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The effect of fault current limiter size and type on current limitation in the presence of distributed generation

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Abstract: One of the effective mitigation solutions of the problems due to the penetration of distributed generation (DG) into the distribution network is a fault current limiter (FCL). Main attention is given to designs for resistive and inductive FCLs and others should meet the same requirements. At first in this paper network analysis is used to determine a suitable type of limiting impedance of a FCL in a distribution network in the presence of DG and then a comparative study of resistive, inductive, and complex FCLs is conducted to show the effect of size and type of FCL on the amplitude and phase of DG and network fault current. To illustrate the impact of FCLs on relay coordination restoration, an optimization algorithm is used to determine the minimum size of FCL and subsequently the role of FCL impedance type on the coordination time interval of the main and backup relays in a sample IEEE typical distributed network is investigated. Simulations are carried out by programming in MATLAB and the obtained results are reported and discussed.

Key words: Fault current limiter, power system protection, distributed generation

1. Introduction

Distributed generation (DG) is being applied to the power system and some distribution circuits experiencing significant DG penetration. Distribution systems' protective devices' functioning is completely changed with the presence of DG and they cause several problems to the protection of distribution networks. The most commonly mentioned are changes in short circuit levels in different points of the network, exceeding the breaking capacity of circuit breakers, loss of networks' radial nature, false tripping of feeders, relaying of mal operation, and miscoordination of protection devices[1].

Synchronous-based DG has high fault current contribution as opposed to inverter-based DG and consequently has more impact on protective device coordination [2]. To mitigate DG's impacts on the traditional protection scheme, several methods have been proposed, like limiting DG capacity; modifying the protection system based on using extra circuit breakers, reclosers, and relays; using adaptive protection; and utilizing fault current limiters (FCLs) [3].

One of the effective mitigation solutions of DG's impacts on the traditional protection scheme is utilizing FCLs in the network [4]. FCLs are known as one of the best countermeasures to solve the problems related to excessive short circuit levels in DG networks and microgrids to ensure suitable coordination of the protective

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devices and subsequently safe operation of the grid [5,6]. The FCL is a low impedance device that has no action during normal operation. However, during a fault it takes fast action by inserting high impedance in series with the power delivery system to limit the fault current value to a preset limit [7]. The impact of the FCL on a distribution network in the presence of DG is investigated and the possible use of FCLs for mitigating protection system faults due to DG is discussed [8]. The FCL in series with DG and a utility interconnection point is used to restore fault current levels to original values, and the FCL impedance is determined by particle swarm optimization [9].

FCLs have emerged as an alternative to limit prospective short-circuit currents to lower levels and improve power system reliability, stability, and security by reducing the fault currents [10].

How and when FCL impedance enters the network is different regarding the type of FCL. Moreover, the value of this impedance is variable in some FCLs. For the sake of simplicity, the value of this impedance is assumed to be constant at the time of fault occurrence [11]. Presently two basic designs are given main attention: resistive and inductive. Most other proposed devices are based on these designs and must meet the same requirements [11].

The FCL impedance leads to limitation of fault current and since the cost of the FCL is relative to its impedance, the optimum size and cost of FCL is preferred to be used [12]. Selection of the FCL impedance type and its size by genetic algorithm (GA) is presented to restore the effective coordination of overcurrent (OC) relays [13], and optimal resistance of a superconducting FCL and its protective coordination are determined when it is connected to a wind-turbine generation system in series [14]. Another method is used to find the optimized resistance of resistive FCLs based on the GA to handle the requirements of restoration of original relay settings [15]. Electrical and thermal behaviors of resistive and inductive superconducting FCLs are used to investigate the effect of superconducting FCL parameter variations on its performance based on multiple criteria decision-making techniques [16].

Methods for the estimation of the effects of FCLs on the short circuit are essential for power system development including the FCL. These papers show the effects of type and size of FCLs in limitation but do not investigate the analytical and systematic effects of FCLs on the network structure. This paper investigates the required limiting impedance of a FCL installed in a distribution network by using network analysis and comparative study of resistive FCLs (R-FCLs) and inductive FCLs (X-FCLs) for power systems in the presence of DG. In network analysis, the limiting impedance was constant. For determining the impedance of FCLs and investigating the size and type of FCL impedances, the optimization algorithm [13] is used and optimum sizes of R-, X-, and complex (C-)FCLs are obtained. The effects of the installed FCLs in series with DG on the coordination restoration of the protection system and the coordination time interval (CTI) between main and backup relays are investigated and simulations are carried out for R-, X-, and C-FCLs, and the results are shown and discussed.

2. System study and formulation analysis

R- and X-FCLs were introduced to limit fault currents in the distribution network in many articles. In this paper, a range of fault current limitation by R-, X-, and C-FCLs in the presence of DG is investigated. A sample distribution network with DG and FCLs is shown in Figure 1 where Z_{N-DG} is the network equal impedance up to the installed DG and Z_{DG-F} is equal impedance from the DG to the fault point, so the short circuit current in the fault point would be achieved by:

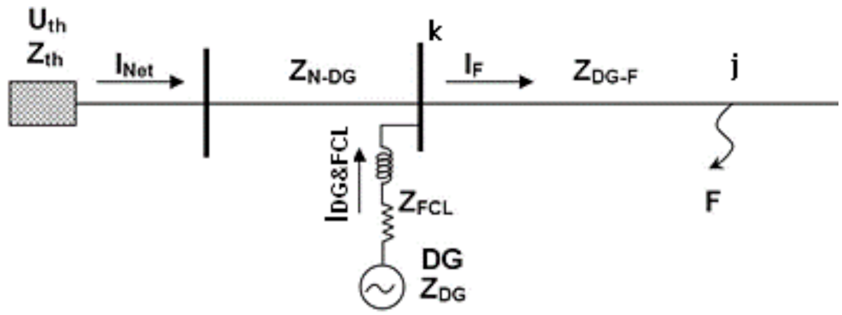

Figure 1. DG and FCL connected to the distribution network.

$$I_F = I_{Net} + I_{DG\&FCL}, \tag{1}$$

where I_{Net} is the network fault current and $I_{DG\&FCL}$ is the DG fault current, which is limited by the FCL. It is obvious that the amplitude of fault current is reduced by increasing FCL impedance, so the resistance and reactance of the FCL have a great effect on reducing DG fault current. Supposing that $Z_{eq} = R_{eq} + jX_{eq}$ is the impedance of the network from DG to the fault point without FCL and $Z_{FCL} = R_{FCL} + jX_{FCL}$ is FCL impedance, if the Z_{eq} and Z_{FCL} vectors are in the same direction the maximum DG fault current limitation would be achieved, which means $R_{eq} = R_{FCL}$ and $X_{eq} = X_{FCL}$. To reduce the total fault current through the network, the sum of the DG fault current and network fault current should be minimized.

FCLs, by inserting high impedance into the network, not only decrease the amplitude of the fault current but also change the angle of DG fault current. Consider Figure 2, which is achieved from short circuit analysis by Thevenin theory and dividing the circuit in Figure 1 into two parts. The upper circuit shows the network short circuit without any load and the bottom shows load current in the network. Fault current at any point of the network is achieved by calculating the sum of currents in these two circuits.

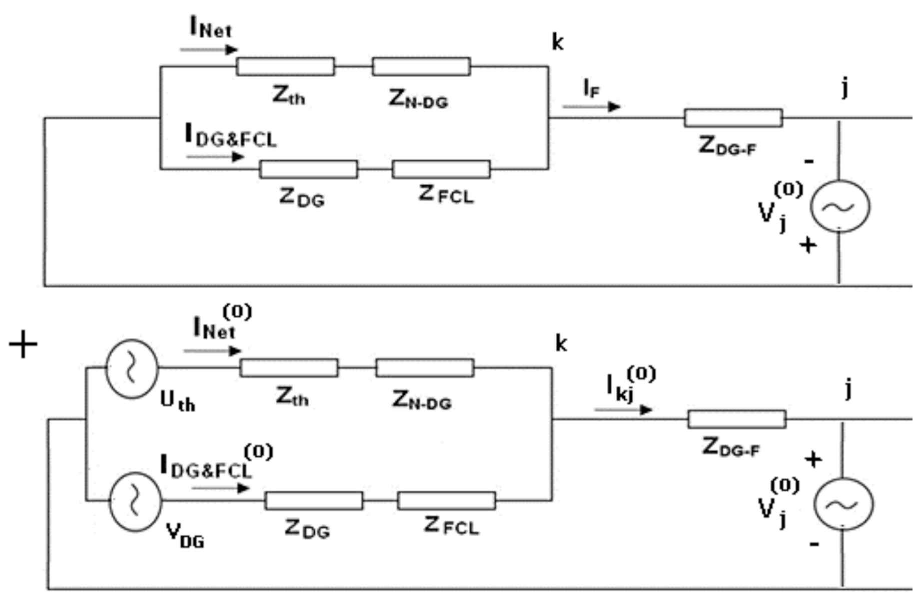

Figure 2. Short circuit network in Thevenin theory.

When DG was installed in the network, the network impedance matrix changed; the DG impedance is added between the node and ground so one row and one column are added to the network impedance matrix as shown in Eq. (2). By setting DG voltage to zero, a new impedance matrix would be achieved by omitting the DG's row and column (shown in Eq. (3)).

$$\begin{bmatrix} V_1 \\ V_2 \\ ... \\ V_n \\ \hline V_{DG} \end{bmatrix} = \left[\begin{array}{cccc|c} Z_{11} & Z_{12} & ... & Z_{1n} & Z_{1k} \\ Z_{21} & Z_{22} & ... & Z_{1n} & Z_{2k} \\ & ... & ... & ... & ... \\ Z_{n1} & Z_{n2} & ... & Z_{nn} & Z_{nk} \\ \hline Z_{k1} & Z_{k2} & ... & Z_{kn} & Z_{kk}+Z_{DG} \end{array}\right] \begin{bmatrix} I_1 \\ I_2 \\ ... \\ I_n \\ \hline I_{DG} \end{bmatrix} \tag{2}$$

$$Z_{bus,new} = Z_{bus,old} - Z_{col} Z_{common}^{-1} Z_{row} \tag{3}$$

Based on Thevenin theory and using the impedance matrix, fault current through the network can be calculated. The network fault current in the fault point (j) would be:

$$I_f = \frac{V_j^{(0)}}{V_{jj,new}} = \frac{V_j^{(0)}}{Z_{jj} - \frac{Z_{kj}Z_{jk}}{Z_{kk}+Z_{DG}+Z_{FCL}}}, \tag{4}$$

where $V_j^{(0)}$ is the voltage of the fault point before short circuit and $Z_{jj,new}$ is the new network Thevenin impedance in the fault point. Maximum DG fault current occurred for faults near the DG; hence, to calculate the maximum DG fault current, Z_{jj} is replaced by Z_{kkj}:

$$I_f = \frac{V_j^{(0)}(Z_{kk}+Z_{DG}+Z_{FCL})}{Z_{kk}(Z_{DG}+Z_{FCL})} = \frac{V_j^{(0)}}{Z_{kk}} + \frac{V_j^{(0)}}{Z_{DG}+Z_{FCL}}. \tag{5}$$

This shows that the network fault current in the DG connection point is equal to the sum of DG fault current and network fault current without DG. Fault current through the network by considering load current can be written as:

$$\begin{aligned} I_{kj} &= \frac{V_k - V_j}{Z_{DG-F}} = \frac{(V_k^{(0)} - Z_{kj}I_f) - (V_j^{(0)} - Z_{jj}I_f)}{Z_{DG-F}} \\ &= \frac{(V_k^{(0)} - V_j^{(0)}) - (Z_{kj} - Z_{jj})I_f}{Z_{DG-F}} \\ &= \frac{V_j^{(0)}}{Z_{kk}} + \frac{V_j^{(0)}}{Z_{DG}+Z_{FCL}} + \frac{V_k^{(0)} - V_j^{(0)}}{Z_{DG-F}} \end{aligned} . \tag{6}$$

The vector diagram of the network current and DG current with and without DG and using R- and X-FCLs is illustrated in Figure 3. The horizontal axis is chosen as a reference and shows the angle of voltage at the fault point before the fault occurred. According to this, DG limited fault current by FCL ($I_{FCL\&DG}$), network fault current without DG branch (I_{Net}), and load current ($I^{kj(0)}$) are summed and established the total network fault current near the DG. If the sum of load current and the network fault current (I_{Net}) is calculated, it can be seen that load current is very small against the network fault current and does not affect the network current angle sensitively, so the equivalent current of the network fault current and load current can be shown as I_{Net} in Figure 3. It is clear that the fault current results from the DG fault current and network fault current. When there is no FCL in the network, the angles of DG and network fault currents would be close to each other. Based on Eq. (6) the angle between the DG and network fault currents vectors has an important role for reducing total fault current through the network. In Figure 3, R- and X-FCLs not only limited DG fault current amplitude but also increased the phase difference between the DG and network fault currents vectors, so this causes the sum of vectors to be larger than in the case where there is no FCL in the network. It should be noted that in Figure 3, the FCL has large impedance.

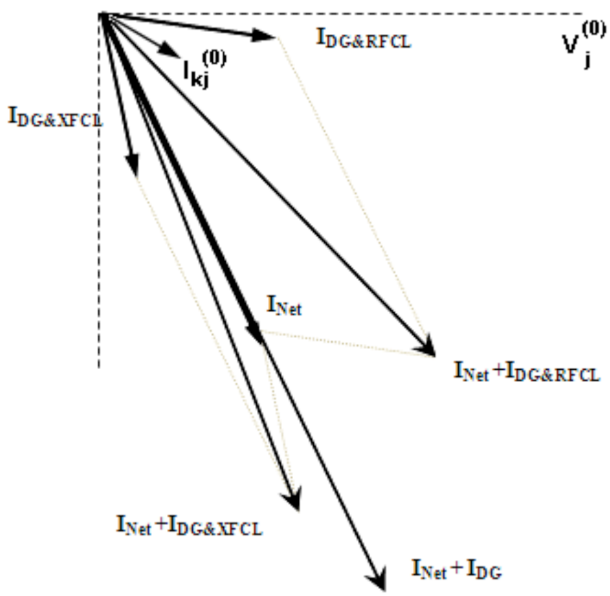

Figure 3. Vector diagram of DG fault current limitation by FCL.

The distribution network has large resistance and the X/R ratio is low, so the network fault current (I_{Net}) is independent of the network's other parameters. As shown in Figure 3, network fault current is placed between DG fault currents in pure resistive and pure inductive modes. The angle of the DG fault current is:

$$\theta = \tan^{-1}(\frac{X_{FCL} + X_{DG}}{R_{FCL}}). \tag{7}$$

At lower impedance of the FCL, if inductance of the FCL increases, the angle of DG fault current approaches 90°, and if the resistance of the FCL increases, this angle approaches the network fault current angle and limitation is reduced in comparison to the X-FCL. With large FCL impedance (more than 7 times the DG impedance), the angle between DG fault current and the network fault current increases, so more limitation will be achieved by which R- and X-FCLs can make more phase difference.

In a distribution network that has more reactive fault current due to the inductive upstream network, the R-FCL has more capability to make a phase difference between vectors, so the R-FCL has more limitation in comparison with the X-FCL. Consequently, pure R- and X-FCLs not only reduce DG fault current amplitude but also make a large phase difference, which is very effective in DG fault current limitation. Using the C-FCL can reduce DG fault current amplitude more than R- and X-FCLs but can make less phase difference between the DG fault current and the network fault current, so with high FCL impedance the C-FCL has less limitation in comparison with R- and X-FCLs.

3. Simulation results

The IEEE 30-bus system shown in Figure 4 is used as a case study in this paper to show the effects of type and size of FCL on the fault current limitation in the presence of DG. The IEEE 30-bus system can be considered as a meshed subtransmission/distribution network. The network consists of 30 buses (132 and 33 kV buses), 37 lines, 6 generators, 4 transformers, and 86 OC relays here fed from three primary distribution substations (132/32 kV at buses 1, 6, and 13). The generator, line, and transformer information was given in [17]. It is assumed that directional OC relays were installed on both sides of a line and OC relays were coordinated before DG connection. Three synchronous generators are used as DG in buses 3, 10, and 15 and their specifications are shown in Table 1. These generators are connected to the network via 10 MVA and 0.05 PU reactance transformers.

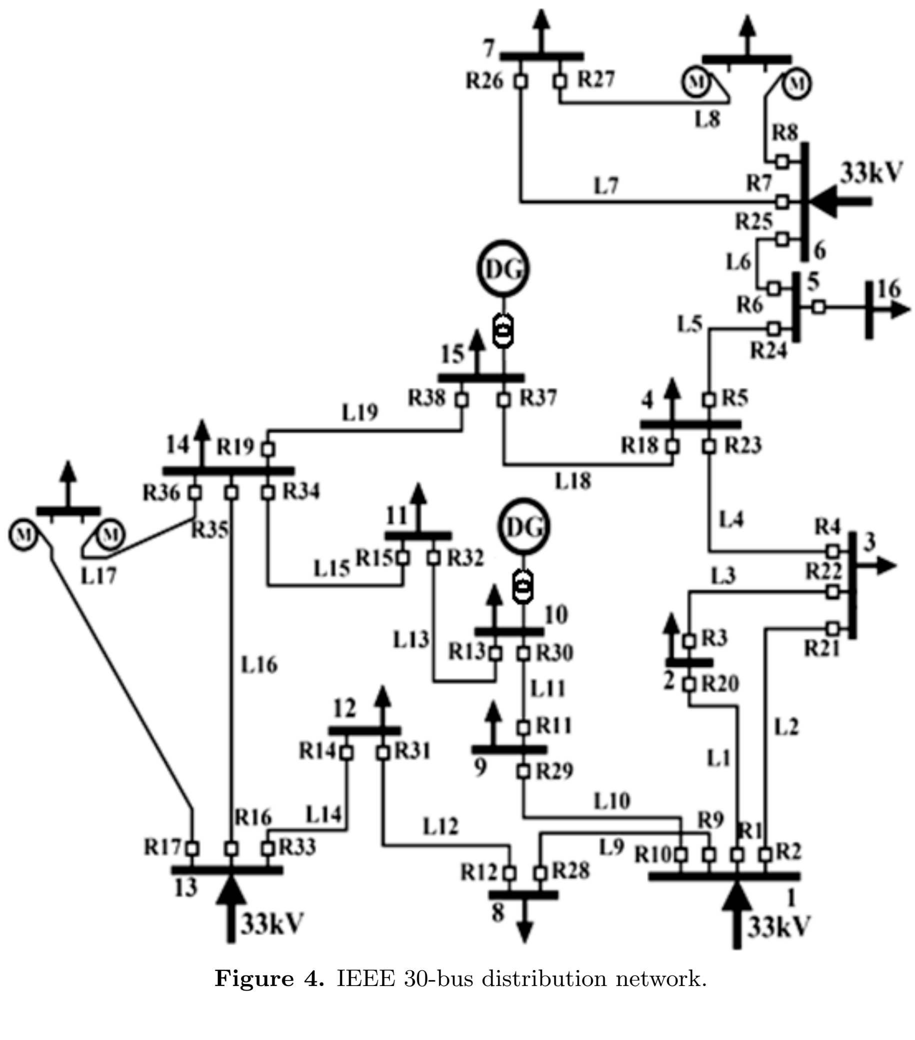

Figure 4. IEEE 30-bus distribution network.

Table 1. DG specifications.

	MVA	Transient reactance	Power factor	Installing bus
DG 1	2	0.15	0.9 lag	3
DG 2	4	0.10	0.9 lag	10
DG 3	7	0.10	0.9 lag	15

For avoiding the large size of FCL impedance and subsequently the high cost of FCL installation, an acceptable range of FCL limitation should be selected instead of full limitation of fault currents. For determining the impedance of FCLs and investigating the size and type of FCL impedances, an optimization algorithm [13] is used. The impedance of FCLs is selected with an optimization algorithm considering that the fault currents flowing (after installing the DG and FCLs) all over the network are limited to an acceptable range. This range is determined as a coefficient of fault current before installing the DG and is shown as parameter k_a in Eq. (8). FCL impedance determination and the coordination flowchart are shown in Figure 5. The objective function (OF) in the optimization algorithm, which should be minimized, is formulated as follows:

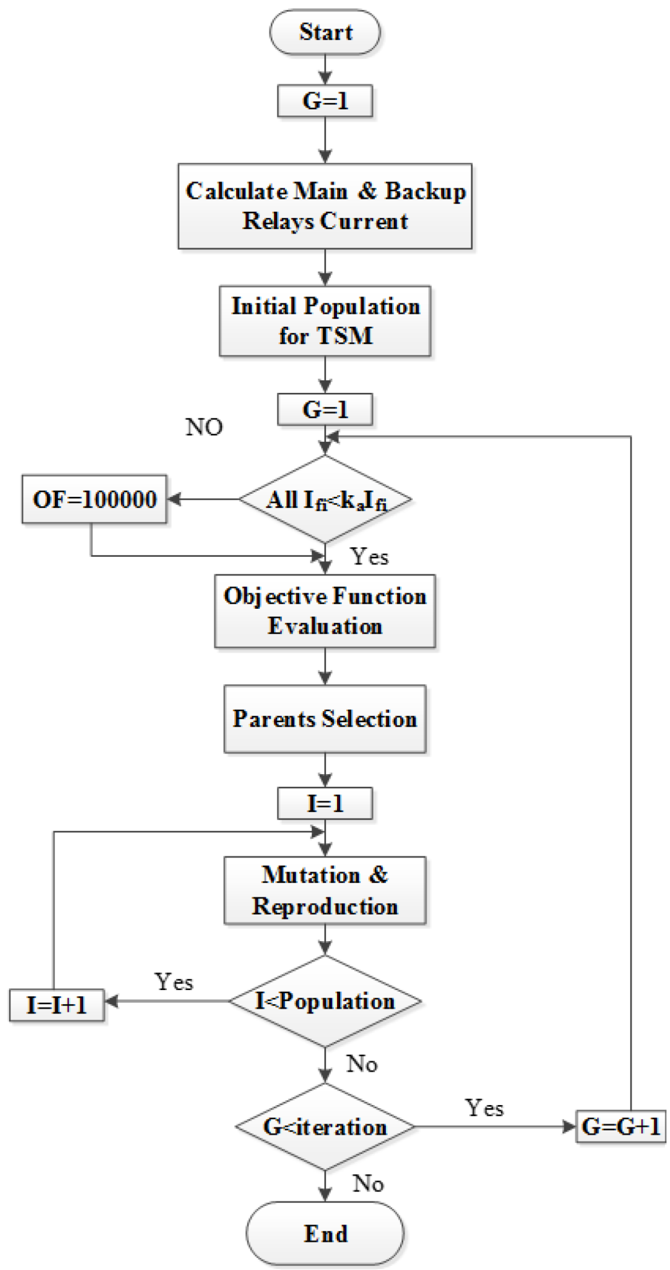

Figure 5. FCL impedance determination and coordination program flowchart.

$$\begin{array}{l} OF = Z_1 + Z_2 + ... + Z_n \\ \text{All}\ \ I_{fi}(\text{with}\, DG)\ \le\ k_a \times I_{fi}(\text{without}\, DG) \end{array}, \tag{8}$$

where parameters Z_1, Z_2 $\ldots Z_n$ are the impedances of FCLs, and I_{fi} is the maximum fault current flow of branch i in the network with/without DG. By analyzing and using the genetic algorithm to overcome the miscoordination of main and backup relays due to inserting DG into the network and changing the short circuit (SC) current, and considering the minimum size of FCL impedances, the OF is introduced as below:

$$OF = \alpha \times \sum_{i=1}^{N} (t_i)^2 + \beta \times \sum_{k=1}^{P} (\Delta t_{mbk} - |\Delta t_{mbk}|)^2, \tag{9}$$

$$\Delta t_{mbk} = t_{bk} - t_{mk} - CTI, \tag{10}$$

where Δt_{mbk} is the operating time difference with CTI for the kth relays pairs, t_i is the ith relay operating time for a fault close to the circuit breaker of the ith relay, t_{mk} and t_{bk} are the operating times of the main and backup relays for a fault close to the circuit breaker of the main relay, and N and P are the number of relays and primary/backup (P/B) current pairs respectively. Each P/B current pair is represented by k and varies from 1 to P and each relay is represented by i and varies from 1 to N.

Looped distribution networks are usually protected with directional OC relays, which are installed on both sides of a line. After installing DG in the network, fault currents levels change at different points of the network and cause miscoordination between relays. If DG rated power is small, recoordination between relays can be achieved by resetting the relays; otherwise, the SC level increases more than the limited range and coordination of relays is lost. One of the effective solutions in restoring the OC relay coordination is using FCLs in the network. To show the results, the SC calculation is investigated on the IEEE 30-bus system in two cases: a) without DG connection and b) with DG connection in buses 3, 10, and 15. Table 2 shows the fault current through the main and backup relays with/without DG (the table is reduced by the authors to some specific main and backup relays). According to Table 2, fault current passing through the relays changes because of DG current injection. This change depends on the size and placement of the DG. After DG connection, fault currents increased and maximum fault current for backup relay belonged to the (9–29) relay pairs, which increased from 834.6 to 1242 A, and maximum fault current for the main relay belonged to the (18–38) relay pairs, which increased by 41.2%. This increase changes the relay operating time and time interval (TI) between all main and backup relays. Sometimes this change does not affect the CTI but some relays are miscoordinated because of fault current changes. In this application the relay CTI is 0.3 and after DG connection the acceptable value changes to 0.25 to coordinate relays. Table 3 shows some main and backup relay CTIs, where the negative values show miscoordination because of DG fault current.

Now to limit the fault current amplitude and restore coordination of relays, which is missed by adding DG, the optimization algorithm is implemented to determine series FCL optimum impedances individually to reduce the overall costs. By using the R-FCL, FCL impedance in buses 3, 10, and 15 is obtained as 9, 18, and 11 PU, respectively. Subsequently X- and C-FCL impedances are calculated and Table 4 shows comparison results between them (impedances are calculated in 100 MVA base). The R-FCL with 38.0 PU has better current limitation than the X-FCL and C-FCL with 51 PU and 52.3 PU impedances, respectively.

Table 2. Main and backup relay fault currents without/with DG.

Main relay no.	Backup relay no.	Main relay fault current (A) without DG	Backup relay fault current (A) without DG	Main relay fault current (A) with DG	Backup relay fault current (A) with DG
19	15	4996	1169	5363	1445
38	18	2226	2226	3143	2302
9	20	6415	950	7141	1200
10	20	6933	942	7485	1191
9	21	6414	620	7241	784
10	21	6933	616	7485	778
9	29	6415	835	7241	1242

Table 3. Coordination time interval between some main and backup relays after DG installation.

Main relay no.	Backup relay no.	Time interval (s)
19	15	0.133
9	20	–0.041
10	20	–0.017
9	21	0.040
10	21	0.063

Table 4. The worst time interval and sum of R-, X-, and C-FCL impedances by optimization method.

FCL type			Impedances (PU)	Worst time interval (s)	Sum of FCL impedances
	FCL-bus 3	FCL-bus 10	FCL-bus 15		
R-FCL	9	18	11	0.25	38
X-FCL	19	24	8	0.25	51
C-FCL, Z (1+j)	7.8(1+j)	13.4(1+j)	4.9(1+j)	0.25	52.3

Figure 6 shows DG fault current limited by R- and X-FCLs. As it can be seen, by installing DG, the current through the relay near the DG is increased by 41.2%. To limit DG fault current a FCL is used and results show that the fault current is limited saliently at lower impedance of the FCL. DG fault current limiting rate is not changing linearly with FCL impedance; limitation at low impedances of the FCL is increased with a severe slope and by increasing the FCL impedance is not changed very much. Using a 6.0 PU X-FCL, the fault current of DG reaches 10%, but by increasing FCL reactance to 25.0 PU the fault current is not limited linearly and is limited less than before, reaching 4.4%. By using the 6.0 PU FCL, a high percentage of limiting can be achieved, the cost of the FCL is reduced impressively, and relay miscoordination can be solved by resetting relays so it is not necessary to use a 25.0 PU bulky and expensive FCL to limit the fault current. As was explained before, at lower impedance of the FCL, by increasing the inductance of the FCL, the angle of DG fault current approaches 90° and has more limitation effect in comparison with increasing the resistance. As Figure 6 shows, the X-FCL at low impedances (up to 4 PU) is more effective than the R-FCL, but at higher impedances due to the difference between the network fault current and DG current phases, the R-FCL has better results in current limitation.

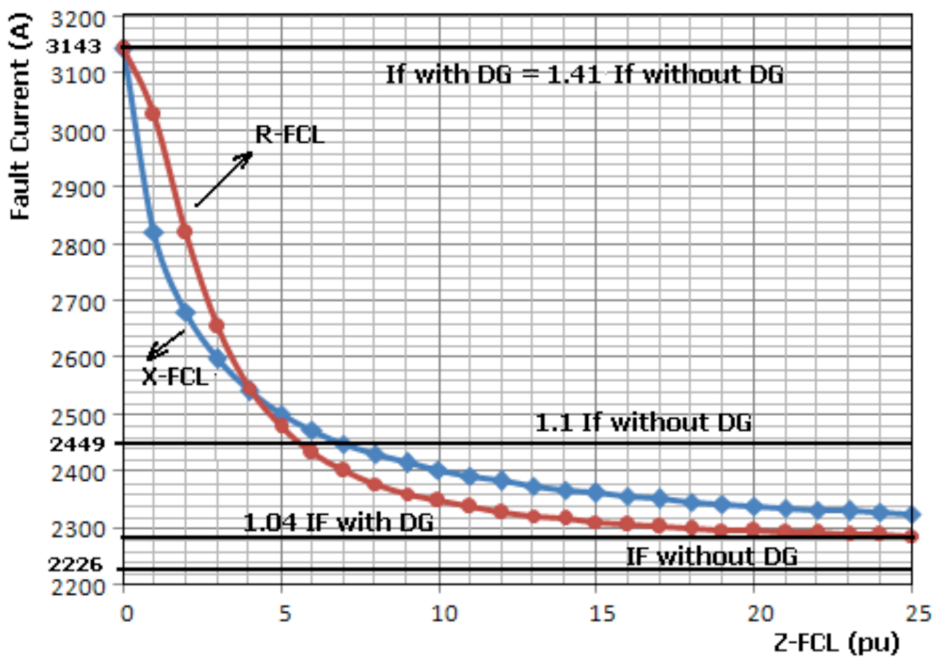

Figure 6. DG fault current limitation by R-FCL and X-FCL.

As mentioned before, to restore coordination, the optimization algorithm should be used to minimize TI and OF when the CTI for relays and other protection devices, which is set before entering DG, remains constant after DG and FCL initiation. Figure 7 shows the TI between the (9–29) relay pair, which is the worst miscoordination. In this case the X-FCL has more effects with low impedance and the R-FCL has the best role in the relay coordination restoration. By increasing the FCL impedances the TI approach to the acceptable range and relay coordination is not missed by the DG fault current.

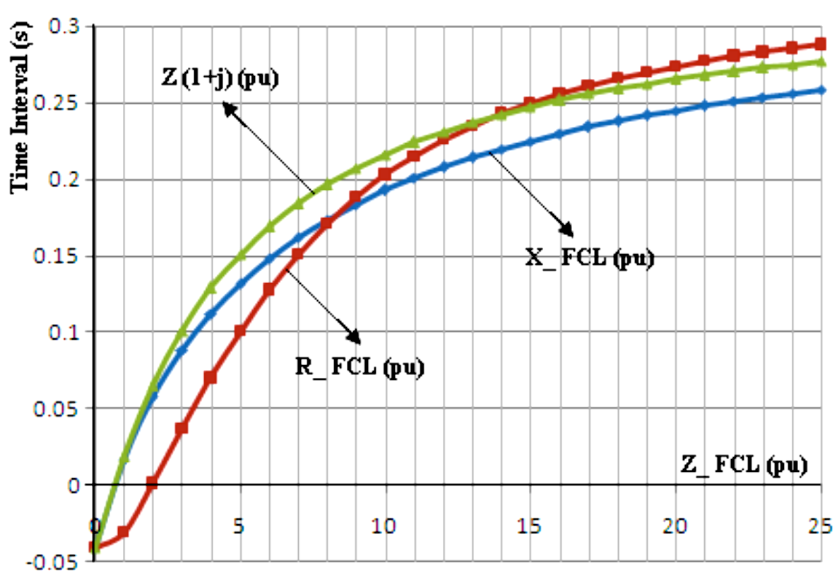

Figure 7. Time interval between (9–29) relay pairs after installing R-, X-, and C-FCLs.

Figure 8 shows relays restoring coordination in 4 cases: a) without FCL, b) using the X-FCL, c) using the X-FCL, and d) using the R-FCL. This investigation is based on 5 current pairs with more miscoordination after DG installation. FCL impedance is 20 PU for all cases (in C-FCL, $Z = \sqrt{R^2 + X^2}$). It shows that the R-FCL has the greatest effect on relays restoring coordination.

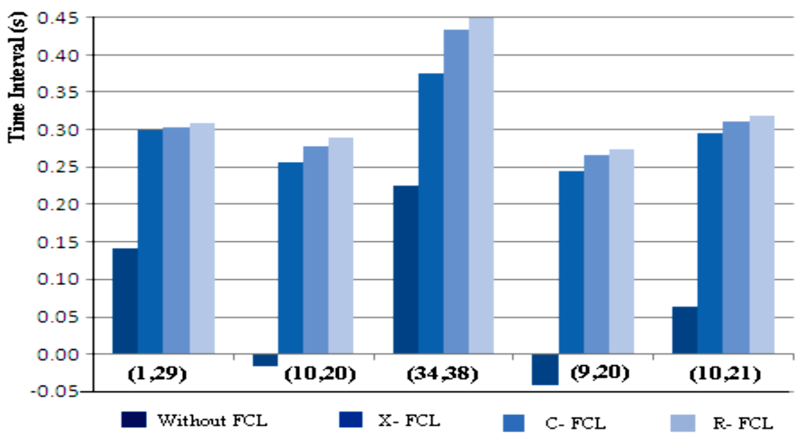

Figure 8. Time interval for the worst miscoordination between some relay pairs in 4 cases, without FCL and with R-, X-, and C-FCLs.

Furthermore, for illustrating the effect of resistance and reactance of FCLs in restoration coordination of relays, a simulation is implemented on the sample network (Figure 4) and the results are shown in Figure 9. The simulation shows the resistive-inductive FCL impedance effect on DG fault current limitation and relays coordination. The impact of the type and size of series FCLs with DG in bus 3 on CTI between relays (9–20) is shown in Figure 9. The CTI shows the current through this relay pair; in other words, if FCL limitation increases, the CTI approaches its value before DG installation. In Figure 9, the x, y, and z axes show the reactance of FCL and resistance of FCL and CTI between relays, respectively. As can be seen, a 15 PU R-FCL causes the CTI between the relays to be 0.253 s and a 15 PU X-FCL causes the CTI to be 0.227 s. As mentioned earlier, this happened because the R-FCL has more capability to make a phase difference between the DG fault current and the network fault current. On the other hand, at low impedance of the FCL like 6 PU, the X-FCL has more limitation. The limitation in the edge of the curve belonging to pure R- and X-FCLs is more than the other points and if an inductive impedance is added to the pure R-FCL not only does it increase the cost but it also decreases the CTI. A (15+j9) PU C-FCL causes CTI between relays to be 0.240 s, which is lower than a 15 PU R-FCL CTI, because the angle between vectors has more impact than the amplitude of FCL impedance. In this case, increasing the FCL impedance reduces DG fault current, but because of reducing the phase difference between fault current vectors, the result of these effects is a reduction in the CTI in comparison to the R-FCL.

At high FCL impedance, the C-FCL has lower limitation in comparison with pure R- and X-FCLs. This is because of the negative effect of the C-FCL on the phase difference of the fault current. Besides this, at high impedance of the FCL, the I_{Net} vector is placed between the DG fault current in inductive and resistive modes, and based on the network parameters, which of them is farther away from the I_{Net} make a big phase difference and consequently the limitation is more than the other.

It should be noted that the pure X-FCL causes a DC component in the fault current and makes some problems in fault current limiting. In the distribution system, resistance of the network is large and causes damping of the DC current, but for faults near the DG, resistance of lines is small and the DC component

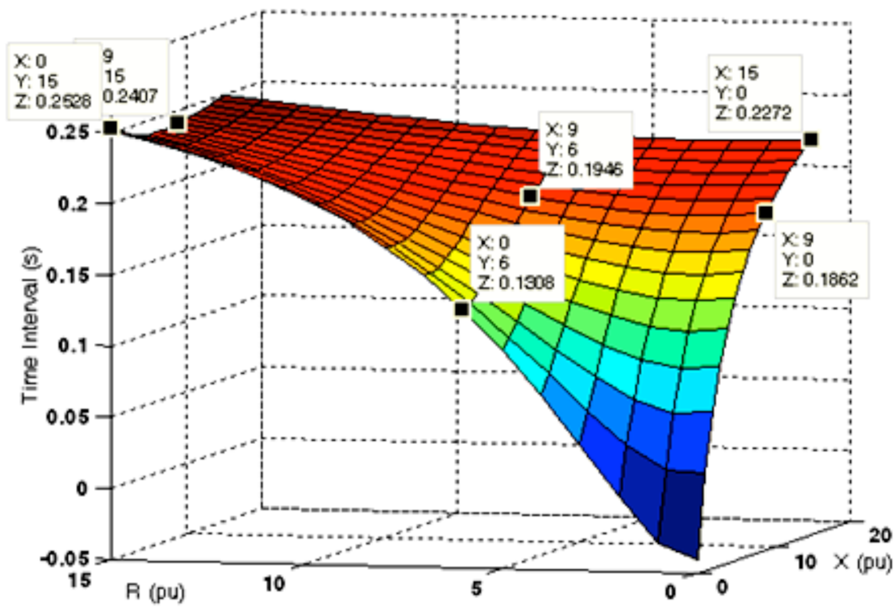

Figure 9. R-, X-, and C-FCL impacts on coordination time interval.

of the fault current has less damping by X-FCL installation. If the FCL is operated in zero current crossing time, the DC component of the fault current is not created. In other cases, a solution should be considered for fault current increased by the DC component in the X-FCL. One solution can be increasing resistance in FCL impedance (using the C-FCL) for increasing the damping of the DC component. If the X-FCL is used, the reactance of the FCL should be increased in a specific range to prevent increasing of current peak from the acceptable range. On the other hand, when the X-FCL is used, it should be ensured that the reactance of the FCL with the capacitor of the system does not make a resonant circuit. If FCL reactance is large it can cause resonance and overvoltage in the system. Figure 10 shows a capacitor in connection with the DG bus. Inductance of the FCL is determined by considering load harmonics and the capacitor of the system to prevent resonance, so the equivalent inductance to prevent resonance would be:

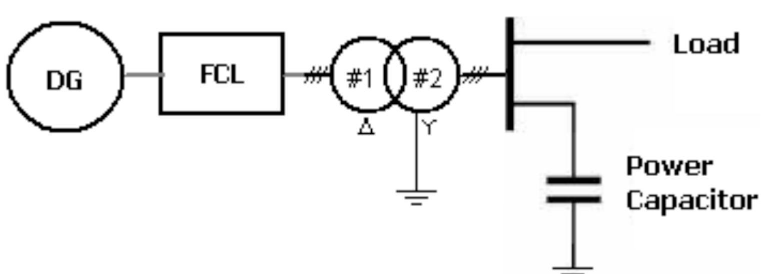

Figure 10. FCL impedance impact in restoration of relay coordination.

$$L \leq \frac{1}{C(2\pi f h)^2}, \tag{11}$$

where h is the number of the highest harmonic and f is main system frequency. It is possible to install a capacitor far from the DG or in the DG branch. In the overall case, harmonic load flow should be implemented to determine the maximum reactance of the FCL.

4. Conclusion

In this paper, the FCL is used in series with the DG unit to minimize the negative effects of the DG on the protection system of the distribution network. The effects of size and type of FCL (resistive, inductive, and complex) in series with DG are investigated in fault current limitation. It is shown that besides the impedance range of the FCL the angle between the DG current vector and the network current vector has an important role for reducing total fault current through the network. R- and X-FCLs not only limited DG fault current amplitude but also increased the phase difference between DG and network fault current vectors. At low impedance of FCL, the X-FCL has better limitation, and at high impedance of FCL the R-FCL has better limitation. CTI shows the current through the relay pairs; in other words, if the FCL limitation increases, the CTI approaches its value before DG installation. The limitation of pure R- and X-FCLs is more than the other points and if an inductive impedance is added to the pure R-FCL not only does it increase the cost but it also decreases the CTI. The impact of type and size of series FCL with DG on CTI between relays was investigated and the results were discussed.

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