A Classification Technique for Recloser-Fuse Coordination in Distribution Systems With Distributed Generation

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***Abstract*—In this paper, a novel approach is presented to study the impact of distributed-generation penetration on recloser-fuse coordination. The main core of this approach is based on an assessment process using a classification technique to classify the recloser-fuse coordination status at fault conditions to either coordination holds or coordination lost. Accordingly, the distribution system operator can take the proper decision. Then, two complementary actions are recommended in the proposed approach as a solution to decrease the number of cases where coordination is lost. The first one is to search for the best DG locations, where such locations are characterized by the minimum number of cases classified as coordination lost. The second one is based on changing the recloser setting in such a way to minimize the cases where coordination is lost. This new approach has been implemented on the IEEE 37-node test feeder using MATLAB-based developed software and the obtained results are presented and discussed.**

***Index Terms*—Distributed generation (DG), distribution systems, IEEE 37-node test feeder, recloser-fuse coordination.**

I. INTRODUCTION

ELECTRIC distribution systems (EDSs) that are usually designed using a radial structure with protection schemes mainly depend on reclosers, fuses, and circuit breakers (CBs). Reclosers are located in the main feeders to protect EDSs against temporary faults, while fuses are located at the beginning of laterals and sublaterals to protect the system against persistent faults. The recloser-fuse coordination is usually performed based on fuse-saving principles [1], [2].

With the penetration of distributed generation (DG) in EDSs, recloser-fuse miscoordination problems may appear due to the unplanned contribution of DGs to fault currents causing a probable change of temporary faults to permanent faults.

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

In [3], Girgis and Brahma, discussed in detail, the fuse-recloser coordination in the presence of DG, where the DG connection can result in coordination being lost between these devices. In [4], the same authors proposed a solution based on replacing relays and reclosers in the distribution network by microprocessor-based devices. In this solution, the proper recloser curve should be selected from predefined curves so that coordination can be reattained. This solution requires high initial equipment costs to replace the existing relays; also, it involves the frequent change of recloser curves for every new condition which may be impractical.

The same authors in [5] proposed a solution based on dividing the distribution system into zones separated by special breakers that were remotely communicated and controlled by a computer-based substation relay. The faulted zone is isolated by tripping the appropriate remotely controlled breakers and DG. This solution involves expensive infrastructure, and the communication systems required may be very impractical for long feeders with remote location DG while presenting a new component that must be backed up.

Tailor and Osman in [6] proposed a scheme based on the disconnection of all DGs instantly before the recloser or any fuse that has a chance to operate after fault inception. In this way, the radial nature of system is restored and the protection scheme originally designed for the radial system works well and isolates the faulty section. The instantaneous disconnection of DGs can be performed by using semiconductor devices called gate-turnoff (GTO) thyristors that were introduced in [7] as a current limiter to minimize the impacts of DG on protective device coordination. This solution has a major disadvantage which is the disconnection of all DGs each time a fault occurs even for temporary faults.

Chaitusaney and Yokoyama in [8] studied, in detail, the impact of DG penetration on distribution system reliability considering the loss of protection coordination aspect. The authors showed through numerical examples that distribution reliability became worse with DG penetration. The same authors in [9] proposed a method to find the threshold value of the DG capacity, beyond which recloser-fuse coordination is lost. This solution puts a limit on the DG penetration level.

As a conclusion, the impact of DG penetration on recloser-fuse coordination is considered to be the hottest point of research. Accordingly, the main concern in this paper is to present a novel approach to deal with the recloser-fuse coordination problems without introducing major changes in the working protection scheme. This approach is based mainly on two steps.

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- Step 1) The first step is to classify the recloser-fuse coordination status at fault conditions to either coordination holds or coordination lost.
- Step 2) The second step is to apply two complementary solutions to decrease the number of cases where coordination is lost. The first one is based on finding the best DG location from the protection coordination point of view, and the second one is based on changing the recloser setting.

The main contribution in this paper is the development of a classifier that is able to classify the recloser-fuse coordination status to either coordination holds or coordination lost. Then, this classifier is used to implement two complementary solutions to decrease the cases where coordination is lost. The main advantage of the proposed approach is that using the classification process for the coordination status discriminates between the cases that require an action against DG penetration and the cases where no action is required. Also, the proposed solutions to decrease the cases where coordination is lost are effective and do not acquire any major changes in the existing protection scheme unlike other solutions in the literature that involve major changes like the proposed solutions in [5] and [6], which require the insertion of special breakers that are remotely communicated and controlled.

This paper is organized in the following manner. Section II introduces the selected study system and the required modeling equations. Section III describes the problem under study. Section IV highlights the main outlines of the proposed approach to deal with that problem. Section V 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 Section VI

II. SYSTEM UNDER STUDY

In this paper, the IEEE 37-node 4.8-kV test feeder, which is an actual feeder in California, has been selected as a study system. The data of this feeder are obtained from the IEEE's Distribution System Analysis Subcommittee [10]. This feeder is shown in "Fig. 1," where a single-line diagram of this feeder is shown after being modified, by removing the regulator, to clearly see the effect of DG on the system. Also, the nodes are renumbered for the sake of simplicity. Finally, a protection scheme is implemented based on the method given in [11], where one recloser is added at the beginning of the main feeder and 20 fuses are added at the beginning of each lateral and sublateral feeder. This system is characterized by the following modeling issues:

A. Line Model

The series impedance of each line section is represented by a 3×3 matrix as in

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

B. Load Model

Loads are modeled as constant power (PQ), constant impedance (Z), or constant current (I) type with modeling equations provided in Table VII [12]. Table I shows the load data for the system under study.

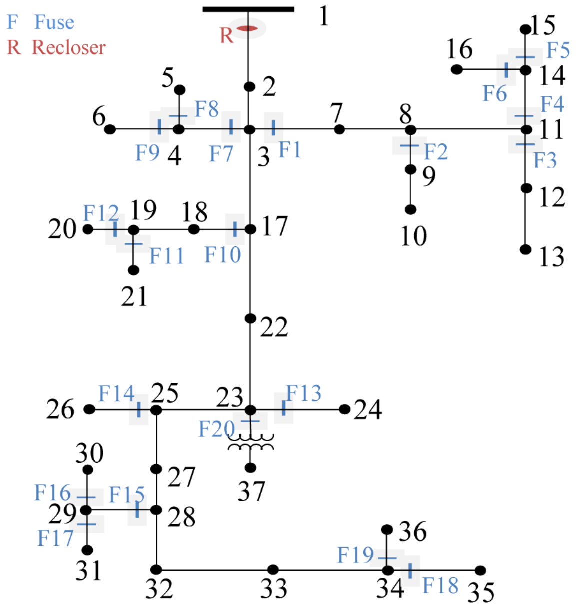


Fig. 1. Modified IEEE 37-node test feeder with implemented protection devices.

TABLE I
LOAD DATA OF THE IEEE 37-NODE TEST FEEDER

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-3 kVAr
2	D-PQ	140	70	140	70	350	175
5	D-PQ	0	0	0	0	85	40
7	D-PQ	0	0	0	0	85	40
9	D-I	17	8	21	10	0	0
10	D-Z	85	40	0	0	0	0
11	D-PQ	0	0	0	0	85	40
16	D-I	0	0	140	70	21	10
15	D-Z	0	0	42	21	0	0
13	D-PQ	0	0	42	21	0	0
18	D-PQ	0	0	0	0	42	21
21	D-PQ	42	21	42	21	42	21
20	D-I	42	21	0	0	0	0
22	D-Z	0	0	0	0	85	40
23	D-Z	0	0	85	40	0	0
26	D-PQ	0	0	0	0	42	21
28	D-I	85	40	0	0	0	0
29	D-PQ	0	0	0	0	42	21
31	D-PQ	0	0	0	0	85	40
27	D-Z	0	0	42	21	0	0
32	D-I	140	70	0	0	0	0
33	D-PQ	126	62	0	0	0	0
36	D-PQ	0	0	0	0	85	40
35	D-I	0	0	0	0	42	21
6	D-Z	8	4	85	40	0	0
19	D-PQ	42	21	0	0	0	0

C. DG Model

For load-flow analysis, the DG can be modeled as constant PQ or PV nodes. For the PQ model, it is the same as the constant power load models except that the current is injected into the system. While for the PV model, the reactive power generation Q is calculated to maintain the specified power and voltage for the DG and if it is out of reactive generation limits, then it will be set to the limit and the DG will act as a PQ node. In this research, the PV model is adopted where the magnitude of the positive-sequence voltage is set at 1 p.u.

For protection studies, knowing the DG contribution to fault currents is required, which highly depends on the DG type. Two main types for DG are well known: the first is the inverter/converter type which is characterized by a limited contribution to short-circuit currents, up to 4 p.u. of the rated current [13], while the second is the synchronous/induction type and is characterized by a high contribution to short-circuit current that may reach 10 p.u. of the rated current [13].

Since the second type has a high contribution to short-circuit currents and specifically the synchronous generators that are able to feed a sustained short-circuit current, then this type will be adopted in this research to model the DG in fault analysis.

For fault analysis, the internal voltage of the DG is assumed to be constant at the fault instant, and the DG injected current to keep the generator's internal voltage constant directly after fault inception is found using the hybrid compensation method.

D. Protection Devices Model

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

Fuses have an inverse current-time characteristic that is usually plotted as a log-log curve, which is better approximated by a second-order polynomial function. The part of interest in this curve approaches a straight line, and a linear equation can be used to reduce the calculation task as expressed in (2) [14].

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

where

t: fuse operating time;

I: fault current seen by the fuse;

a & b: fuse constants to be determined as in [9].

Reclosers are normally equipped with inverse-time over-current trip devices and the general characteristics of such devices are expressed as in (3) [15]

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

where

t: recloser operating time;

I: fault current seen by the recloser;

TD: time dial setting;

M ratio of $I/I_{\text{pick}-\text{up}}$;

$I_{\text{pick}-\text{up}}$ relay current set point;

A, B, p 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 parameter.

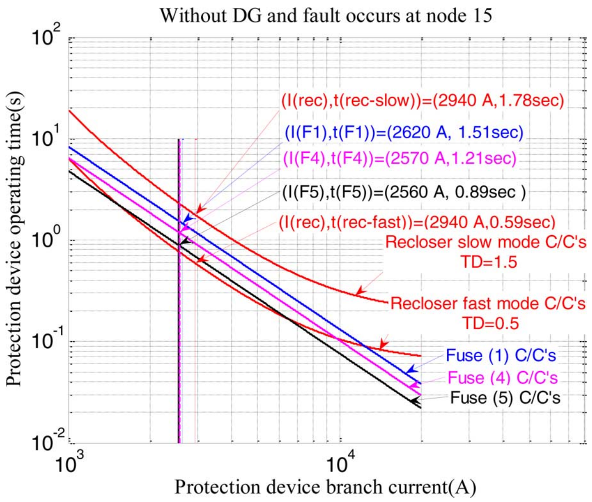


Fig. 2. Operating curves for the recloser and fuses F5, F4, and F1 with a three-phase fault at node 15.

III. PROBLEM STATEMENT

Normally, reclosers and fuses are initially selected to achieve a coordination sequence that is based on the fuse-saving principle. The coordination process is initially done knowing that the only current source is the substation current which makes the current in both devices be approximately the same at fault conditions. After penetration of DG in distribution networks, the current flow will be due to the contribution of the substation current and the DG current; this makes the current in reclosers and fuses to be no more the same leading to a probable miscoordination between both devices.

An example to clarify this problem using the IEEE 37-node test feeder is presented by assuming a three-phase fault at node 15. The protection devices responsible to clear that fault are the recloser (R) and the fuses (F5, F4, and F1). Based on the fuse-saving principle, these devices should be coordinated so that the recloser operates first in the fast mode to give a chance for the fault to be self cleared. If the fault still exists, then the nearest fuse (F5) should operate, and in case of fuse failure, the upstream fuses should then operate in sequence (F4 and F1). Finally, the recloser in the slow mode should operate as a final backup step. Fig. 2 shows the coordinated curves for the devices (R, F5, F4, and F1) along with their operating points based on the modeling (2) and (3), from which it can be shown that the required operating sequence is achieved.

Now, a DG with a penetration level of 400 kW (16% of the total system input power) is connected at node 8 and the same fault is applied at node 15, the contribution of DG to fault currents leads to an undesirable operating sequence of the devices (R, F5, F4, and F1) where F5 operates before the R fast mode operation as shown in "Fig. 3." This undesirable operating sequence leads to the following consequences:

1) unnecessary fuse blowing;
2) changing temporary faults to permanent faults;
3) increasing fault maintenance time;
4) decreasing system reliability.

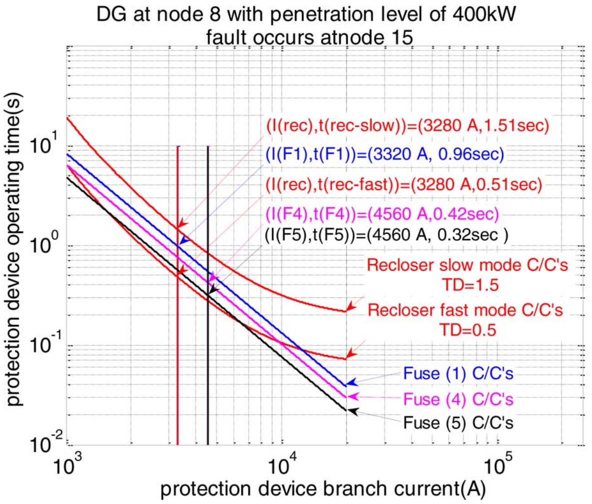


Fig. 3. Operating curves for the recloser and fuses F5, F4, and F1 with a three-phase fault at node 15 and a DG at node 8.

Studying different cases while changing fault location, DG location, and DG penetration level shows that the coordination between reclosers and fuses due to DG penetration may or may not hold depending on the DG location relative to fault location, DG type, and DG penetration level.

IV. Description of the Proposed Approach

The main outlines of the proposed approach are described using the following two steps:

Step 1) Protection coordination assessment.

In this step, a classifier is developed to classify the coordination status at fault conditions to either coordination holds or coordination lost. The main benefit from this step is to avoid taking disciplinary actions, such as the disconnection of DG each time a fault takes place even for the cases where the coordination is not lost. For a given fault location, the tasks that are required in the classification process are as follows.

1) Find the devices responsible to clear that fault.
2) Find the fault currents in such devices.
3) Find the operating times of these devices by using the obtained fault currents and the devices' modeling equations.
4) Arrange the operating times in order to find the operating sequence of the devices responsible to clear the fault.
5) Compare the obtained sequence with a pre-required sequence based on the fuse-saving principle.
6) Decide whether coordination holds or is lost according to the comparison results. If a close match occurs between the obtained and the pre-required sequence, then coordination holds; otherwise, coordination is lost.

The classification process is repeated while changing the DG location and penetration level in order to discriminate between the cases where coordination holds and the cases where coordination is lost.

Step 2) Protection coordination improvement.

In this step, two complementary actions are recommended as a partial solution to the recloser-fuse miscoordination problem. Both actions are used to decrease the number of cases where coordination is lost and, hence, improve the system's protection coordination behavior.

The first one is based on searching for the best location at which DG can be connected. The best DG location considered is that one with the highest number of cases where coordination holds while changing the fault location and the 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. Fig. 4(a) shows a flowchart to summarize the steps required to apply this solution.

The second one is based on changing the characteristics of the recloser by changing the TD parameter in (3) assuming that the DG is connected at the best location found previously. This action is practically acceptable these days, 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.

To apply this solution, for a given DG location and penetration level, the following sequence should be followed. When a fault is detected at a certain node, the coordination status should be classified at first. If coordination is found to be lost then the TD parameter for recloser fast mode is decreased in steps from its initial value to a defined final value. After each decreasing step the coordination status should be re-classified. If the coordination status is changed from being lost to being holds after any decreasing step, then stop and no further action is required. Otherwise the DG should be disconnected if no value for TD can re-attain coordination. "Fig. 4(b)" shows a flow chart to summarize the steps required to apply this solution.

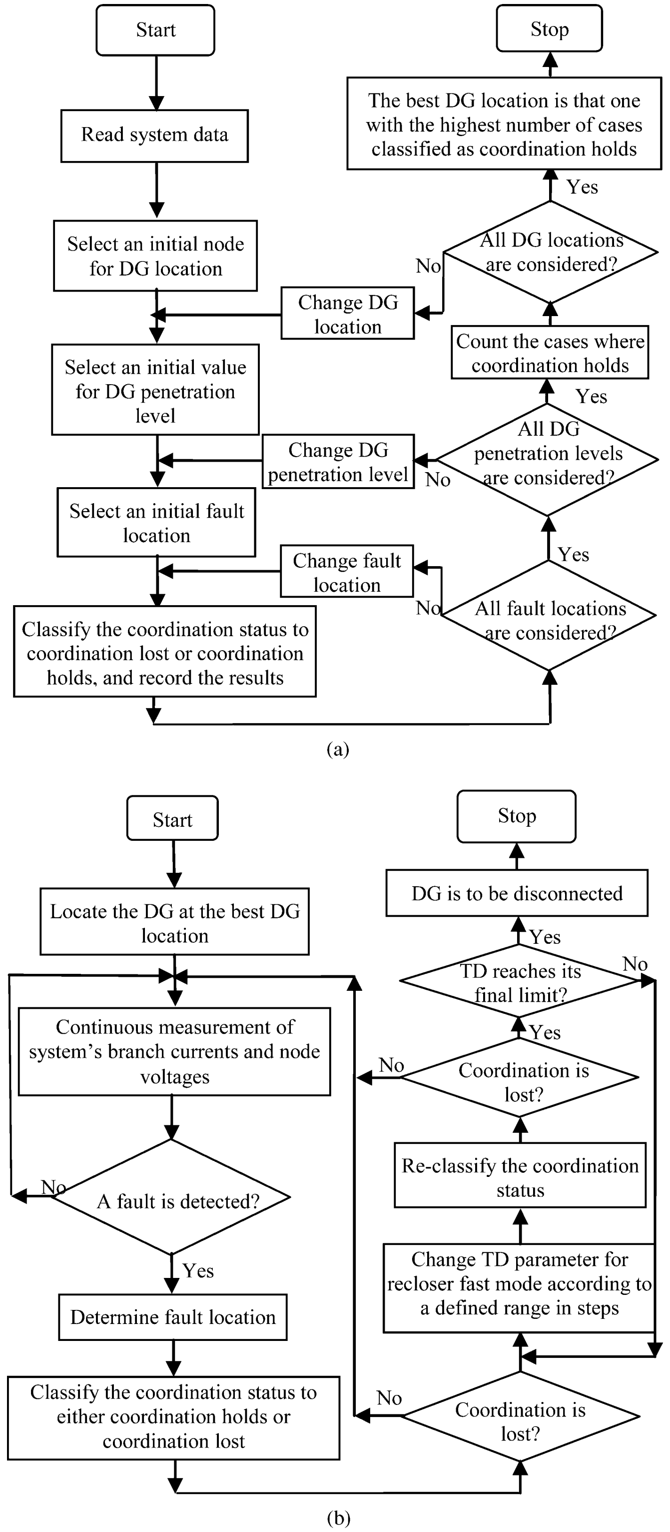
V. Results and Discussions

The proposed approach is implemented on the selected study system, and the main procedures along with the obtained results are presented in details as follows.

A. Load-Flow Analysis

Load-flow analysis is considered as a pivot step in the proposed approach since its results are used in the fault analysis program to find the branch fault currents.

The backward/forward sweep method is presented by Shirmohammadi *et al.* [16] for load-flow analysis and it is widely



(a)

(b)

Fig. 4. (a) Protection coordination improvement by searching for the best DG location. (b) Protection coordination improvement by changing the recloser setting.

TABLE II
BRANCH CURRENTS OF THE IEEE 37-NODE FEEDER WITHOUT DG PENETRATION

Branch Number	From Node-to Node	Phase currents, A		
		|*I*a|	**|*I*b|**	**|*I*c|**
1	1-2	373.5450	276.6691	354.9676
2	2-3	271.5437	219.4930	252.9197
6	3-7	59.9729	71.8094	87.9759
7	7-8	41.5751	71.8094	72.3469
10	8-11	25.0328	52.1284	67.7191
13	11-14	4.8457	42.0974	44.6135
14	14-15	0	9.4881	9.4881
15	14-16	4.8457	32.6093	35.1803
11	11-12	0	10.0310	10.0310
12	12-13	0	10.0310	10.0310
8	8-9	23.0234	25.8368	4.8457
9	9-10	19.1092	19.1092	0
3	3-4	21.1001	20.1631	34.0262
5	4-6	1.8262	20.1631	19.2120
4	4-5	20.1004	0	20.1004
16	3-17	192.6970	136.3555	134.0333
17	17-18	43.5554	36.0343	26.6707
18	18-19	35.9696	36.0343	17.4230
19	19-20	9.7828	9.7828	0
20	19-21	17.4217	17.4220	17.4230
21	17-22	149.4119	100.3255	107.4905
22	22-23	133.0903	100.3255	89.2989
36	23-37	0	0	0
23	23-24	0	19.0885	19.0885
24	23-25	133.0903	88.1157	76.4686
25	25-26	10.1929	0	10.1929
26	25-27	124.7190	88.1157	66.3315
27	27-28	107.4985	68.6200	66.3315
28	28-29	20.5352	9.4904	26.4632
29	29-30	0	9.4904	9.4904
30	29-31	20.5352	0	20.5352
31	28-32	82.5502	63.2512	30.3711
32	32-33	52.6501	30.6422	30.3711
33	33-34	30.3711	0	30.3711
35	34-36	20.5901	0	20.5901
36	34-35	9.7828	0	9.7828

accepted as one of the most relevant methods used in this aspect. This method is capable of solving the load-flow problem for unbalanced distribution systems with DG modeled as a PV bus in two steps. The first step is a backward sweep in which Kirchoff's current law is used to find load branch currents at all nodes starting from the end nodes. The second step is a forward sweep which starts in the opposite direction to find nodal voltages by applying Ohm's law.

A load-flow program based on the backward/forward sweep method is developed using MATLAB as a platform and then applied to the IEEE 37-node test feeder.

Table II shows the magnitude of the branch currents in the base case (without DG penetration). These results are very close to the load-flow results published in [17] for the same system, which ensures the validity of the developed program.

B. Short-Circuit Analysis

Short-circuit analysis of EDSs is an essential step in the proposed approach, since beside its basic role in the protection devices coordination process, it is also used in the classification process to find the branch fault currents.

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 [18]. One of these methods is the hybrid compensation method [19] where it uses the power-flow solution as a prefault condition and uses a compensation technique to find the injected node currents at DG, fault, and loops breakpoint nodes.

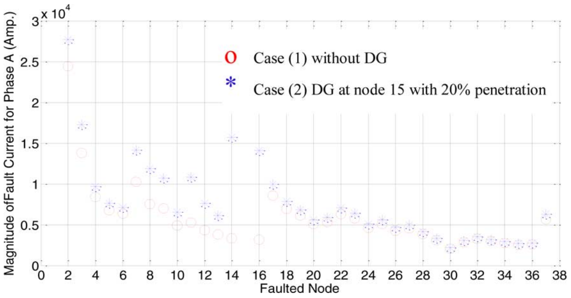


Fig. 5. Magnitude of fault currents of phase A for different fault locations.

Then, the backward–forward sweep iteration is performed once to find the short-circuit currents and the node voltages immediately after the 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.

Some of the results of applying the developed short-circuit program on the IEEE 37-node feeder are presented here. Fig. 5 shows the magnitude of fault currents at the faulted node for phase (A) for two cases. In case (1), the system has no DG and a three-phase fault is applied at different locations.

In case (2), one DG is connected at node 15 with a 20% penetration level and again a three-phase fault is applied at the same locations as in case (1). It is clearly shown from Fig. 5 that when the fault takes place at nodes 14 or 16, which are very close to node 15 at which the DG is connected, an appreciable increase in the fault current, compared with case (1), is remarked. In general, it can be concluded from Fig. 5 that the severity of the effect of DG penetration on fault currents and, consequently, on the protection system becomes less as the electrical distance between fault and DG location increases. Table III 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 different nodes in the system. From the results, it is concluded that the fault currents decrease when the faulted node moves away from the substation as it is clear when comparing the fault currents at nodes 8, 14, and 15.

C. Protection Coordination Setting

The protection coordination setting for fuses and reclosers is made based on (2) and (3), assuming that there is no DG connected initially.

For setting the reclosers, it is assumed that they are equipped with relays having extremely inverse characteristics, and the recloser pickup current $I_{\text{pick-up}}$ is found as in [1] using.

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

where

OLF overload factor depends on the protected equipment;

I_{nom} recloser current obtained from the load-flow results.

TABLE III
BRANCH FAULT CURRENTS OF THE IEEE 37-NODE FEEDER WITHOUT DG PENETRATION

Branch	**Faulted node**									
Number	**15**	**14**	**8**	**13**	**5**	**6**	**20**	**21**	**24**	**26**
1	2940	3720	7870	4160	7170	6760	5460	5710	5020	4640
2	2840	3620	7770	4060	7070	6660	5350	5610	4920	4540
3	–	–	–	–	6820	6410	–	–	–	–
4	–	–	–	–	6820	–	–	–	–	–
5	–	–	–	–	–	6390	–	–	–	–
6	2620	3410	7560	3840	–	–	–	–	–	–
7	2610	3390	7540	3830	–	–	–	–	–	–
8	–	–	–	–	–	–	–	–	–	–
9	–	–	–	–	–	–	–	–	–	–
10	2590	3370	–	3810	–	–	–	–	–	–
11	–	–	–	3780	–	–	–	–	–	–
12	–	–	–	3780	–	–	–	–	–	–
13	2570	3350	–	–	–	–	–	–	–	–
14	2560	–	–	–	–	–	–	–	–	–
15	–	–	–	–	–	–	–	–	–	–
16	–	–	–	–	–	–	5270	5530	4840	4460
17	–	–	–	–	–	–	5130	5380	–	–
18	–	–	–	–	–	–	5120	5370	–	–
19	–	–	–	–	–	–	5090	–	–	–
20	–	–	–	–	–	–	–	5360	–	–
21	–	–	–	–	–	–	–	–	4790	4420
22	–	–	–	–	–	–	–	–	4780	4400
23	–	–	–	–	–	–	–	–	4650	–
24	–	–	–	–	–	–	–	–	–	4400
25	–	–	–	–	–	–	–	–	–	4280

The 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) [15]. The recloser nominal current I_{nom} is 373.54 A as obtained from Table II and the OLF parameter in (4) is set to 1.5. The parameter TD is taken to be equal to 1.5 and 0.5, respectively, for the slow and fast tripping modes of the recloser.

On the other hand, the fuse setting is based on the concept that all fuses in the fault path (i.e., the path from the fault location to the substation) should operate slower than the recloser fast mode and faster than the recloser slow mode. The fuse setting implies the determination of the 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 equal to -1.8 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 running the short-circuit program while fuse operating time is obtained 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, using (5) which is developed by the authors

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

where

$t_{\text{fuse}-i}$ operating time for the ith fuse in the fault path where $i = 1$ for the fuse closest to the faulted node;

n total number of fuses in the fault path;

TABLE IV
FUSE CONSTANT

Fuse number	Fuse Constant 'b'	Fuse number	Fuse Constant 'b'
1	6.3236	11	6.2242
2	6.1840	12	6.2183
3	6.1662	13	6.2806
4	6.2117	14	6.2684
5	6.0837	15	6.2685
6	6.0932	16	6.1187
7	6.4202	17	6.1299
8	6.3134	18	6.2139
9	6.2715	19	6.2177
10	6.3704	20	6.3206

$t_{\mathrm{rec-slow}}$ recloser slow mode operating time;

$t_{\mathrm{rec-fast}}$ recloser fast mode operating time.

For calculating the constant b, a three-phase fault is applied at each end node successively and the obtained short-circuit currents are substituted into (5) to obtain one operating point for the fuse. Consequently, the constant b is found by rearranging (2). For example, to find the constant b of fuses F5, F4, and F1, a three-phase fault is applied at node 15 and the short-circuit currents in the branches containing the recloser and these fuses are found by running the short-circuit program as in Table III. From the recloser current, $t_{\mathrm{rec-slow}}$ and $t_{\mathrm{rec-fast}}$ are found from (3) equal to 1.7778 s and 0.5926 s, respectively. Using (5), the operating times for F5, F4, and F1 are found to be 0.8889, 1.1852, and 1.4815 s, respectively. These operating times with the corresponding fuse fault currents are used in (2) after rearrangement to find the constant b for each fuse.

Table IV summarizes the values of the constant b for all fuses in the system. Using these results, the fuse characteristics can be constructed.

D. Protection Coordination Assessment

A program has been developed using MATLAB as a platform, to use it as a classifier to assess the protection coordination status to either coordination holds or coordination lost. The developed program is applied to the IEEE 37-node test feeder, where a three-phase fault is applied at a specified node and one DG is connected, in turn, to all system nodes except the faulted node and the substation node (i.e., 35 different DG locations). 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 35 $\times$11 $=$ 385 for each specified faulted node.

Fig. 6 shows the results of the classification process when a fault is applied at node 15 while changing the DG penetration level and location.

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 is equal to 128/385 $=$ 33.24%.

As a result, 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 action is required, and, consequently, system reliability will be improved.

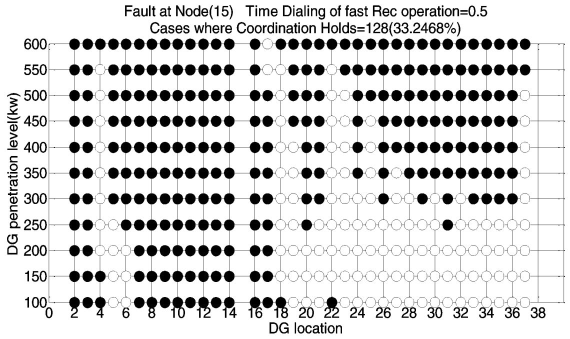


Fig. 6. Classification pattern for a fault at node 15 with TD being equal to 0.5 for recloser fast operation.

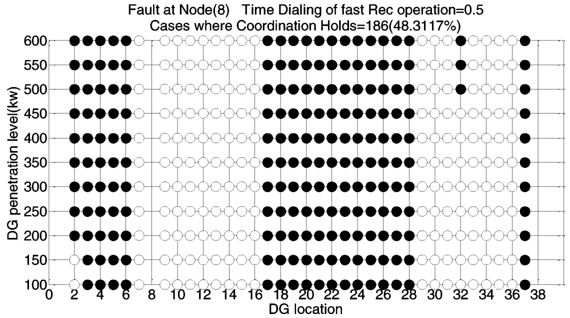


Fig. 7. Classification pattern for a fault at node 8 with TD being equal to 0.5 for recloser fast operation.

The same analysis is repeated by changing the faulted node, where a three-phase fault is applied at node 8 while changing the DG penetration level and location. The number of cases where coordination holds is found to be 186/385 $=$ 48.31%. Fig. 7 shows the classification pattern for a fault at node 8.

Comparing the results obtained from applying the fault at node 15 and node 8 shows that the number of cases where coordination holds is higher when the fault is applied at node 8 than the case when the fault is applied at node 15. This is because the number of fuses in the fault path for node 8 (one fuse) is less than that for node 15 (three fuses). A conclusion is reached that as the number of fuses in the fault path decreases, the number of cases where coordination hold will increase and so does the system reliability.

E. Protection Coordination Improvement

As mentioned in Section IV, two complementary actions are recommended to decrease the cases where miscoordination occurs due to DG penetration, from which the general behavior of the protection coordination can be improved. The first one is to search for the best DG locations and the second one is to change the recloser setting. Both actions are applied to the study system as follows.

- Search for the best DG location.

  To search for the best DG locations regarding the number of cases where coordination is lost, one DG is connected at a specified node, while changing the fault location over all nodes in the laterals and sublaterals feeders. Also, the

TABLE V
NUMBER OF CASES (AS A PERCENTAGE) WHERE THE 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	41.09	**20**	15.27
3	18.91	**21**	16.00
4	26.91	**22**	11.27
5	20.00	**23**	9.82
6	17.82	**24**	11.64
7	33.09	**25**	8.73
8	28.36	**26**	14.55
9	33.82	**27**	10.55
10	25.82	**28**	18.18
11	21.45	**29**	32.73
12	36.36	**30**	55.64
13	50.18	**31**	39.27
14	56.36	**32**	26.91
15	74.55	**33**	30.55
16	63.27	**34**	36.00
17	26.55	**35**	45.45
18	22.91	**36**	44.36
19	16.00	**37**	13.45

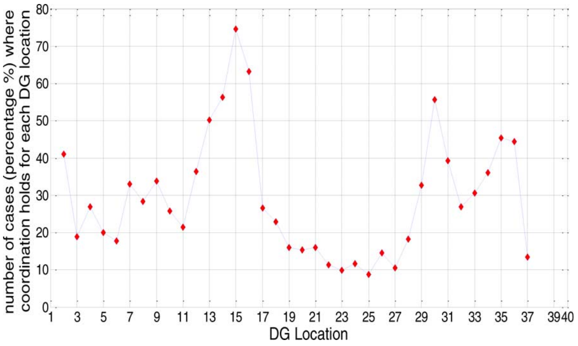


Fig. 8. Number of cases (in percentage) where coordination holds for each DG location.

DG penetration level is changed from 100 to 600 kW in steps of 50 kW. This process is repeated for all possible DG locations. The results obtained are summarized in Table V, where the number of cases at which coordination holds as a percentage is presented for each DG location.

Fig. 8 shows a plot for the results obtained in Table V, from which it is clear that node 15 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 16, 14, 30, and so on.

- Change recloser setting.

  This solution is based on changing the recloser characteristics by changing the TD parameter in the recloser modeling (5) for the fast mode operation from its initial value at 0.5 to a value of 0.1 in steps of 0.2. To show the effectiveness of this solution, a three-phase fault is applied at node 15 while changing the DG location and penetration level. Figs. 9 and 10 show the new classification patterns for TD being equal to 0.3 and 0.1, respectively.

The number of cases where coordination holds as a percentage, for these two values of TD is 256/385 = 66.49% and 286/385 = 74.28%, respectively. Comparing the results obtained after changing the recloser setting with that before changing the recloser setting, which is shown in Fig. 6, indicates a significant reduction in the number of cases classified as coordination lost, from which the effectiveness of the proposed solution to improve the protection coordination behavior is verified.

For a more general study, the fault location is changed over all nodes in the lateral and sublateral feeders. For each faulted

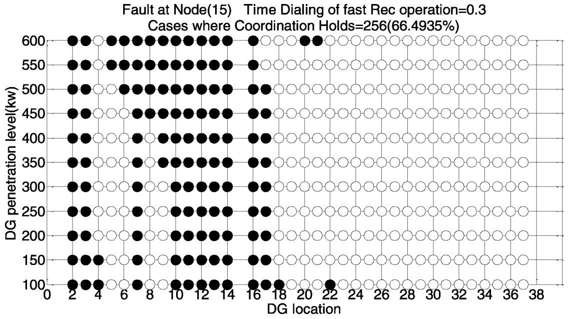


Fig. 9. Classification pattern for a fault at node 15 with TD being equal to 0.3 recloser fast operation.

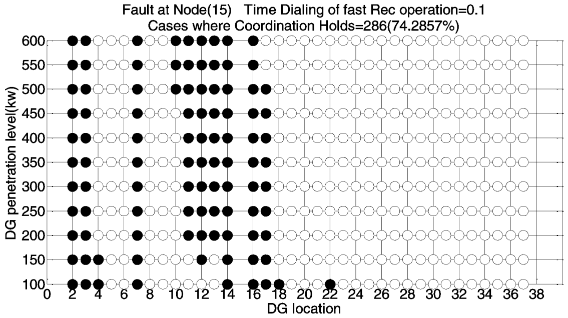


Fig. 10. Classification pattern for a fault at node 15 with TD being equal to 0.1.

TABLE VI
NUMBER OF CASES (IN PERCENTAGE) CLASSIFIED AS COORDINATION HOLDS FOR DIFFERENT VALUES OF TD AND FAULT LOCATIONS

Fault location	TD 0.1	0.2	0.3	0.4	0.5
4	100.00	94.29	87.79	74.81	48.83
5	94.29	93.51	82.60	63.12	38.70
6	94.29	93.77	81.82	57.92	34.03
7	97.14	84.68	58.70	42.34	25.71
8	100.00	93.51	80.78	61.56	48.31
9	91.43	73.77	40.78	23.90	2.86
10	95.58	87.53	69.87	43.38	18.18
11	100.00	99.48	95.06	82.86	62.60
12	87.01	78.18	64.16	41.56	16.36
13	90.91	79.22	71.43	53.25	25.19
14	86.75	80.52	76.36	71.95	58.44
15	74.29	71.17	66.49	55.32	33.25
16	66.70	64.21	61.27	49.87	42.00
18	95.32	82.60	61.04	51.95	30.13
19	96.62	87.01	68.57	54.03	36.88
20	88.57	74.29	53.77	28.57	7.53
21	87.53	72.99	51.69	25.19	6.75
24	80.52	63.90	43.64	28.31	17.66
26	76.62	55.58	37.92	27.01	16.36
29	72.99	55.32	48.57	42.08	32.47
30	66.75	54.81	46.23	33.77	22.86
31	61.04	46.49	37.14	24.68	10.65
35	67.27	55.84	45.19	35.58	25.97
36	67.27	56.36	45.19	35.58	26.75
37	76.10	62.08	38.44	24.16	14.81

TABLE VII
LOAD MODELS

Load type	Star	Delta
Constant PQ	$Il_i^{ph} = \left(\frac{S_i^{ph-n}}{V_i^{ph-n}}\right)^*$	$Il_i^{ph} = \left(\frac{S_i^{ph-ph}}{V_i^{ph-ph}}\right)^*$
Constant Z	$Z_i^{ph-n} = \frac{\lvert V_i^{ph-n}\rvert^2}{\left(S_i^{ph-n}\right)^*}$ $Il_i^{ph-n} = \left(\frac{V_i^{ph-n}}{Z_i^{ph-n}}\right)$	$Z_i^{ph-ph} = \frac{\lvert V_i^{ph-ph}\rvert^2}{\left(S_i^{ph-ph}\right)^*}$ $Il_i^{ph-ph} = \left(\frac{V_i^{ph-ph}}{Z_i^{ph-ph}}\right)$
Constant I	$Il_i^{ph-n} = \lvert Il_i^{ph-n}\rvert * \angle\left(\delta_i^{ph-n} - \theta_i^{ph-n}\right)$	$Il_i^{ph-ph} = \lvert Il_i^{ph-ph}\rvert * \angle\left(\delta_i^{ph-ph} - \theta_i^{ph-ph}\right)$

node, the number of cases at which coordination holds as a percentage is counted for different values of the TD parameter. The obtained results are summarized in Table VI.

VI. CONCLUSION

A novel approach is presented and applied to the IEEE 37-node test feeder to evaluate the effect of the DG penetration on the protection devices coordination. The approach is based on two main steps: protection coordination assessment and protection coordination improvement. In the coordination assessment step, the coordination status after integrating DG to the system is classified as either *coordination holds* or *coordination lost*. Different cases are studied by changing DG penetration levels and locations for each possible fault location. Applying this step discriminates between the cases that require an action against DG penetration and the cases where an action is not required. The coordination improvement step is based on decreasing the number of cases where coordination is lost. This is done through two complementary actions: the first is to search for the best DG locations and the second is to change the recloser setting. Applying both actions leads to a significant reduction in the cases classified as coordination lost.

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