (SCC) of networks to exceed the tolerable SCCs of equipment. The utilization of fault current limiter (FCL) in such networks is needed to address this issue. This paper presents a new method for optimal allocation of FCLs to restrain the SCCs under permissible value. In this method, it is suggested to select a line as FCL location where the addition of FCL to this line will have the greatest impact on reducing the SCC of buses which their SCCs exceed the permissible value (known as exceeded buses). Since the optimization algorithms are not capable for optimal allocation of FCL especially in large networks, therefore, the proposed FCL allocation method is presented in the form of a computational process. In this computational process, the candidate lines for FCL location are firstly prioritized by a new index based on the effect of location of FCL on the reduction of SCCs. Then, the FCL size is determined by solving a quadratic equation firstly presented in this paper. The proposed method is implemented on networks with different sizes, and the obtained results show the performance of the proposed method over previous FCL allocation methods.

Keywords: Fault Current Limiter, Impedance Matrix of Network, Optimal Location, Optimal Size, Sensitivity Analysis, Short-Circuit Current.

Nomenclature

Abbreviation

B	Bus
L	Line
G	Generator

Indices

p, q	Indices for buses that FCL installed between them
r	Index for buses whose SCCs exceed I_{tr}
i	Index for line
k	Index for discrete amounts of I_{tr}
n	Index for number of discrete amounts of I_{tr}

Parameters

Z	Impedance matrix of network
I_{tr}	permissible value for SCC of bus r

z_L	Impedance of line
m	Number of buses whose SCCs exceed I_{tr}

Variables

z_{PRL}	Alternative parallel impedance instead of z_{FCL}
z_{FCL}	Impedance of FCL
s_i^r	Index related to effect of line i on bus r
S_i	Index related to effect of line i on all exceeded buses
I_{fr}	SCC of bus r

1 Introduction

DUE to the demand increasing, power systems expand rapidly in the form of construction of new power plants and lines. One of the challenges ahead for the expansion of power systems is the increase of SCCs over than tolerable SCCs of equipment [1]. Since upgrade of power system equipment such as circuit breakers has high cost and needs power outage, the utilization of FCL is required in these networks. The utilization of FCL has other benefits including reliability increasing [2, 3], security and stability increasing [4-8], overcurrent relays coordination improving [9-11] and reconfiguration improving [12].

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However, the main purpose of utilization of FCL is reducing the SCCs of buses, and the most important issue in FCL allocation problem is determining the FCL location which reduces the SCCs of buses by the minimum size of FCL.

By reviewing the previous studies, it is found that only a few of them have presented analytical FCL allocation methods such as eigenvalue analysis [13] and equal-area criterion [14], and most of them have used optimization algorithms such as cuckoo search algorithm [15] and linear programming [16] for this purpose. In [17], two optimization algorithms have been simultaneously used in two steps. The location of FCLs has been firstly determined by the Hashing-integrated genetic algorithm (GA), and then, the size of FCLs has been determined by particle swarm optimization (PSO). Authors of [18] have presented a method to reduce the search space and select some lines as the candidate locations for the installation of FCLs based on SCC reducing index. In this case, the size of FCLs has been obtained through the GA. In [19], network equivalent reduction procedure has been used to reduce the network size in addition to search space of GA for FCL allocation process. In [20], the bus with the maximum SCC exceeding from the permissible value has been firstly identified. Afterward, the line which the installation of FCL on it has the greatest impact on the reduction of SCC of the specified bus, have been obtained in addition to the size of FCL. This process will repeat until the SCCs of all exceeded buses reach the permissible value. The mentioned FCL allocation method is based on a one-by-one method, thus, the FCL is allocated to limit the SCC of one bus at every step. However, it is better to select a line that has the greatest impact on all exceeded buses not only one of them. In this case, the FCLs are allocated considering the SCC limitation of all exceeded buses.

This paper presents a new method for FCL allocation. The proposed method identifies the line where addition of FCL to this line has the greatest impact on the reduction of SCCs of all exceeded buses by new index; and this line is selected as the suitable location for the installation of FCL. Then, the bus whose SCC is most affected by addition of FCL to that specified line is identified using sensitivity factor. The size of FCL is determined so that the SCC of the specified bus reaches the permissible value I_t . By updating the impedance matrix of network with allocated FCL, this process will continue until SCCs of all exceeded buses reach I_t . Since the optimization algorithms are not able to obtain optimal results especially for large networks, the proposed FCL allocation method is presented as a computational process without any need to use the optimization algorithms. The proposed method is implemented on small (8-bus), medium (30-bus) and large (57-bus and 118-bus) networks; and the results show the efficiency of the proposed method compared to other FCL allocation methods.

2 Proposed FCL Allocation Method

The suggestion about the choice of FCL location is determining the line which the lowest size of FCL installed on it has the greatest impact on the reduction of SCCs of exceeded buses. For this purpose, an index is presented in Section 2.1 for identification of suitable lines as the FCL location. The FCL size is also determined by solving a quadratic equation presented in Section 2.2.

2.1 Determining the Location of FCL

The purpose of this part is determining the line that the lowest size of FCL added to it will cause the most change in the SCCs of the exceeded buses. Since the update of impedance matrix of network based on the addition of series impedance z_{FCL} between two buses is complicated, therefore, the parallel impedance z_{PRL} is added instead of the series impedance z_{FCL} , see Fig. 1. The parallel impedance z_{PRL} given in (1) is obtained from $z_{PRL} \parallel z_L = z_{FCL} + z_L$.

$$z_{PRL} = -\frac{z_L \times (z_L + z_{FCL})}{z_{FCL}} \quad (1)$$

Assume that the SCC of bus r exceeds the permissible value and FCL is installed between the buses p and q to limit the SCC of exceeded bus r according to Fig. 2. In this case, element $r-r$ of impedance matrix is updated using (2). By substituting (1) in (2), Z_{rr}^{new} is rewritten as given in (3).

$$Z_{rr}^{new} = Z_{rr}^{old} - \frac{\overbrace{\left(Z_{rp}^{old} - Z_{rq}^{old} \right)^2}^a}{\underbrace{Z_{pp}^{old} + Z_{qq}^{old} - 2 \times Z_{pq}^{old} + z_{PRL}}_b} \quad (2)$$

$$\begin{aligned} Z_{rr}^{new} &= \frac{\overbrace{\left((b - z_{L_i}) \times Z_{rr}^{old} - a \right) \times z_{FCL} - Z_{rr}^{old} \times z_{L_i}^2}^c}{\underbrace{(b - z_{L_i}) \times z_{FCL} - z_{L_i}^2}_f} \\ &= \frac{c \times z_{FCL} - d}{e \times z_{FCL} - f} \quad (3) \end{aligned}$$

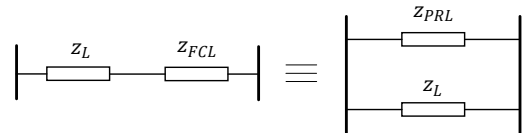


Fig. 1 FCL modeling in a form of a parallel impedance.

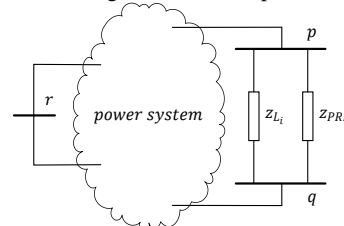


Fig. 2 Part of studied network.

According to (4), the new SCC of bus r after FCL installing is a function of z_{FCL} . The change of SCC of bus r for adding small size of FCL (Δz_{FCL}) between buses p and q is defined in (5) as the derivative of If_r relative to z_{FCL} . The higher sensitivity factor shown in (6) means that the allocated location has a greater effect on the reduction of SCC of bus r . The defined sensitivity factor in (6) is independent of FCL size and only depends on network parameters.

$$If_r^{new} = \frac{1}{Z_r^{new}} = \frac{e \times z_{FCL} - f}{c \times z_{FCL} - d} \quad (4)$$

$$\lim_{\Delta z_{FCL} \rightarrow 0} \frac{\Delta If_r}{\Delta z_{FCL}} = \left. \frac{dIf_r}{dz_{FCL}} \right|_{z_{FCL}=0} \quad (5)$$

$$\left. \frac{dIf_r}{dz_{FCL}} \right|_{z_{FCL}=0} = \left| \frac{Z_{rp}^{old} - Z_{rq}^{old}}{Z_{rr}^{old} \times z_{L_i}} \right|^2 \quad (6)$$

Since each exceeded bus can be effective in the computation process based on its exceeding level from It , the sensitivity factor between the location of FCL (line i) and the reduction of SCC of exceeded bus r is presented in (7) by weighting (6). This index is generalized for all exceeded buses according to (8). If FCL is installed on a line that has the highest value of this index, it will be able to reduce the SCC of all exceeded buses with the lowest z_{FCL} . Therefore, the index in (8) can be used to prioritize the lines of network and determine the best FCL location.

$$s_i^r = \left. \frac{dIf_r}{dz_{FCL}} \right|_{z_{FCL}=0} \times (If_r - It_r) \quad (7)$$

$$S_i = \sum_{r=1}^m s_i^r = \sum_{r=1}^m \left| \frac{Z_{rp}^{old} - Z_{rq}^{old}}{Z_{rr}^{old} \times z_{L_i}} \right|^2 \times (If_r - It_r) \quad (8)$$

2.2 Determining the Size of FCL

After identifying the appropriate installation location, the exceeded bus whose SCC will be most affected by installation of FCL on the specified location is identified. This identification is accomplished through the sensitivity factor in (6), which indicates the influence of exceeded buses from location of FCL. Any exceeded bus that has the maximum sensitivity is selected as the specified bus for limiting its SCC. Assume that the best location for installation of FCL is between buses p and q , and this location has the greatest impact on the SCC of exceeded bus r . The aim is determining the size of FCL to reduce the SCC of bus r from If_r to It_r . For this purpose, the SCC of bus r is considered equal to It_r according to (9). With assuming $c = |c| \exp^{j\alpha c}$, $d = |d| \exp^{j\alpha d}$, $e = |e| \exp^{j\alpha e}$, $f = |f| \exp^{j\alpha f}$, and $z_{FCL} = |z_{FCL}| \exp^{j\alpha 2}$, a quadratic equation given in (10) is obtained to determine the size of FCL. The coefficients of this equation are also given in (11)-(13).

The smallest positive value obtained from (14) is selected as the size of FCL. Defining z_{FCL} as $|z_{FCL}| \exp^{j\alpha 2}$ illustrates that inductive type FCL is considered for this study.

$$If_r = It_r \rightarrow \left| \frac{e \times z_{FCL} - f}{c \times z_{FCL} - d} \right| = It_r \quad (9)$$

$$A \times |z_{FCL}|^2 + B \times |z_{FCL}| + C = 0 \quad (10)$$

$$A = It_r^2 |d|^2 - |f|^2 \quad (11)$$

$$B = -2 \times \left[It_r^2 |d| |e| \cos\left(\frac{\pi}{2} + \alpha d - \alpha e\right) - |f| |g| \cos\left(\frac{\pi}{2} + \alpha f - \alpha g\right) \right] \quad (12)$$

$$C = It_r^2 |e|^2 - |g|^2 \quad (13)$$

$$|z_{FCL}| = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \quad (14)$$

2.3 Implementation of the Proposed Method

Fig. 3 shows the flowchart of proposed method for FCL allocation. The steps of the proposed method are as follows:

- Step 1:** Identify the buses whose SCCs exceed permissible value It .
- Step 2:** Prioritize network's lines by the presented index in (8) based on the ability of each line to reduce the SCCs of the identified exceeded buses in step 1.
- Step 3:** Determine the line with the highest index value as the location of installation of FCL.
- Step 4:** Determine the bus using the sensitivity factor in (6) whose SCC is reduced more than other buses

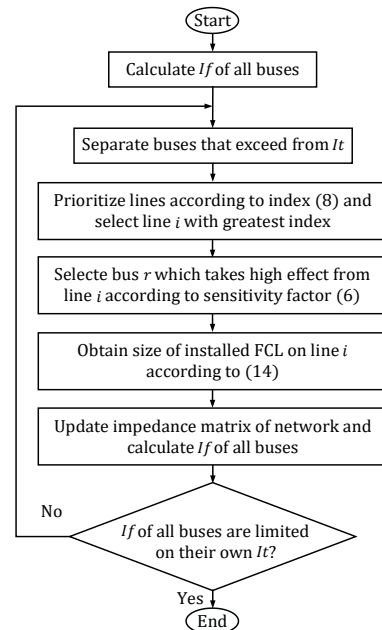


Fig. 3 Flowchart of the proposed FCL allocation method.

because of FCL installation on the selected line.

Step 5: Obtain the size of FCL using (14).

Step 6: Update impedance matrix of network based on obtained z_{FCL} , and determine new SCCs.

Step 7: Return to step 1 if the SCCs of all buses are not limited.

3 Simulation Results

In this section, the proposed method is implemented on IEEE 8, 30, 57, and 118 bus networks whose data are in [21]; and the proposed method is compared with methods presented in [17] and [20] to demonstrate the efficiency of the proposed method in FCL allocation problem. The method in [17] uses two simultaneous optimization algorithms to determine FCL location and size. The method in [20] tries to limit the SCC of one exceeded bus at each step using optimization process in the form of MINLP. It is worth noting that the SCC reduction of generator installed buses is not considered in the implementation of these three methods (proposed methods and methods [17] and [20]). Also, transient impedances of generators have been used for these studies to validate the proposed method for transient conditions.

3.1 Study on 8-Bus Network

The 8-bus network is shown in Fig. 4. The permissible value of this network is assumed to be 4 p.u. According to Fig. 5(a), the SCCs of buses B1, B5, and B6 have exceeded the permissible value, and the FCL allocation must be implemented in such a way that these SCCs are limited to I_t .

Table 1 shows the sensitivity of SCCs of buses B1, B5, and B6 obtained from (6) for FCL allocation on each line. The index for FCL location based on (8) is also listed in the last column of Table 1. In the first iteration, line L9 has the highest index, thus, it is the best location for FCL installation ($S_{L9} = 0.22873$). According to Table 1, the bus whose SCC has the most affected from the installation of FCL on line L9 is B5 ($\left. \frac{df_{B5}}{dz_{FCL_{L9}}} \right|_{z_{FCL_{L9}}=0} = 0.06847$ in the fourth column).

The size of first installed FCL on the network is determined using (14), and it is equal to 0.41362 p.u. according to Table 2. The SCCs of the buses change

after the first FCL allocation as shown in Fig. 5(b). As it is obvious, SCCs of B5 and B6 have reached the permissible value, however, SCC of B1 is still larger than I_t . After obtaining the size of FCL in the first iteration, the impedance matrix of network is updated and the new sensitivity factors are calculated (second iteration in Table 1). Again, L9 is chosen as the second FCL location, therefore, the size of installed FCL on the line L9 is equal to 2.91972 p.u. after the second iteration, see Table 2. Fig. 5(c) shows the SCCs of the buses after the second iteration of proposed method. As it is clear, SCCs all buses are less than the permissible value and there is no need to repeat the proposed method.

Because of increase in the impedance of line L9 due to FCL installation in the first iteration, this line was also selected as FCL location in the second iteration, too. Although due to the proximity of bus B1 to generator G1, it was more appropriate that the line L8 was chosen to install the second FCL. In order to obtain better results, it is recommended to apply this method in several steps with reducible permissible value. For this purpose, the distance between the maximum SCC in the network and the permissible value is divided into n steps; and the proposed method is applied to the network with a permissible value obtained from (15) in step k . One FCL is assigned at each step, and the next

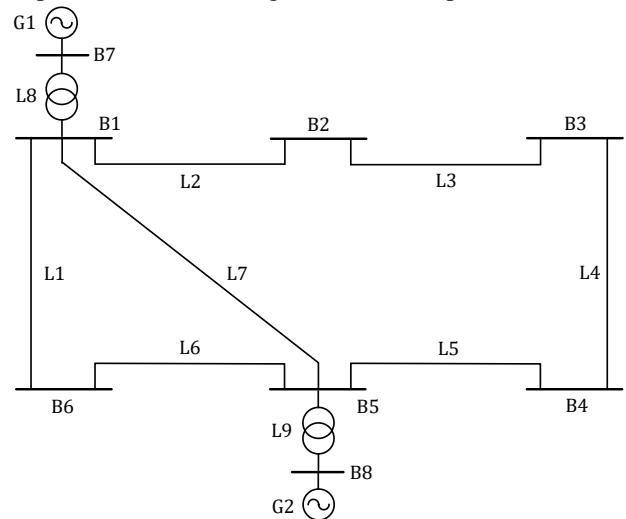


Fig. 4 IEEE 8-bus network.

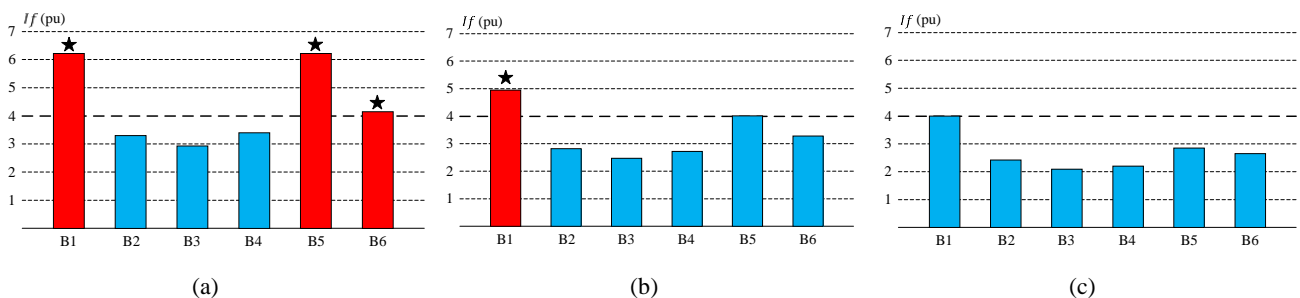


Fig. 5 SCCs of 8-bus network: a) without FCL allocation, b) first iteration of proposed method, and c) second iteration of proposed method.

Table 1 Calculated sensitivity factors and indices for 8-bus network.

First Iteration							
Line	B1		B5		B6		S
	$I_{f_{B1}} - I_{t_{B1}} = 2.23628$		$I_{f_{B5}} - I_{t_{B5}} = 2.23628$		$I_{f_{B6}} - I_{t_{B6}} = 0.15829$		
	$\frac{df_{B1}}{dz_{FCL}}$	S_i^{B1}	$\frac{df_{B5}}{dz_{FCL}}$	S_i^{B5}	$\frac{df_{B6}}{dz_{FCL}}$	S_i^{B6}	
L1	0.00134	0.00300	0.00134	0.00300	0.00968	0.00153	0.00753
L2	0.00035	0.00079	0.00035	0.00079	4.27e-07	6.76e-08	0.00158
L3	0.00023	0.00052	0.00023	0.00052	2.81e-07	4.45e-08	0.00104
L4	0.00023	0.00052	0.00023	0.00052	2.81e-07	4.45e-08	0.00104
L5	0.00023	0.00052	0.00023	0.00052	2.81e-07	4.45e-08	0.00104
L6	0.00088	0.00197	0.00088	0.00197	0.00747	0.00118	0.00513
L7	0.00485	0.01084	0.00485	0.01084	5.86e-06	9.27e-07	0.02169
L8	0.06847	0.15312	0.03225	0.07212	0.02122	0.00335	0.22860
L9	0.03225	0.07212	0.06847	0.15312	0.02206	0.00349	0.22873

Second Iteration							
Line	$I_{f_{B1}} - I_{t_{B1}} = 0.93642$		$I_{f_{B5}} - I_{t_{B5}} = -$		$I_{f_{B6}} - I_{t_{B6}} = -$		S
	L1	0.00031	0.00029	-	-	-	
L2	0.00008	0.00007	-	-	-	-	0.00007
L3	0.00005	0.00005	-	-	-	-	0.00005
L4	0.00005	0.00005	-	-	-	-	0.00005
L5	0.00005	0.00005	-	-	-	-	0.00005
L6	0.00021	0.00019	-	-	-	-	0.00019
L7	0.00115	0.00108	-	-	-	-	0.00108
L8	0.06847	0.06411	-	-	-	-	0.06411
L9	0.32708	0.30628	-	-	-	-	0.30628

Table 2 Results of two iterations of proposed method.

	First iteration	Second iteration
Location	L9	L9
Size [p.u.]	0.41362	2.50610
Final allocation	0.41362 p.u. on L9	2.91972 p.u. on L9

Table 3 Results of proposed method for fixed and reducible I_t .

	Fixed I_t	Reducible I_t	
Number of FCLs	1	2	
Location of FCLs	L9	L8	L9
Size of FCLs [p.u.]	2.91972	0.17465	0.17573
Sum of FCLs [p.u.]	2.91972	0.35038	

step is performed by updating the impedance matrix of the network. Finally, all assigned FCLs are aggregated for various installation locations. Table 3 shows the effect of considering the permissible value as a reducible value on the results of proposed method. As it is obvious, two locations on lines L8 and L9 with less FCL sizes compared to the proposed method with fixed permissible value are obtained in this case.

$$I_t^k = \max(I_{f_r}) - \frac{\max(I_{f_r}) - I_t^{Final}}{n} \times k \quad (15)$$

Fig. 6 shows the size of installed FCLs on lines L8 and L9 and the sum of these two amounts for various n . With assuming the number of steps equal to 100, Fig. 7 shows the various amounts of permissible value and FCL allocation process for each step. Comparing the SCCs of buses in Fig. 8 shows all SCCs are limited to I_t^{Final} ($= 4$ p.u.) after applying the proposed method with fixed and reducible I_t s. However, the SCCs obtained from the proposed method with fixed I_t are lower than ones obtained from the proposed method with reducible I_t due to the higher size of FCLs obtained from the proposed method with fixed I_t .

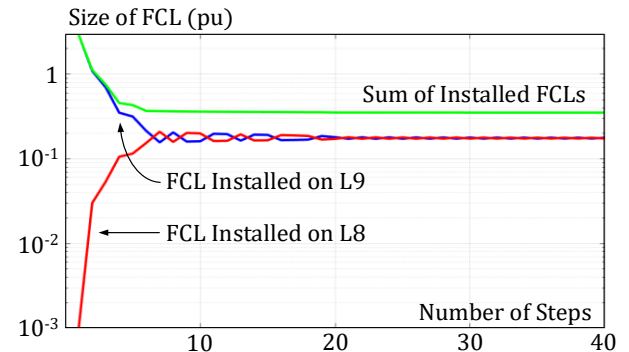


Fig. 6 Size of FCLs obtained from the proposed method with respect to various steps of I_t .

Table 4 contains the results obtained from the proposed methods and methods [17] and [20]. As a result, the proposed method is better than the methods [17] and [20] from the point of size of assigned FCLs. Fig. 9 shows the SCCs of buses after FCL allocation based on the results of Table 4. The SCCs after applying the method [20] are lower than the ones after applying the method [17] and the proposed method due to non-optimal FCL allocation process using method [20].

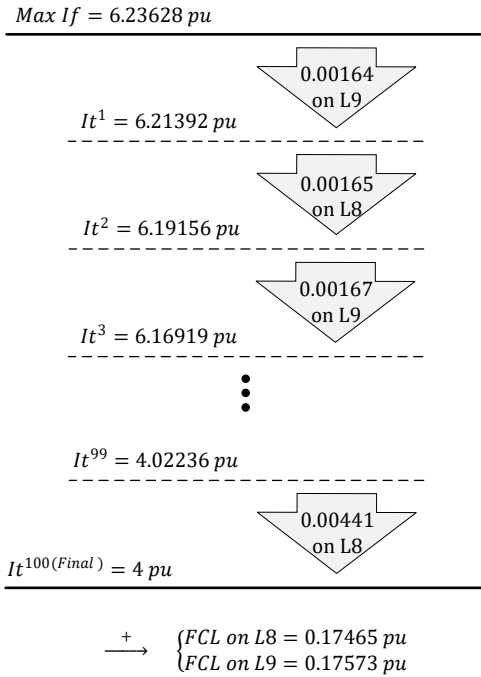


Fig. 7 Allocation of FCLs for steps equal to 100.

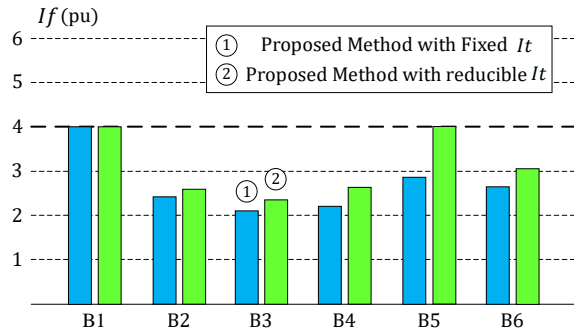


Fig. 8 Comparison of SCCs of 8-bus network after applying the proposed method with fixed and reducible I_t .

Table 4 Comparison of results of proposed method with methods [17] and [20] for 8-bus network.

	Method of [17]	Method of [20]	Proposed method
Number	2	2	2
Size [p.u.] on L8	0.17532	0.11687	0.17465
on L9	0.17532	0.31129	0.17573
Sum [p.u.]	0.35065	0.42816	0.35038

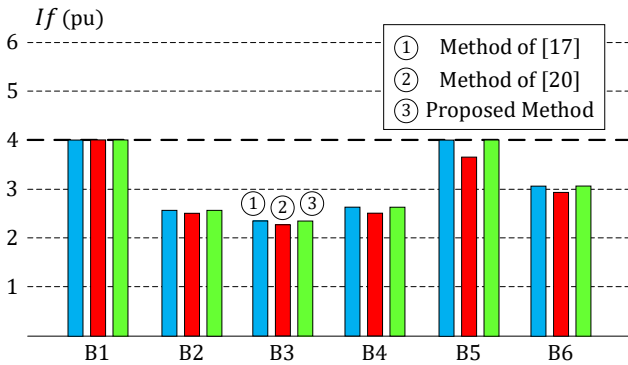


Fig. 9 Comparison of limited SCCs based on proposed method and methods [17] and [20] for 8-bus network.

Table 5 Comparison of results of proposed method with methods [17] and [20] for 30-bus network.

	Method of [17]	Method of [20]	Proposed method
Number	3	3	3
Size FCL1	0.71172	0.58754	0.71561
FCL2 [p.u.]	0.15690	0.10448	0.13275
FCL3	1.27618	7.17916	0.09633
Sum [Ω]	29.74361	97.11387	25.04528

3.2 Study on 30-Bus Network

The 30-bus network consists of 132, 33, and 11 kV buses, and 41 lines as candidate locations for FCL installation. According to Fig. 10, the SCCs of buses B6, B10, and B12 exceed permissible value if I_t is considered to be 12 kA. Table 5 shows the size of the FCLs and Fig. 11 shows the location of FCLs obtained from the proposed methods and methods [17] and [20]. The location of FCL1 and FCL2 obtained from all three

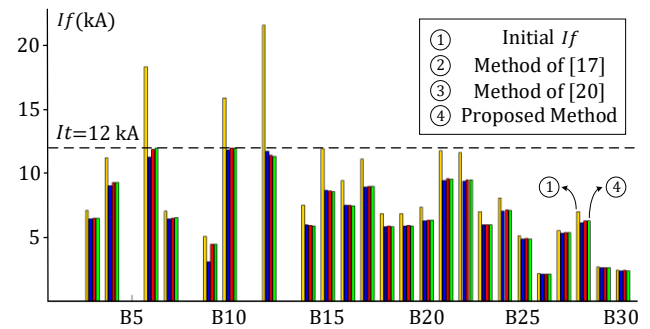


Fig. 10 SCCs of 30-bus networks before and after applying FCL allocation methods.

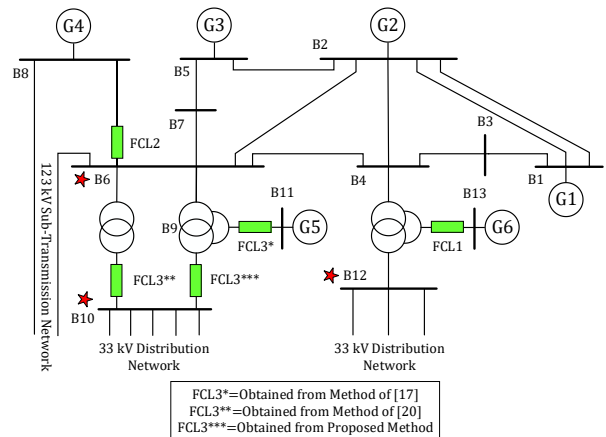


Fig. 11 Locations of obtained FCLs for 30-bus network.

methods are the same; and the differences are in the location of FCL3 and the size of installed FCLs. Fig. 10 shows the SCCs of buses after applying three methods.

According to the results, the SCCs are limited by the lowest sizes of FCLs if the proposed method is used.

3.3 Study on 57-Bus Network

The 57-bus network has 4 voltage levels of 138, 115, 69, 34.5 kV and 80 locations for FCL installation. According to Fig. 12, if I_t is considered equal to 10 kA for this network, 7 buses (B4, B13, B14, B15, B28, B29 and B55) exceed the permissible value. The results of applying the previous and proposed allocation methods are given in Table 6. The optimization algorithms used in method [17] are unable to allocate optimally FCLs due to the weakness of optimization algorithms for large networks, therefore, 7 FCLs are proposed for limiting SCCs of 57-bus network. Method [20] allocates 6 FCLs, and the obtained sizes of FCLs are in the range of 14.9488 p.u. to 0.0382 p.u. However, the proposed method employs a smaller number of FCLs (5 FCLs) with fewer sizes than methods [17] and [20], and also the difference between minimum and maximum sizes of obtained FCLs from the proposed method is less than this difference in method [20]. This indicates that the results of proposed method are optimal.

3.4 Study on 118-Bus Network

The 118-bus network consists of three voltage levels 345, 161 and 138 kV, and also has 186 candidate

locations for FCL installation. With considering the permissible value equal to 20 kA, 10 buses (5B, 7B, 11B, 17B, 35B, 37B, 60B, 68B, 75B, 78B) require SCC limiting. The results of applying three methods are given in Table 7. It is clear that the proposed method performs better than the two other methods in terms of number and size of FCLs. It is also important to note that the simulation time of methods [17], [20] and the proposed method on a system with an Intel CPU i5 running at 2.5 GHz with 4 GB of RAM using MATLAB 2015b are approximately equal to 5 hours, 1 hour and 6 seconds, respectively. Therefore, the proposed method is able to optimally allocate FCLs in the shortest possible time.

3.5 Investigation about Cost-Benefit of Proposed Method

Limiting the SCCs of network with less impedance is the main aim of FCL allocation methods, however, these methods must be confirmed in terms of being cost effective. For this purpose, two main cost field for FCL allocation process must be priced. Table 8 illustrates the cost of location and impedance for different voltage levels [20]. According to these amounts, the cost of FCL allocation for various location and impedances can be obtained.

Table 6 Comparison of results of proposed method with methods [17] and [20] for 57-bus network.

	Method of [17]	Method of [20]	Proposed method
Number	7	6	5
Sum [Ω]	486.20723	3410.60519	415.56674
Max size [p.u.]	0.7259	14.9488	0.61846
Min size [p.u.]	0.2415	0.0382	0.26651

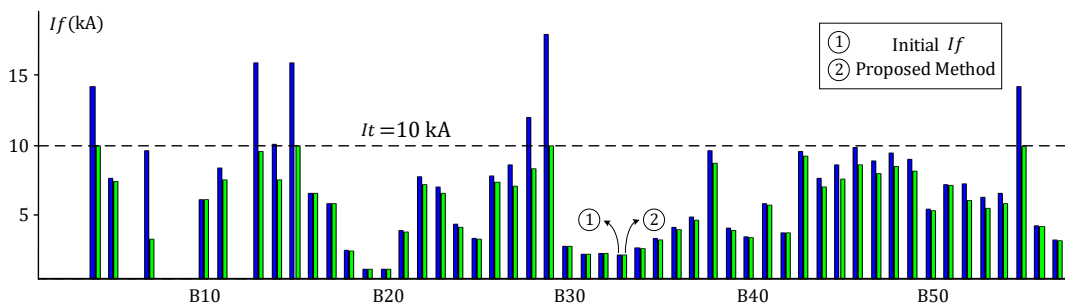


Fig. 12 SCCs of 57-bus network before and after applying the proposed method.

Table 7 Comparison of results of proposed method with methods [17] and [20] for 118-bus network.

	Method of [17]	Method of [20]	Proposed method
Number	11	8	7
Sum [Ω]	848.05550	635.65206	324.29170
Max size [p.u.]	0.9050	1.0473	0.5501
Min size [p.u.]	0.0523	0.0216	0.0727

Table 8 Cost of FCLs locations and impedances.

Voltage [kV]	Cost of location [million \$]	Cost of impedance [million \$]
< 75	0.5	0.1
< 115	1	0.2
< 230	1.5	0.3
< 500	3	0.6

Table 9 Comparison of cost of proposed method with methods [17] and [20] for all case studies.

Networks	Methods	Number of FCLs	Impedance of FCLs [p.u.]	Cost [million \$]
8-bus	Method of [17]	2	0.3506	1.0351
	Method of [20]	2	0.4281	1.0428
	Proposed Method	2	0.3503	1.0350
30-bus	Method of [17]	3	2.1448	2.7459
	Method of [20]	3	7.8712	3.3080
	Proposed Method	3	0.9447	2.6210
57-bus	Method of [17]	7	2.7800	10.2857
	Method of [20]	6	17.9091	14.3727
	Proposed Method	5	2.1821	8.1546
118-bus	Method of [17]	11	3.5724	19.1221
	Method of [20]	8	2.9557	14.4085
	Proposed method	7	1.3208	12.4181

After pricing the location and impedance of FCLs for various voltage levels, the cost of implementation of methods [17], [20] and proposed one have been obtained as listed in Table 9. As shown in this table, the implementation cost of the proposed method is less than two methods [17] and [20] for all case studies. As a conclusion, the proposed method has better results in comparison to the previous methods in terms of number and impedance of FCLs and also the cost of implementation.

5 Conclusion

This paper presents a computational method for optimal FCL allocation. The proposed method has been expressed in the form of a computational approach because the FCL allocation methods based on optimization algorithms are weak especially for large networks. The formulation of proposed method is such that it can be applied to all networks (distribution, sub-transmission and transmission). In the proposed method, the line that has the greatest impact on reducing the SCC of exceeded buses has been identified by a new index, and that line has been selected as the location of FCL. Then, the bus which its SCC gets the greatest reduction from adding FCL to the selected line has been selected by the presented sensitivity factor in the paper. The FCL size has also been determined by a quadratic equation to limit the SCC of selected bus to desired level. In order to improve the results of proposed method, it has been suggested to consider the permissible value of SCC as a reducible variable. In case of using the reducible permissible value, FCLs has been obtained with smaller sizes than the proposed method with fixed permissible value. To evaluate the performance of proposed method, this method along with two other FCL allocation methods was applied to 8-bus, 30-bus, 57-bus, and 118-bus networks and the simulation results show the optimal allocation of FCLs using the proposed method in comparison with other methods. It should be noted that the proposed method cannot address the improvement of security, stability, and reliability indices, however, the proposed method has less cost of implementation than previous FCL

allocation methods which have been presented only for limitation of SCCs.

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