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A Classification Technique for Protection Coordination Assessment of Distribution Systems with Distributed Generation

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A Classification Technique for Protection Coordination Assessment of 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 on recloser-fuse coordination. This approach is based on the assessment of the recloser-fuse coordination due to the penetration of distributed generation with specified location and capacity for a given fault location. This assessment process acts as a classifier, based on finding the operating sequence of all reclosers and fuses in the path from the faulted node to the substation. This sequence is compared with a pre-required sequence obtained from the protection coordination philosophy, and then provides the distribution system operator with a result indicating whether the recloser-fuse coordination still holds or lost. Consequently, the operator can take the proper decision according to this classification process. One of the proper decisions that can be taken into account in case of recloser-fuse miscoordination is to adapt the recloser setting such that the coordination can be re-attained.**

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.

Keywords: IEEE 37-node test feeder, recloser-fuse coordination, Distributed Generation, Distribution Systems.

I. INTRODUCTION

Electric Distribution Systems (EDSs) are usually radial in nature and are supplied from distribution substations. The main advantages of these radial systems are their low cost and simplicity in protection schemes. This protection scheme uses simple protection devices such as reclosers, fuses and, in some cases, over-current relays. The coordination between these protection devices is well established and is, usually, done assuming system radiality [1, 2]. Reclosers are used in main feeders of EDSs to protect them against temporary self-clearing faults, while fuses are located at the beginning of laterals and sub-laterals to protect the EDS against persistent faults. The main idea behind the recloser-fuse coordination philosophy is that when a fault occurs, the recloser should operate in its fast mode and disconnects the circuit to give the fault a chance to clear. If the fault still exists after re-connection, then the nearest fuse to the fault should open. If, for any reason, this fuse fails to operate, then the next upstream fuses should act in a descending order as a backup protection and finally if all fuses fail to operate, then the recloser should operate again, but in its slow mode, as a final backup element. In this way, fuses are saved as they will operate only in case of persistent faults, which are less than 20% of EDSs faults.

Recently distributed generation (DG) is attracting both distribution utilities and electricity consumers and can be employed for; backup generation, power loss reduction, power quality improvement, environmental concerns, and peak load service [3].

High penetration of DG may lead to false tripping of feeders, blinding of protection, unwanted islanding, unsynchronized reclosing, protection devices miscoordination [4-6].

The main concern in this paper is to present a novel approach to:

- Assess the effect of DG penetration on the recloser-fuse coordination problem that significantly affects the reliability of typical radial EDSs [7], and
- Propose solutions to miscoordination problems, if they appear.

The proposed approach is based on classifying the coordination between protection devices in the fault path to either *coordination holds* or *coordination lost*. If the system is classified as *coordination lost*, then a solution is applied by changing the recloser setting, which results in a significant reduction in the number of cases that can be usually classified as *coordination lost*.

II. SYSTEM UNDER STUDY

In this paper the IEEE 37-node 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 [8]. 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 re-numbered for the sake of simplicity. Finally a protection scheme shown in "Fig. 2" is implemented based on the method given in [9]. In this scheme one recloser is added at the beginning of the main feeder and 20 fuses are added at the beginning of each lateral and sub-lateral. This system is characterized by the following modeling issues:

A. Line Model

This system contains underground and overhead three phase lines with different spacing between phase conductors. The series impedance of each line section is represented by a 3x3 matrix as follows:

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

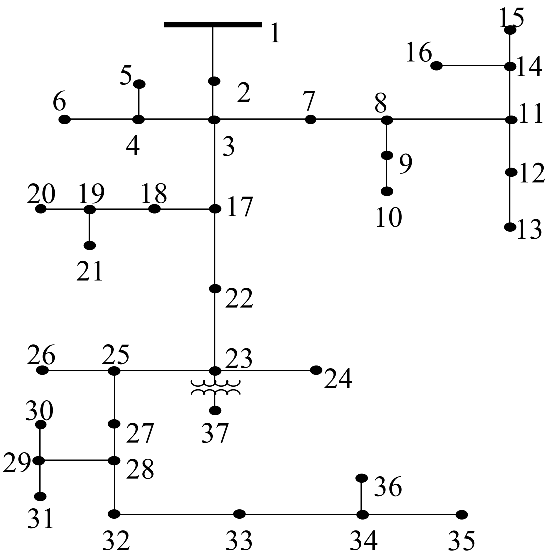

Figure 1. Modified IEEE 37 Node Test Feeder

B. Load Model

System loads are single-phase or three phase ones. Three-phase loads are balanced- or unbalanced-, and star- or delta-connected. Loads are modeled as constant power (PQ), constant impedance (Z) or constant current (I) type with modeling equations as shown in Table I [10].

C. DG Model

The DG can be modeled as constant PQ or PV nodes. For PQ model, it is the same as the constant power load models except that the current is injected into the system. 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 1p.u.

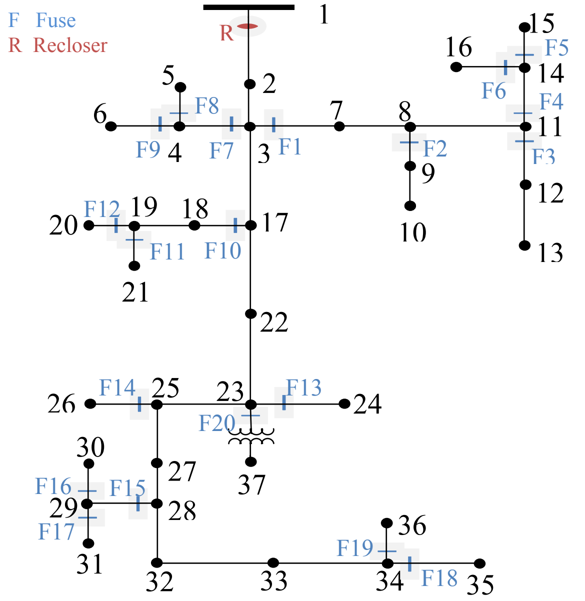

Figure 2. Modified IEEE 37 Node Test Feeder with protection devices

TABLE I

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	$Z_i^{ph-n} = \frac{\left\|V_i^{ph-n}\right\|^2}{\left(S_i^{ph-n}\right)^*}$ $Il_i^{ph-n} = \left(\frac{V_i^{ph-n}}{Z_i^{ph-n}}\right)$	$Z_i^{ph-ph} = \frac{\left\|V_i^{ph-ph}\right\|^2}{\left(S_i^{ph-ph}\right)^*}$ $Il_i^{ph-ph} = \left(\frac{V_i^{ph-ph}}{Z_i^{ph-ph}}\right)$
Constant I	$Il_i^{ph-n} = \left\|Il_i^{ph-n}\right\| * \angle\left(\delta_i^{ph-n} - \theta_i^{ph-n}\right)$	$Il_i^{ph-ph} = \left\|Il_i^{ph-ph}\right\| * \angle\left(\delta_i^{ph-ph} - \theta_i^{ph-ph}\right)$

D. Protection Devices Model

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

Fuses have 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 Eqn. (2) [11].

$$\log(t) = a.\log(I) + b \qquad (2)$$

where

t : fuse operating time.
I : fault current seen by the fuse.
a & b : fuse constants to be determined as in [12].

Reclosers are normally equipped with inverse-time over-current trip devices and the general characteristics of such devices are expressed as in Eqn. (3) [13].

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

where

t : recloser operating time
I : fault current seen by the recloser
TD : time dial setting
M : ratio of $I/I_{pick\text{-}up}$
$I_{\text{pick-up}}$: 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*.

III. OUTLINES OF THE PROPOSED APPROACH

A brief description of the proposed approach is presented in the following steps:

A. Load flow analysis

The backward/forward sweep method is presented by Shirmohammadi et al. [14] for load flow analysis and it is widely 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 is started in the opposite direction to find nodal voltages by applying Ohm's law.

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.

B. 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[15]. One of these methods is the hybrid compensation method [16] 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, a 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.

C. Protection coordination setting

Protection coordination setting for fuses and reclosers is made based on equations (2) & (3) for appropriate devices, 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, the recloser pick-up current $I_{pick\text{-}up}$ is found as in [1] using Eqn. (4).

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

where

OLF : Overload factor depends on the protected equipment

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

On the other hand, 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. 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 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 Eqn (5) which is developed by the authors.

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

where

$t_{fuse\text{-}i}$:operating time for the i^{th} fuse in the fault path where i=1 for the fuse nearest to the faulted node.

n :total number of fuses in the fault path.

$t_{rec\text{-}slow}$:the recloser slow mode operating time.

$t_{rec\text{-}fast}$:the recloser fast mode operating time.

D. Protection coordination assessment

After doing protection coordination between fuses and reclosers in the system without DG, it is required to assess this coordination after the penetration of DG, to avoid taking disciplinary actions like disconnection of DG each time a fault takes place even for the cases where the coordination is not lost. In the assessment process, it is required for a fault at a certain node to check the operating sequence of the protection devices in the fault path after DG connection, by finding the operating times of these protection devices from Eqns. (2) and (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.

One solution for the miscoordination problem is proposed in this paper. It is based on changing the characteristics of the recloser by changing the TD parameter in Eqn. (3). This action is practically acceptable nowadays thanks 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. The number of cases where the coordination holds with respect to the total number of studied cases is monitored for different values of the TD parameter. For this purpose a program has been developed using MATLAB to use it as a classifier to assess the protection coordination and evaluate the effectiveness of the proposed solution. "Fig. 3" shows a flow chart for this program.

IV. RESULTS AND DISCUSSIONS

In this section some results related to each step in the proposed approach are presented.

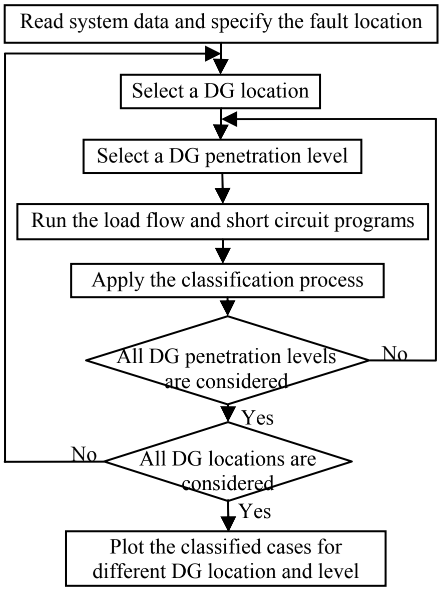

Figure 3. Flow chart for Fuse-Recloser coordination assessment

A. Load flow results

The developed load flow program is applied to the IEEE 37-node test feeder and some of the results are presented. 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 assures the validity of the developed program. "Fig. 4" shows the line voltage V_{ab} for different cases of the modified IEEE 37-node test feeder. In case 1 the test feeder has no DG penetration. In cases (2) and (3) one DG is connected to the system at node 15 with 10 % and 20% penetration level, respectively. From these two cases, it is clearly shown that the presence of DG in the system improves the voltage profile for the whole system and especially at the node 15 at which the DG is connected. In case (4), two DGs with 10% penetration level are connected at nodes 15 and 20.

From this case, it is clearly seen that dividing the same penetration level on more than one node in the system has a better effect on the voltage profile compared with concentrating it at one node.

B. Short circuit results

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 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 location and the DG location increases.

TABLE II
Branch Currents of the IEEE 37-node feeder without DG penetration

Branch No.	**From**	**Phase currents, A**		
	Node-to Node	**|*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

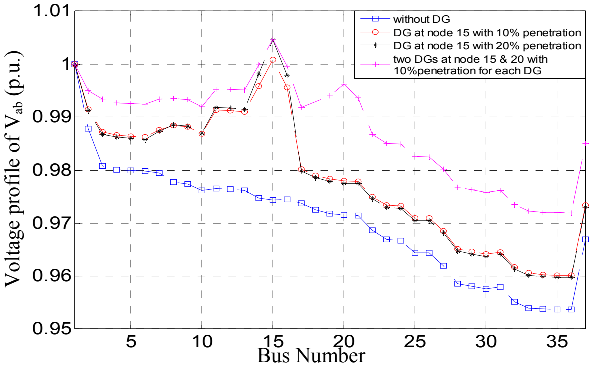

Figure 4. Line Voltage (V_{ab}) for different cases of the modified IEEE 37-node test feeder

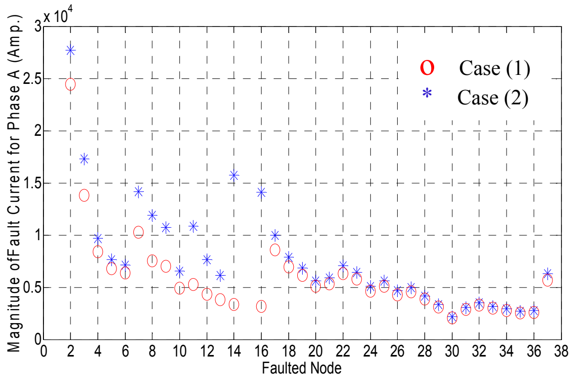

Figure 5. Magnitude of fault currents of phase A for different fault locations, case (1) without DG, case (2) with DG at node 15 and 20%penetration level.

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 decreases 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 setting results

Reclosers having standard extremely inverse characteristics are used. The parameters A, B, and p in Eqn. (3) are taken equal, respectively, to 28.2, 0.1217, and 2 [13]. The recloser nominal current I_{nom} is 373.54 A as obtained from Table II and the OLF parameter in Eqn. (4) is taken equal to 1.5. The parameter TD is arbitrary set to be 1.5 and 0.5, respectively, for the slow and fast tripping modes of the recloser as in [12].

For fuse setting, the fuse constant 'a' in Eqn. (2), is chosen equal to -1.8 and will be fixed for all fuses in the system.

TABLE III
Branch fault Currents of the IEEE 37-node feeder without DG penetration

Branch	**Faulted node**									
No.	**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

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 Eqn. (5) to obtain one operating point for the fuse. Consequently the constant 'b' is found by re-arranging Eqn. (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, $t_{rec\text{-}slow}$ and $t_{rec\text{-}fast}$ are found from Eqn. (3) equal to 1.7778s and 0.5926s, respectively. Using Eqn. (5), the operating times for F5, F4 and F1 are found to be 0.8889s, 1.1852s and 1.4815s, respectively. These operating times with the corresponding fuse fault currents are used in Eqn. (2) after re-arrangement 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. "Fig. 6" shows the operating curves for the recloser and fuses F5, F4 and F1.

D. Protection coordination assessment results

The coordination assessment process is applied to the IEEE 37-node test feeder using the developed program, where one DG is connected in turn to all system nodes except the faulted node and the substation node, i.e. 35 different locations. The DG penetration level is also changed from 100 kW to 600 kW in steps of 50 kW resulting in 11 different penetration levels with total different possible cases equal to 35x11=385. "Fig. 7" shows the results of the classification process when a fault is applied at node 16 while changing the DG penetration level and location.

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

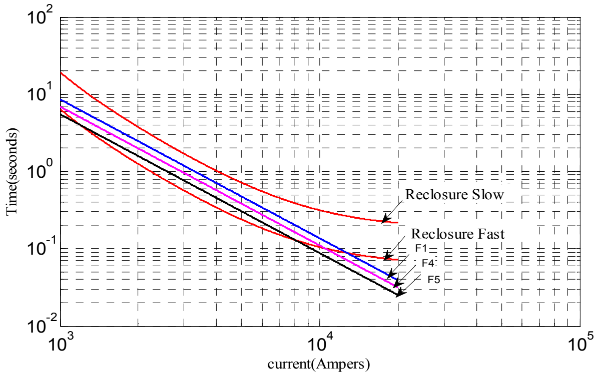

Figure 6. Operating curves for the recloser and fuses F5, F4 and F1.

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 164/385= 42.6%. 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 an action is required, and, consequently, the system reliability will be improved.

To decrease the number of cases where coordination is lost, a solution based on changing the recloser characteristics is proposed and applied. According to this solution the *TD* parameter of the recloser fast operation is changed from its initial value at 0.5 to a value of 0.1 in steps of 0.2. “Fig. 8” and “Fig. 9” show the new classification pattern for *TD* equals 0.3 & 0.1 respectively. The number of cases where coordination holds as a percentage, for these two values of *TD* is 235/385 = 61% and 257/385 = 66.7%, respectively, which shows the effectiveness of the proposed solution to improve the protection coordination behavior.

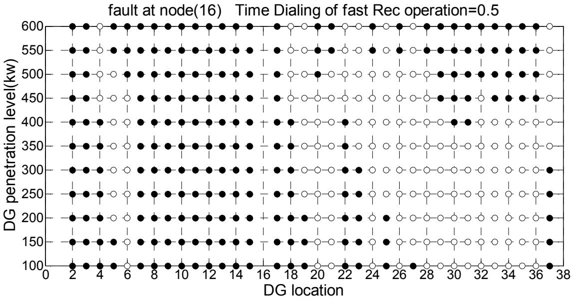

Figure 7. Classification pattern for a fault at node 16 with TD equals 0.5 for recloser fast operation.

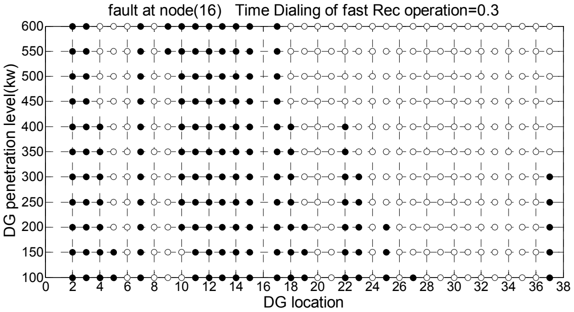

Figure 8. Classification pattern for a fault at node 16 with TD equals 0.3 for recloser fast operation.

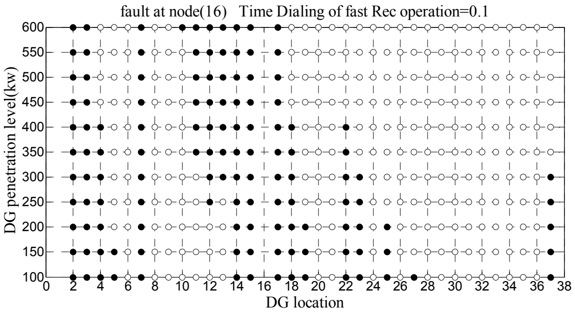

Figure 9. Classification pattern for a fault at node 16 with TD equals 0.1 for recloser fast operation.

V. CONCLUSION

A protection coordination assessment process is proposed and applied to the IEEE 37-node test feeder to evaluate the effect of the DG penetration on the protection devices coordination by classifying the system to either *coordination holds* or *coordination lost*. Different DG penetration levels and locations are studied. To decrease the number of cases where coordination is lost, a solution is proposed based on changing the recloser characteristics by changing the *TD* parameter for the recloser fast mode. This solution is evaluated by re-assessing the system for different DG penetration levels and locations which shows that the number of cases where coordination is lost is significantly reduced. This study is a mile stone for developing an efficient and simple solution for the recloser-fuse coordination problem due to DG penetration.

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