Electr Eng (2016) 98:271–282
DOI 10.1007/s00202-016-0365-6

ORIGINAL PAPER

A novel protection strategy for distribution systems with distributed generation

A. F. Naiem[1] · A. Y. Abdelaziz[1] · Y. G. Hegazy[1] · M. A. Elsharkawy[1]

Received: 21 August 2014 / Accepted: 11 April 2016 / Published online: 26 April 2016

Abstract In this paper, a new strategy is proposed to provide a solution to the recloser–fuse coordination problem that appears after distributed generation penetration in distribution systems. The core of this strategy is based on classifying the coordination status at fault conditions to either coordination holds or coordination lost. The main benefit from this classification process is to indicate if the existing protection scheme can deal with the fault or an additional action is required. Three different actions are then proposed in this strategy to decrease the cases where coordination is lost. The first is based on searching for the best DG location, while the second is based on changing the recloser characteristics and the last one is based on preparing information about which DG when disconnected, the protection coordination can be re-attained. The proposed strategy is evaluated by being implemented to the IEEE 34-node test feeder. The obtained results show the ability of the classification process to discriminate between the cases where coordination holds and those where coordination is lost. Moreover, a considerable decrease in the cases classified as coordination lost after applying the proposed solutions is achieved. All the required software is developed by the authors using MATLAB m-files as a platform.

Keywords Recloser–fuse coordination · Distributed generation · Distribution systems

1 Introduction

With the penetration of distributed generation (DG) in Electric distribution systems (EDSs) EDSs, recloser–fuse coordination problems may appear due to the unplanned contribution of DG to fault currents causing probable change of temporary faults to permanent faults.

Several ideas were introduced in the literature as possible solutions to these coordination problems, some of which are presented as follows:

In [1], Girgis and Brahma proposed a solution based on replacing reclosers in distribution network by microprocessor-based devices. The main task is to find a recloser curve that would coordinate with fuse in the presence of DG. The authors' conclusions were based on simulating a small test distribution system from which the results could not be generalized. The same authors in [2] proposed another solution based on dividing the distribution system into zones each with a reasonable balance of load and DG. All zones are separated by special breakers that are controlled by a computer-based substation relay. One of the main limitations of this solution is the frequent fluctuation of the load and DG power throughout the day, so it is difficult to define a zone that has reasonable balance of load and DG power all the time.

Viawan et al. [3] proposed a protection scheme that intended to keep all DGs in the system to be online during fault while ensuring that the conventional protection coordination holds. The basic idea behind the proposed scheme is to connect the DG to two feeders that are operated in a loop by closing the normally open switch. Such that when a fault occurs, the DG has to be disconnected from the faulted feeder while its connection to the un-faulted feeder has to be kept to deliver the DG power. To implement the proposed protection scheme, a microprocessor-based high speed line protection

---

✉ A. Y. Abdelaziz
almoataz_abdelaziz@eng.asu.edu.eg

[1] Department of Electrical Power and Machines, Faculty of Engineering, Ain Shams University, Cairo, Egypt

relay is needed. It was shown by the authors that the proposed scheme works well for meshed distribution systems; however, more study is required to implement the proposed scheme to radial systems.

Tailor and Osman [4] proposed a protection scheme using Power Electronics Switch and based on disconnection of all DGs instantly before the recloser or any fuse has a chance to operate after fault inception. By this way, the radial nature of system is restored and the originally designed protection scheme works well. This solution has a major disadvantage which is the disconnection of all DGs each time a fault occurs even for temporary faults which frequently occurs; this may cause voltage instability for the system.

Gutierres et al. [5] proposed a technique that identifies critical margins for proper recloser–fuse coordination and monitors distribution line ratings in real time. In case of violations, only distributed generators attributed to effectively increasing short-circuit level are disconnected from the grid by gate turn-off thyristors. Therefore, fault current is reduced to a satisfactory level, restoring the coordination between reclosers and fuses in radial distribution feeders.

Nikolaidis et al. [6] proposed an efficient communication-based protection scheme that implemented common directional overcurrent relays instead of reclosers at the line, assisted by inter-tripping and blocking transfer functions. The proposed protection strategy guarantees selectivity regardless of whether the generating units are connected to the network or not, and can be designed retaining either the fuse-blowing or fuse-saving philosophy.

Chaitusaney and Yokoyama [7] proposed a solution based on determining the appropriate DG size such that the existing protection scheme of recloser and fuse can be maintained with the presence of DG. The same authors in [8] proposed a method to find the threshold value of the DG capacity, beyond which recloser–fuse coordination is lost using the mathematical equations for protective devices, a method which is simpler than that in [7]. In addition, the authors suggested the modification of the protection system depending on the influence of DG on the fault current, where only the fuse that determines the DG threshold will be modified. The main advantages of the proposed method are that sticking to the calculated threshold will prevent the system reliability degradation and the suggested that modification for protection systems only affects a lateral feeder. However, this method puts a limit on the DG penetration level.

The use of fault current limiters (FCL) is considered as one of the solutions proposed to minimize coordination problems. Kumara and Atputharajah [9] presented a study to prove the ability of FCL to minimize the coordination problems. The study was based on changing the FCL impedance and location and it was shown that locating the FCL near the DG has a better effect on limiting the fault currents. The authors used a relatively small study system with only one DG considered; in addition, the method for allocating the FCL was done manually. Thus, the presented study may not be efficient and more time consuming when studying larger systems.

Singh et al. [10] proposed a new hybrid protection schemes based on application of fault current limiter and microprocessor based overcurrent relays to eliminate the impact of distributed generation on distribution system relay coordination. In this scheme, the covariance matrix adaptation evolution strategy directed target to best perturbation-based optimizer algorithm is applied for optimizing the setting of overcurrent relays. The authors showed that the proposed algorithm is better than the earlier heuristic and meta-heuristic-based optimization algorithm.

Yazdanpanahi et al. [11] proposed a field discharge circuit to limit the generator's fault current, thus leading to a synchronous-machine DG with little impact on distribution system protection. The authors studied the operation of a solid-state switch-based field discharge circuit and its effects on the generator's output current during the fault. It was shown that the proposed field discharge circuit is sufficient to prevent miscoordination of the feeder protections when short time-delay and/or inverse-time overcurrent relays are involved in the protection scheme.

Shahriari et al. [12] described a method based on genetic algorithms (GAs) to search for the optimal number, locations, and size of Solid State Fault Current Limiters. Using GAs avoids the manual allocation and size of FCL optimization. The described method was applied to a real 13-bus distribution network and the results presented showed the efficiency of this method to find the optimal number, locations and size of FCL. However, in spite of the excellent performance of FCLs, their real application in distribution systems is delayed due to technical and economical issues [13].

To sum up, the problem under study still considered to be one of the hottest research topics since no clear coordination scheme has been approved by scientists in the literature. Accordingly, the main concern in this paper is to present an integrated novel strategy to deal with the recloser–fuse coordination problem. Actually the work in this paper is considered to be an extension to the work done by the authors in [14]. In [14], only one DG is considered to be connected to the system while in this paper the presence of multiple DGs is considered. To account for the presence of multiple DGs in the system, one more action besides those in [14] is proposed to decrease the cases that are classified as coordination lost. This action is based on an offline study to prepare information about which DG when disconnected, the coordination can be re-attained. This offline study is considered to be the main contribution in this paper.

The proposed strategy is based on two main phases:

- The first phase starts automatically once a fault is detected in the system. In this phase, the protection coordination

of all protection devices in the fault path is assessed by being classified to either coordination holds or coordination lost. If coordination holds then no further action is required, otherwise a solution should be applied to avoid the consequences of losing coordination.
- In the second phase, three different solutions are proposed to minimize the cases where coordination is lost. The first is based on searching for the best DG locations that are characterized by minimum number of cases where coordination is lost. The second depends on changing the recloser characteristics. The third one is based on finding which DG when disconnected, the coordination can be re-attained.

This paper is organized as follows. Section 2 presents the selected study system and the required modeling equations. Section 3 highlights the main outlines of the proposed strategy. Section 4 presents the detailed steps required to implement the proposed approach on an actual test feeder along with the obtained results, and the conclusion is drawn in Sect. 5.

2 System under study

In this paper, the IEEE 34 node test feeder which is an actual feeder in Arizona with a nominal voltage of 24.9 kV is selected as the study system. The data of this feeder are obtained from the IEEE's distribution system analysis subcommittee [15]. Figure 1 shows a single line diagram of this feeder after re-numbering nodes for the sake of simplicity. An overcurrent protection scheme is applied to this feeder based on the method in [16], by adding one recloser at the beginning of the main feeder that appears as a thick line and adding one fuse at the beginning of each lateral or sub-lateral feeder. This system is characterized by the following modeling issues:

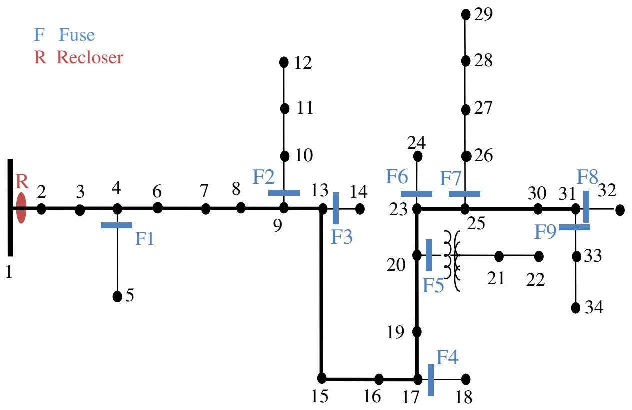

Fig. 1 Modified IEEE 34 node test feeder

2.1 Line model

The series impedance of each line section is represented as in (1).

$$z_{\text{line}} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{bmatrix} \tag{1}$$

2.2 Load model

Six different types of load are considered with modeling equations as in [17]. These types are constant power (PQ), constant impedance (Z) or constant current (I) either star or delta connected.

2.3 DG model

The DG can be modeled as constant PQ or PV nodes. Modeling DG as a PQ node, i.e., a negative load, is relatively simple and does not require any special calculations, while treating the DG as a PV node needs special calculations. It should be noted that modeling DG as PV node pave the way for using renewable energy systems, where this type of systems usually works on a specified terminal voltage and is able to supply and absorb reactive power.

In this research, the PV model is adopted where the magnitude of the positive sequence voltage is set at 1 p.u.

2.4 Protection devices model

According to the implemented protection scheme, only reclosers and fuses are used to protect the system.

Fuses' characteristic is usually plotted as a log–log curve. The part of interest in this curve approaches a straight line and is expressed as in (2) [18].

$$\log(t) = a.\log(I) + b \tag{2}$$

where t is the fuse operating time, I is the fault current seen by the fuse, a, b fuse constants to be determined as in [8].

Reclosers are normally equipped with inverse-time overcurrent trip devices and the general characteristics of such devices are expressed as in (3) [19].

$$t(I) = \text{TD}\left[\frac{A}{M^{p} - 1} + B\right] \tag{3}$$

where t is the recloser operating time, I is the fault current seen by the recloser, TD is the time dial setting, M is the ratio of $I/I_{\text{pick-up}}$, $I_{\text{pick-up}}$ is the relay current set point, A, B, p is the constants of the selected curve characteristics.

The recloser was set to have one fast trip to account for self-clearing faults and one delayed trip for fuse backup protection by setting proper values for the TD.

3 Outlines of the proposed approach

The following steps represent the main procedures required to implement the proposed approach. A brief description of each step is presented as follows:

3.1 Load flow analysis

Load flow analysis is considered as a basic and important step for proper operation and design of DSS. It provides the system operator with the steady state values of the real and reactive powers flowing in each line along with the magnitude and phase angle of the voltage at each bus for various load demands. The backward/forward sweep method is presented by Shirmohammadi et al. [20] for load flow analysis and it is widely accepted as one of the most relevant methods used in this aspect.

In this paper, a load flow program based on the backward/forward sweep method is developed using MATLAB as a platform. The developed program is able to deal with radial unbalanced distribution systems with n-buses and with different DG penetration levels and locations.

3.2 Short circuit analysis

Short circuit analysis of EDSs is essential because protection devices are selected, installed and coordinated based on its results. For symmetrical three-phase EDSs, the symmetrical component method provides acceptable results for short circuit currents calculations. However, for unsymmetrical EDSs, this method is inaccurate, and other methods based on the actual phase representation should be applied [21]. One of these methods is the hybrid compensation method [22], where it uses the power flow solution as pre-fault condition and uses a compensation technique to find the injected node currents at DG, fault and loops break-point nodes. Then, backward–forward sweep iteration is performed once to find the short circuit currents and the node voltages immediately after fault.

In this paper, a short circuit program based on the hybrid compensation method is developed using the MATLAB as a platform. This program is designed to handle three-line to ground, double-line to ground, single-line to ground, and line to line fault. The DG is simulated as a PV node with constant internal voltage at the fault instant.

The developed program is applied to the system under study. Table 1 shows the magnitudes of the nonzero branch fault currents for phase (A) without the presence of DG when a three-phase fault is applied at each end node in the system.

3.3 Protection coordination setting

Protection coordination setting for fuses and reclosers is made based on (2) and (3) for appropriate devices, while assuming that no DG is connected to the system. For setting the reclosers, it was assumed that they are equipped with relays having extremely inverse characteristics; the recloser pick-up current $I_{\text{pick-up}}$ is found as in [23] using (4).

$$I_{\text{pick}-\text{up}} = \text{OLF} \times I_{\text{nom}} \tag{4}$$

where OLF is the overload factor depends on the protected equipment, I_{nom} is the recloser current obtained from the load flow results.

Since the standard extremely inverse trip characteristic is usually used for the CB breaker and recloser, the recloser's parameters A, B, and p in (3) are taken equal, respectively, to 28.2, 0.1217, and 2 according to the IEEE Standard (C37. 112-1996) [8,19]. However, using any other type of inverse trip characteristics will not significantly affect the proposed strategy. While the parameter TD is set to 1.5 and 0.5, respectively, for the slow and fast tripping modes of the recloser. The OLF parameter in (4) is chosen to be 1.5 as in [8] while the recloser nominal current I_{nom} is equal to 49.24 A as obtained from running the load flow program.

On the other hand, fuse setting is based on the concept that all fuses in the fault path should operate slower than the recloser fast mode and faster than the recloser slow mode. Fuse setting implies the determination of fuse constants 'a' and 'b'. The constant 'a' represents the slope of the straight line I^2t log–log plot and is fixed at a specified value for all fuses in the system. This condition is practically acceptable because all fuses in the system should be of the same type. The constant 'b' is calculated using the value of 'a' and the coordinates of one operating point of the fuse (fuse fault current and fuse operating time). Fuse fault current is obtained from short circuit results as shown in Table 1 for the system under study, while fuse operating time is obtained from (5) by dividing the time range of the recloser (i.e., the difference between the operating times of the slow and fast operating modes) by the number of fuses in the fault path.

$$t_{\text{fuse}-i} = t_{\text{rec}-\text{fast}} + \frac{i * (t_{\text{rec}-\text{slow}} - t_{\text{rec}-\text{fast}})}{n+1} \quad i = 1, 2, \ldots, n \tag{5}$$

where $t_{\text{fuse}-i}$ is the operating time for the ith fuse in the fault path where $i = 1$ for the fuse nearest to the faulted node, n is the total number of fuses in the fault path, $t_{\text{rec}-\text{slow}}$ is

Table 1 Branch fault currents for phase (A) of the IEEE 34-node feeder without the presence of DG

Branch number	From	Faulted node								
	Node to node	5	12	14	18	22	24	29	32	34
1	1–2	1440	261	456	364	268	272	255	256	256
2	2–3	1440	261	456	364	268	272	255	256	256
3	3–4	1440	261	456	364	268	272	255	256	256
4	4–5	1400	–	–	–	–	–	–	–	–
5	4–6	–	261	456	364	268	272	255	256	256
6	6–7	–	261	456	364	268	272	255	256	256
7	7–8	–	261	456	364	268	272	255	256	256
8	8–9	–	261	456	364	268	272	255	256	256
9	9–10	–	229	–	–	–	–	–	–	–
10	10—11	–	227	–	–	–	–	–	–	–
11	11–12	–	220	–	–	–	–	–	–	–
12	9–13	–	–	441	349	252	257	240	240	241
13	13–14	–	–	409	–	–	–	–	–	–
14	13–15	–	–	–	349	252	257	240	240	241
15	15–16	–	–	–	349	252	257	240	240	241
16	16–17	–	–	–	348	251	255	239	239	239
17	17–18	–	–	–	317	–	–	–	–	–
18	17–19	–	–	–	–	251	255	239	239	239
19	19–20	–	–	–	–	251	255	239	239	239
20	20–21	–	–	–	–	232	–	–	–	–
21	21–22	–	–	–	–	232	–	–	–	–
22	20–23	–	–	–	–	–	243	227	227	228
23	23–24	–	–	–	–	–	225	–	–	–
24	23–25	–	–	–	–	–	–	226	226	227
25	25–26	–	–	–	–	–	–	214	–	–
26	26–27	–	–	–	–	–	–	213	–	–
27	27–28	–	–	–	–	–	–	210	–	–
28	28–29	–	–	–	–	–	–	210	–	–
29	25–30	–	–	–	–	–	–	–	218	218
30	30–31	–	–	–	–	–	–	–	211	212
31	31–32	–	–	–	–	–	–	–	209	–
32	31–33	–	–	–	–	–	–	–	–	209
33	33–34	–	–	–	–	–	–	–	–	209

Table 2 Fuse constant ‘b’ for the IEEE 34-node test feeder

Fuse number	Fuse constant ‘*b*’	Fuse number	Fuse constant ‘*b*’
1	2.4386	6	2.7263
2	2.7709	7	2.7625
3	2.5569	8	2.7486
4	2.6258	9	2.7486
5	2.7528		

the the recloser slow mode operating time, $t_{\text{rec}-\text{fast}}$ is the the recloser fast mode operating time.

The constant ‘a’ is taken equal to -1.0 for all fuses in the system. While fuse constant ‘b’ is calculated for each fuse and the values are presented in Table 2.

The coordination time interval (CTI) between recloser and fuses and between fuses can be found based on the results of Eq. (5) and hence it is considered to be a free parameter in this study, with a minimum value that can be set to be 0.2 s.

For more clarification, consider the simplified network shown in Fig. 2 where it is required to coordinate fuses F1, F4, F5, and the recloser R based on the fuse saving principle. A three-phase fault is considered at node (15) for that purpose, the devices responsible to clear that fault are the recloser (R) and the fuses (F5, F4, and F1). These devices should be coordinated so that the recloser operates first in the

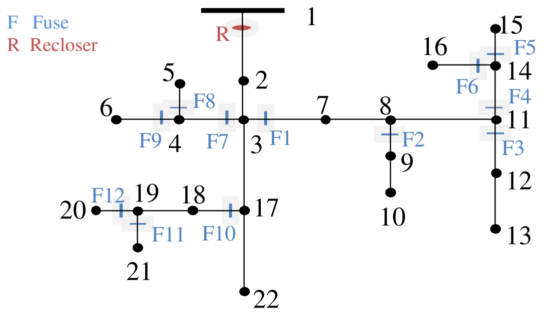

Fig. 2 Simplified distribution network

fast mode to give a chance for the fault to be self-cleared in case it is a temporary fault. If the fault is a permanent one, then the nearest fuse (F5) should operate as a primary protective device, and in case of its failure, the upstream fuses should then operate in sequence (F4 and F1) as backup protective devices. Finally, the recloser in the slow mode should operate as a final backup step. To achieve this sequence, the developed short circuit program is used to find the fault currents in the protective devices in the fault path and hence the operating times of these devices are found using (5). These operating times are found to be 0.59, 0.89, 1.21, 1.51, and 1.78 s for R (fast), F5, F4, F1, and R (slow), respectively. The difference between each primary and the backup devices' operating times (CTI) is checked and if it is found to be less than its settled minimum value (0.2 s), then the backup device operating time is modified in such a way to achieve that minimum value. This in turn will lead to a change in the operating curve of that backup protective device. In this way, protection coordination between all fuses and reclosers can be done without the presence of DGs.

3.4 Protection coordination assessment

After doing protection coordination between fuses and reclosers in the system without the presence of DG, now it is required to assess this coordination after the penetration of DG. This assessment process can prevent taking disciplinary actions, like disconnection of DG, when there is no need to take these actions. The main steps of the proposed assessment process are to determine the fault path and consequently all the protection devices on that path at first. Then, the operating sequence of these devices should be checked. This can be done by finding the operating times of these protection devices from (2) to (3) after substituting into them the calculated short circuit currents. Having found the operating times of protection devices, the operating sequence is determined and then compared with the pre-required sequence. If a close match between the obtained sequence and the required sequence occurs, then the coordination holds and no further action is required, otherwise the coordination is lost and the DS operator should take a proper decision to avoid the consequences of miscoordination between protection devices.

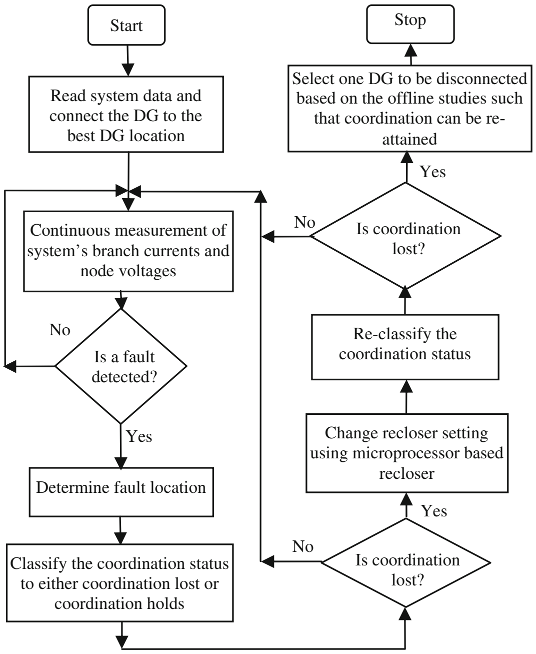

Fig. 3 Flow chart for protection coordination enhancement

For this purpose, a program has been developed using MATLAB to use it as a classifier to assess the protection coordination to either coordination holds or coordination lost.

3.5 Protection coordination enhancement

Three different proposed actions are integrated to enhance the protection coordination behavior after DG penetration by decreasing the number of cases where coordination is expected to be lost.

The first one is based on searching for the best DG location. Where the best DG location considered is that one with the highest number of cases where coordination holds while changing fault location and DG penetration level. To apply this solution, a DG is connected at a specified node while changing the fault location and the DG penetration level; the number of cases where coordination holds is compared for different DG locations from which the best location can be specified.

The second one is based on changing the characteristics of the recloser by changing the TD parameter for the fast mode operation in (3). This action is practically acceptable nowadays, due to the availability of microprocessor-based reclosers in the market. Microprocessors can be easily used to adjust recloser current-time characteristics according to system protection requirements. To evaluate the effectiveness of this solution on the coordination problem, different cases are studied by changing DG penetration level and location for a fault at a specified node. Then, the number of cases where coordination holds with respect to the total number of studied cases is monitored for different values of the TD parameter.

The third one is usually applied in case of the presence of multiple DGs in the system. This solution is based on an offline studies to prepare information about which DG that can be disconnected for each possible fault location such that the protection coordination can be re-attained. This can be done using the following steps for each fault location.

- Use the previously developed classifier to classify the coordination status to either coordination holds or coordination lost.
- If coordination is lost, then start disconnecting one DG in the system and reclassify the coordination status.
- If coordination still lost, then reconnect the disconnected DG and disconnect another DG and check the coordination status.
- Repeat the previous step until coordination holds or all DGs in the system are disconnected each at a time, and then store this result.

Based on the stored results from this offline study, the distribution system operator can select the appropriate DG to be disconnected when a fault occurs.

Figure 3 shows a flow chart that summarizes the main procedures for applying the proposed solutions to enhance the protection coordination behavior.

4 Results and discussion

In this section, the proposed strategy is implemented to the system under study and the obtained results are presented as follows.

4.1 Protection coordination assessment results

The developed classifier in Sect. 3.4 is applied to the IEEE 34-node test feeder to discriminate between the cases where coordination holds and the cases where coordination is lost while changing the fault location and the DG penetration level. The fault location is changed over all nodes in the lateral and sub-lateral feeders resulting in 16 different fault locations. While the DG penetration level is changed from 100 kW (4 %) to 600 kW (24 %) in steps of 50 kW resulting in 11 different penetration levels with total different possible cases equal to $16 \times 11 = 176$ for each specified DG location.

Figures 4 and 5 show the results of the classification process for two different DG locations. The white circles represent the cases where coordination holds and the black circles represent the cases where coordination is lost. The number of cases where coordination holds as a percentage from the total number of cases studied is equal to 128/176 = 72.72 % when a DG is connected at node 6 and $57/176 = 32.28\,\%$ when a DG is connected at node 28. Applying the classification process discriminates between the cases where an action is required against the DG penetration at fault conditions and the cases where no need for an action is required. The results show that the DG location highly affects the number of cases where coordination holds.

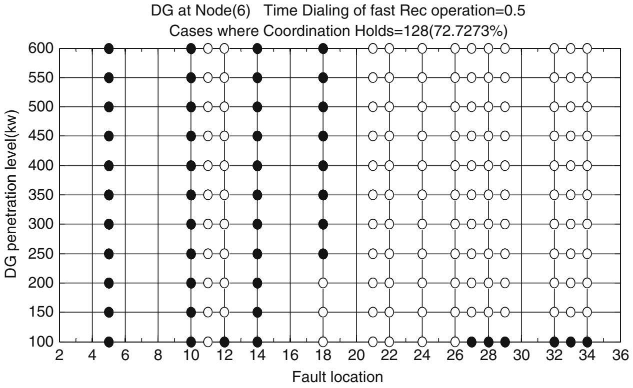

Fig. 4 Classification pattern for a DG at node 6 with TD equals 0.5 for recloser fast operation

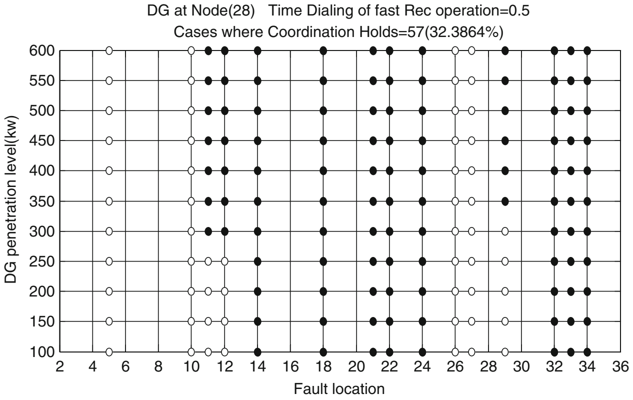

Fig. 5 Classification pattern for a DG at node 28 with TD equals 0.5 for recloser fast operation

To have a more spot on the results obtained, the recloser and the fuse characteristics are drawn in Fig. 6 for the case when a fault occurs at node 8 and one DG will be connected at node 6. The solid vertical lines in the figure represent the currents of the protective devices in the fault path (i.e., recloser and fuse 4) in the case where no DG is connected. In this case, a proper coordination (based on the fuse saving principle) between the fuse and the recloser occurs as it is obvious from their operating times indicated in the figure. The recloser operates at first in its fast mode, then the fuse and finally the recloser in its slow mode. On the other hand, the dotted vertical lines represent the case where one DG is connected at node 6 with 500 kW penetration level. As it is

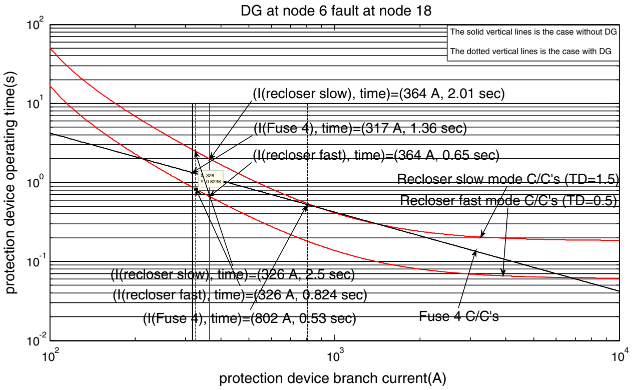

Fig. 6 operating curves for recloser and fuse 4 when a fault occurs at node 18

clear from the figure, the fault current in fuse 4 considerably increased due to DG penetration leading to a loss in coordination between the fuse and the recloser. In this case, the fuse will operate before the recloser fast mode operation leading to the violation of the fuse saving principle. Checking this case in Fig. 3 proves that the developed classifier properly classifies this point as a point where coordination is lost.

4.2 Protection coordination enhancement results

To increase the number of cases where coordination holds and hence improve the coordination behavior, the three actions proposed in Sect. 3.5 are applied to the system under study as follows:

4.2.1 Search for the best DG location

To search for the best DG locations regarding the number of cases where coordination holds, one DG is connected at a specified node, while changing the fault location and the DG penetration level. The coordination status for each case is classified to either coordination holds or coordination lost using the developed classifier in Sect. 3.4. Then the number of cases where coordination holds with respect to the total number of studied cases is recorded. This process is repeated for all possible DG locations and the results obtained are summarized in Table 3, where the number of cases at which coordination holds with respect to the total number of cases studied is presented for each DG location.

Figure 7 shows a plot for the results obtained in Table 3, from which it is clear that node 6 is considered as the best DG location, since this node has the highest number of cases where coordination holds. Also the subsequent best locations can be found as 7, 8, 29, and so on.

Table 3 Number of cases (as a percentage) where coordination holds while changing fault location and DG penetration level

DG location	Number of cases where coordination holds (%)	DG location	Number of cases where coordination holds (%)
2	6.2500	19	16.4773
3	6.2500	20	16.4773
4	9.0909	21	19.8864
5	10.7955	22	23.2955
6	72.7273	23	17.0455
7	39.7727	24	17.0455
8	39.2045	25	17.0455
9	34.0909	26	25.5682
10	27.2727	27	28.9773
11	12.5000	28	32.3864
12	10.7955	29	35.7955
13	13.0682	30	17.0455
14	15.9091	31	17.0455
15	11.3636	32	17.0455
16	7.3864	33	19.3182
17	7.3864	34	21.0227
18	9.6591		

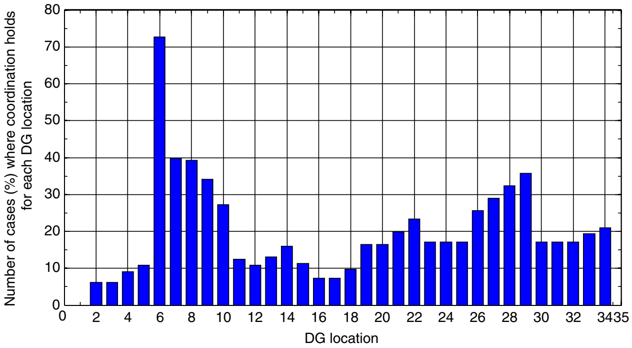

Fig. 7 Number of cases (percentage %) where coordination holds for each DG location

4.2.2 Change recloser setting

To apply this solution on the IEEE 34-node test feeder, the recloser characteristics are changed by changing the TD parameter in the recloser modeling (Eq. (3)) for the fast mode operation from its initial value at 0.5 to a value of 0.1 in steps of 0.2. Figures 8 and 9 show the new classification patterns for TD equals 0.3 and 0.1, respectively, when a DG is connected at node 6. The number of cases where coordination holds as a percentage for these two values of TD is $149/176 = 84.66$ and $169/176 = 96.02\,\%$, respectively. Comparing the results obtained after changing the recloser setting with that obtained before changing the recloser setting, i.e., the results in Fig. 4 show a significant increase in

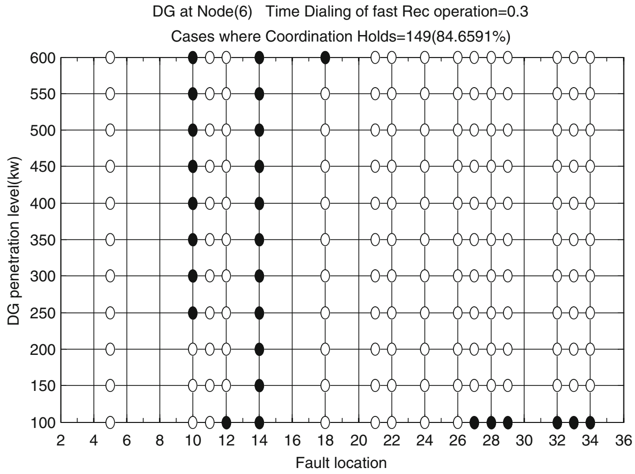

Fig. 8 Classification pattern for a DG at node 6 with TD equals 0.3 for recloser fast operation

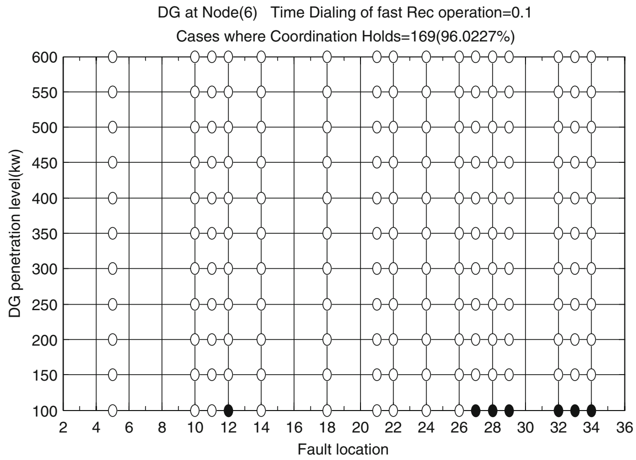

Fig. 9 Classification pattern for a DG at node 6 with TD equals 0.1 for recloser fast operation

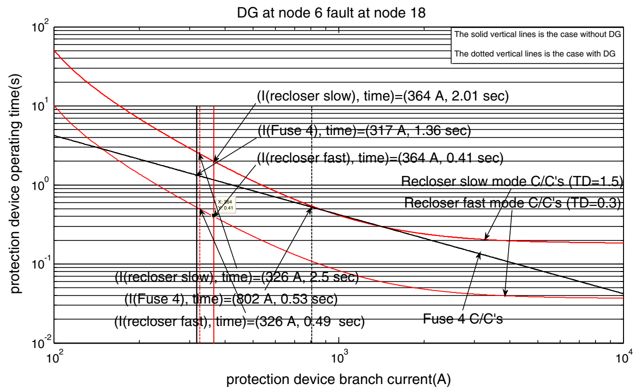

Fig. 10 Operating curves for recloser and fuse 4 when a fault occurs at node 18 after changing the recloser fast mode C/C's

Table 4 Number of cases (%) where coordination holds for each DG location with different values of the TD parameter

DG location	TD		
	0.5	0.3	0.1
2	6.2500	6.2500	6.2500
3	6.2500	6.2500	6.2500
4	9.0909	9.0909	9.0909
5	10.7955	10.7955	10.7955
6	72.7273	84.6591	96.0227
7	39.7727	78.9773	86.9318
8	39.2045	78.9773	86.9318
9	34.0909	67.0455	86.9318
10	27.2727	61.9318	73.2955
11	12.5000	60.2273	87.5000
12	10.7955	68.7500	81.2500
13	13.0682	54.5455	88.6364
14	15.9091	57.9545	89.2045
15	11.3636	52.8409	88.0682
16	7.3864	19.8864	90.3409
17	7.3864	19.8864	90.3409
18	9.6591	26.1364	92.6136
19	16.4773	30.6818	37.5000
20	16.4773	30.6818	37.5000
21	19.8864	36.9318	43.7500
22	23.2955	36.9318	43.7500
23	17.0455	30.6818	37.5000
24	17.0455	30.6818	37.5000
25	17.0455	31.2500	37.5000
26	25.5682	48.2955	56.2500
27	28.9773	48.8636	56.2500
28	32.3864	48.8636	56.2500
29	35.7955	50.0000	56.2500
30	17.0455	31.2500	37.5000
31	17.0455	31.2500	37.5000
32	17.0455	31.2500	37.5000
33	19.3182	33.5227	39.7727
34	21.0227	35.2273	41.4773

the number of cases classified as coordination holds, from which the effectiveness of the proposed solution to improve the protection coordination behavior is verified. For more spot on the results, the case studied in Fig. 6 is re-studied after changing the recloser setting and the new curves are shown in Fig. 10. It is clear from the figure that the coordination is re-attained after applying the solution by changing the TD parameter to be 0.3.

For a more general study, the DG location is changed over all nodes in system and for each DG location the number of cases at which coordination holds as a percentage is counted for different values of TD parameter. The obtained results are summarized in Table 4. Figure 11 shows a plot for the results obtained in Table 4.

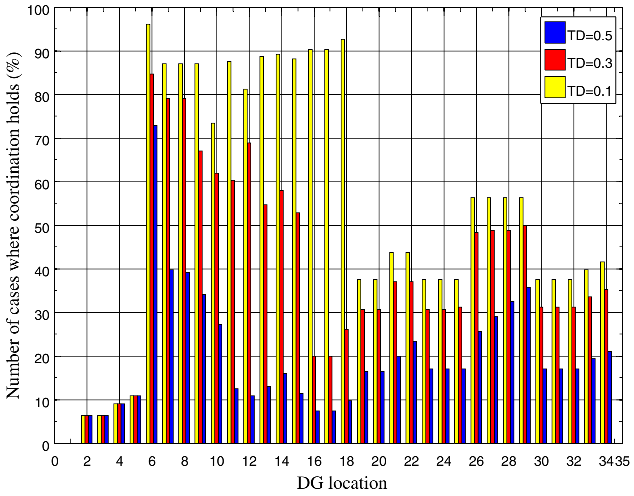

Fig. 11 Number of cases (%) where coordination holds for each DG location with different values of TD parameter

Table 5 Number of cases (as a percentage) where coordination holds for each location of the second DG while the first DG is at node 6

DG location	Number of cases where coordination holds (%)	DG location	Number of cases where coordination holds (%)
2	82.95	19	6.25
3	56.82	20	6.25
4	0	21	6.25
5	0	22	6.25
7	6.25	23	6.25
8	6.25	24	6.25
9	6.25	25	6.25
10	6.25	26	6.25
11	53.97	27	7.32
12	69.88	28	8.52
13	6.25	29	8.48
14	6.25	30	6.25
15	6.25	31	7.32
16	5.68	32	7.32
17	5.68	33	7.32
18	6.81	34	8.52

4.2.3 *Perform offline studies in case of multiple DG penetration*

This solution is applied in case of the presence of multiple DGs in the system. The solution is based on an offline study as stated in Sect. 3.5, to prepare information about which DG when disconnected the coordination will be re-attained. This study is repeated for each possible fault location to have a complete study about the system. The results act as a guide for the distribution system operator to disconnect the appropriate DG when a fault occurs and the coordination status was classified as being lost. This solution is implemented on the IEEE 34-node test feeder by assuming the presence of two DGs connected to the system. The first DG is connected at the best DG location obtained from the single DG scenario which is node 6 according to the results in Fig. 7. While the second DG location will be varied over all nodes in the system except the substation node and the node at which the first DG is connected.

For each possible location for the second DG, the fault location and the total DG penetration level are changed and then the number of cases where coordination holds is monitored. The fault location is changed over all nodes in the lateral and sub-lateral feeders, while the total DG penetration level which is assumed to be divided equally over all DGs in the system will be changed from 100 to 600 kW in steps of 50 kW. The number of cases where coordination holds is summarized in Table 5 for each possible location of the second DG.

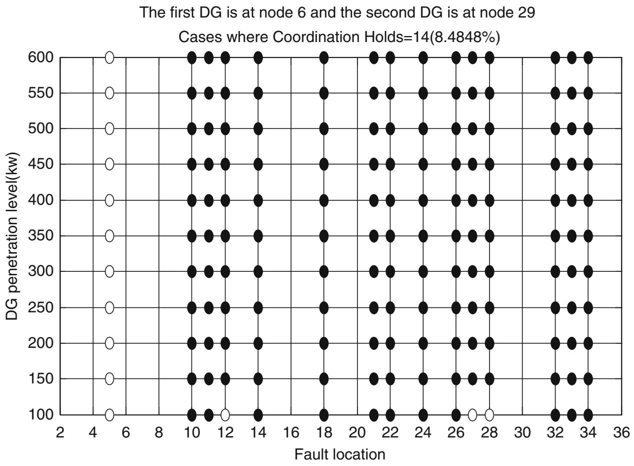

Fig. 12 Classification pattern due to the presence of two DGs in the system

Now it is required to search for the appropriate DG to be disconnected for each fault location such that the coordination behavior can be improved. As an example to show how this solution is applied, consider the case where the second DG is connected at node (29). Figure 12 shows the classification pattern while changing the fault location and the total DG penetration level. For each fault location and DG penetration level, if coordination was classified as being lost, a search for the appropriate DG to be disconnected is done. Figure 13 shows the new classification pattern after disconnecting that DG. The number of cases where coordination holds before applying this solution is found to be 8.48 % according to Fig. 12 while after applying that solution the number of cases where coordination holds is found to be 94.54 % according to Fig. 13.

Applying this solution improves so much the coordination behavior. Table 6 shows the appropriate DG to be discon-

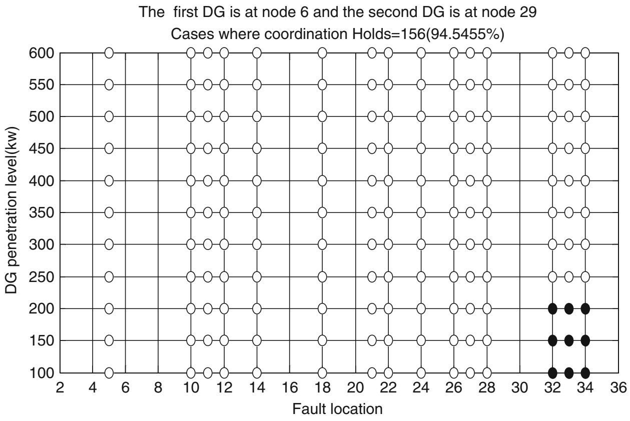

Fig. 13 Classification pattern, after disconnecting one of the two DGs connected to the system

Table 6 The appropriate DG to be disconnected to re-attain coordination

Faulted node	DG level (kw)										
	100	150	200	250	300	350	400	450	500	550	600
5	No	No	No	No	No	No	No	No	Any	Any	Any
10	Any	Any	Any	Any	Any	Any	Any	Any	Any	Any	Any
11	Any	Any	Any	Any	Any	Any	Any	Any	Any	Any	Any
12	DG1	DG1	DG1	Any	Any	Any	Any	Any	Any	Any	Any
14	Any	Any	Any	Any	Any	Any	Any	Any	Any	Any	Any
18	Any	Any	Any	Any	Any	Any	Any	Any	Any	Any	Any
21	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2
22	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2
24	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2
26	DG1	DG1	Any	Any	Any	Any	Any	Any	Any	Any	Any
27	DG1	DG1	DG1	Any	Any	Any	Any	Any	Any	Any	Any
28	DG1	DG1	DG1	DG1	Any	Any	Any	Any	Any	Any	Any
32	Both	Both	Both	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2
33	Both	Both	Both	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2
34	Both	Both	Both	DG2	DG2	DG2	DG2	DG2	DG2	DG2	DG2

where *No* means no one of the DGs is to be disconnected, *Both* means both DGs should be disconnected, *Any* means any one of the DGs is to be disconnected, *DG1* means the DG at node 6 is to be disconnected, *DG2* means the DG at node 29 is to be disconnected

nected for the case when two DGs are connected to the system, the first is at node 6 and the second is at node 29.

The same analysis can be repeated for other possible locations for the second DG. Table 7 summarizes the number of cases where coordination holds for all possible locations of the second DG after disconnecting the appropriate DG for each fault location.

Figure 14 shows a plot for the results obtained in Tables 5 and 7; comparing both results shows a significant increase in the number of cases where coordination holds after applying this solution.

Table 7 Number of cases where coordination holds for the two DG scenario after disconnecting the appropriate DG

DG location	Number of cases where coordination holds (%)	DG location	Number of cases where coordination holds (%)
2	90.41	19	87.55
3	90.41	20	87.55
4	90.41	21	86.22
5	83.83	22	86.22
7	100	23	89.2
8	100	24	86.66
9	100	25	87.55
10	92.04	26	94.54
11	100	27	94.54
12	100	28	94.54
13	100	29	94.54
14	100	30	87.55
15	100	31	87.55
16	100	32	88.48
17	100	33	90.30
18	100	34	90.30

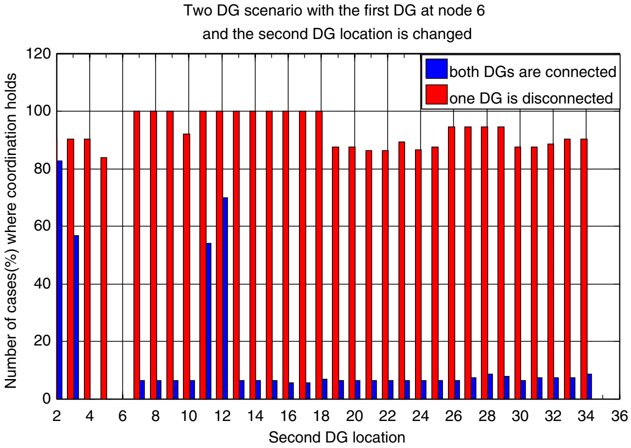

Fig. 14 The number of cases where coordination holds before and after disconnecting the appropriate DG

5 Conclusion

In this paper, a new strategy is developed to deal with the recloser–fuse coordination problem without doing major changes in the working protection scheme. The main core of this strategy is based initially on an assessment process using a developed classifier to classify coordination status to either coordination holds or coordination lost. Then, different actions are recommended as a solution to decrease the cases where coordination is lost. The developed strategy is implemented on the IEEE 34-node test feeder using MATLAB developed software. Implementation of the proposed strategy offers two main benefits for the system operator. The first is that, applying the developed classifier leads to a discrimination between the cases where coordination holds and that where coordination is lost. The second is that applying the proposed solutions leads to a significant reduction in the cases where recloser–fuse coordination was classified as being lost.

References

1. Brahma SM, Girgis AA (2002) Microprocessor-based reclosing to coordinate fuse and Recloser in a system with high penetration of distributed generation. In: Power engineering society winter meeting, January, pp 453–458
2. Brahma SM, Girgis AA (2004) Development of adaptive protection scheme for distribution systems with high penetration of distributed generation. IEEE Trans Power Deliv 19(1):56–63
3. Viawan FA, Karlsson D, Sannino A, Daalde J (2006) Protection scheme for meshed distribution systems with high penetration of distributed generation. In: Power systems conference. Clemson, SC, March, pp 99–104
4. Tailor JK, Osman AH (2008) Restoration of fuse-Recloser coordination in distribution system with high DG penetration. In: Power and energy society general meeting. Pittsburgh, PA, July, pp 1–8
5. Gutierres LFF, Cardoso Jr G, Marchesan G (2014) Recloser–fuse coordination protection for distributed generation systems methodology and priorities for optimal disconnections. In: Developments in power system protection (DPSP 2014), 12th IET international conference, pp 1–6
6. Nikolaidis VC, Papanikolaou E, Safigianni AS (2015) A Communication-assisted overcurrent protection scheme for radial distribution systems with distributed generation. In: IEEE transactions on smart grid, pp 99
7. Chaitusaney S, Yokoyama A (2005) An appropriate distributed generation sizing considering recloser–fuse coordination. In: Transmission and distribution conference and exhibition, Dalian, August, pp 1–6
8. Chaitusaney S, Yokoyama A (2008) Prevention of reliability degradation from recloser–fuse miscoordination due to distributed generation. IEEE Trans Power Deliv 23(4):2545–2554
9. Kumara JRSS, Atputharajah A, Ekanayake JB, Mumford FJ (2006) Over current protection coordination of distribution networks with fault current limiters. In: Power engineering society general meeting, Montreal, Quebec, June
10. Singh M, Panigrahi BK, Abhyankar AR (2013) A hybrid protection scheme to mitigate the effect of distributed generation relay coordination in distribution system. In: Power ans energy society meeting (PES), 2013 IEEE, pp 1–5
11. Yazdanpanahi H, Xu W, Li YW (2014) A novel fault current control scheme to reduce synchronous DG's impact on protection coordination. IEEE Trans Power Deliv 29(2):542–551
12. Shahriari SAA, Yazdian A, Haghifam MR (2009) Fault current limiter allocation and sizing in distribution system in presence of distributed generation. In: Power and energy society general meeting. Calgary, AB, July, pp 1–6
13. Lee BW, Sim J, Park KB, Oh IS (2007) Practical application issues of superconducting fault current limiters for electric power systems. IEEE Trans Appl Supercond 18(2):620–623
14. Naiem AF, Hegazy Y, Abdelaziz AY, Elsharkawy MA (2012) A classification technique for the assessment of recloser–fuse coordination in distributed generation systems. IEEE Trans Power Deliv 27(1):176–185
15. Radial distribution test feeders. Available http://www.ewh.ieee.org/soc/pes/dsacom/testfeeders.html
16. Silva JA, Funmilayo HB, Bulter-Purry KL (2007) Impact of distributed generation on the IEEE 34 node radial test feeder with overcurrent protection. In: Power symposium 39th North American, pp 49–57
17. Khushalani S, Schulz NN (2006) Unbalanced distribution power flow with distributed generation. In: IEEE proceeding transmission and distribution conference, Dallas, TX, May
18. Javadian S, Haghifam M (2008) Maintaining the recloser–fuse coordination in distribution systems in presence of DG by determining DG's size. In: The 9th IET international conference on developments in power system protection, March, pp 124–129
19. IEEE standard inverse-time characteristic equations for overcurrent relays, IEEE Standard C37.112–1996
20. Cheng CS, Shirmohammadi D (1995) A three-phase power flow method for real-time distribution system analysis. IEEE Trans Power Syst 10(2):671–679
21. Anderson PM (1995) Analysis of faulted power systems. IEEE press power systems engineering series. New York, Berlin
22. Zhang X, Soudi F, Shirmohammadi D, Cheng C (1995) A distribution short circuit analysis approach using hybrid compensation method. IEEE Trans Power Syst 10(4):2053–2059
23. Gers JM, Holmes EJ (2011) Protection of electricity distribution networks, 3rd edn. IET, London