Coordination Assessment of Overcurrent Relays in Distribution Feeders with High Penetration of PV Systems

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***Abstract*— This paper investigates the impact of Photovoltaic (PV) systems on the coordination between overcurrent relays in a PV-dominated distribution feeder. The paper shows under what conditions and how significant the PV systems affect the coordination. The paper also proposes a method for assessing the coordination in such feeders. Performance of the proposed methods has been assessed by simulations on a sample distribution feeder.**

***Index Terms*-- Photovoltaic (PV), coordination, overcurrent relay, PSCAD/EMTDC.**

I. INTRODUCTION

One of the main impacts of a Photovoltaic (PV) system on a distribution feeder is on the system protection, as the PVs will contribute to the fault current during a fault [1,2]. Hence, coordination, defined as the sufficient time margin needed between the trip time of a protective device (PD) and that of the corresponding backup protection, is prone to be affected by the PV penetration [3].

The impact of distributed generators (DGs) on the coordination between overcurrent relays has been investigated in literature [1-6]. Different methods have been proposed in [4,5,6] such as utilizing multi-agent systems, adaptive protection methods, and back tracking algorithms to handle this impact. These studies, provide little detail on the impact, and provide only a brief problem statement. Therefore a study is needed to show under what conditions and how significant the PV penetration affects the coordination between PDs overcurrent relays.

This paper begins with an introduction on the PV system behavior under fault in section II. In section III, the impacts of PVs on the operation of overcurrent relays and also on the coordination between them are explained by equations and relays time-current curves. It is shown that under what conditions the impact of PVs may result in mis-coordination between overcurrent relays. Section VI introduces the method for assessing the coordination in a PV-dominated distribution feeder. Conclusions are drawn in section V.

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II. PV SYSTEM BEHAVIOR UNDER FAULT

To analyze the effects of PVs on the PDs coordination, we need to have an understanding on how a PV system contributes to the fault current first.

Figure 1 shows a typical grid connected residential PV system. It is an inverter interfaced system to accommodate 120 Volt or 240 Volt AC connections. When a fault occurs on the feeder, the PV system feeds current to the fault. The current to be injected depends on the PV inverter design. Since the PV systems are designed to push the maximum power available from PV panels to the system, the PV inverter tries to push this power even under low voltage conditions which occur during a fault, i.e., it will try to act like a constant power source. However, if this current gets to be higher than the maximum current rating of the inverter, inverter limits the current at its maximum level. Inverters limit their current to 1 to 2 times the rated current [7]. This limiting property will be used in the next section to explain the impact of PV penetration on the operation of PDs.

Another important factor which affects the current contribution from a PV system during a fault is the protection scheme employed for the inverter. Table I summarizes the protection scheme recommended by the IEEE standard 929 for such systems [8]. As the table indicates, the protection module disconnects the PV from the grid when it detects grid abnormal voltage or frequency. Note that, as the table shows,

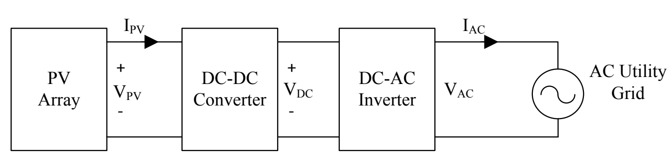

Fig. 1. Main components of a residential PV system.

TABLE I. PROTECTION SCHEME FOR A PV SYSTEM

		trip time
Terminal voltage	V < 0.5pu	6 cycles
	0.5pu ≤ V < 0.88pu	120 cycles
	0.88pu ≤ V < 1.1pu	normal operation
	1.1pu ≤ V < 1.37pu	120 cycles
	1.37pu ≤ V	2 cycles
grid freq.	f < 59.3	6 cycles
	59.3 ≤ f ≤ 60.5	normal operation
	60.5 < f	6 cycles

the time it will take for the protection scheme to disconnect the PV depends on how low the terminal voltage will be during a fault. The effect of this voltage-based self protection on the operation of PV systems during a fault will be explained in the next section.

More details on PV system behavior under fault are presented in [9].

III. ANALYTICAL ASSESSMENT OF PV PENETRATION IMPACT ON COORDINATION BETWEEN OVERCURRENT RELAYS

A. Basics

Figure 2 shows a general case where three groups of PV systems are connected to a feeder at different locations: I_1 which represents all PVs upstream of PD_1, I_2 which represents all PVs between PD_1 and PD_2, and I_3 which represents all PVs downstream of PD_2.

The fault current each PD will see can be approximated by equation 1 and 2 for three-phase and single-phase faults, respectively [9]. Note that for three-phase faults, the PD measures the actual phase current while, for single-phase faults, it measures the ground current (three times the zero sequence current).

$$I_{Rph} = I_S + C_{uPD} I_{uPD} - C_{PDf} I_{PDf} - C_{fd} I_{fd} \tag{1}$$

$$\begin{aligned} I_{Rg} = (3I_S) &+ \left[C^+_{uPD}(3I^+_{uPD}) + C^-_{uPD}(3I^-_{uPD}) + C^0_{uPD}(3I^0_{uPD})\right] \\ &- \left[C^+_{PDf}(3I^+_{PDf}) + C^-_{PDf}(3I^-_{PDf}) + C^0_{PDf}(3I^0_{PDf})\right] \\ &- \left[C^+_{fd}(3I^+_{fd}) + C^-_{fd}(3I^-_{fd}) + C^0_{fd}(3I^0_{fd})\right] \end{aligned} \tag{2}$$

where I_{Rph} and I_{Rg} are the fault current that the PD phase relay and the PD ground relay see, respectively, I_S is the fault current coming from the grid side, I_{uPD} is the fault current contributed by all PVs upstream of the PD, I_{PDf} is the fault current contributed by all PVs between the PD and the fault location, and I_{fd} is the fault current contributed by all PVs downstream of the PD. The superscripts +,-, and 0 indicate the sequence component values of the currents and the 'C's are the coefficients which depend on the fault resistance, R_f, as described below [9]:

$$C_{uPD} \propto \frac{k}{h+R_f}, \quad C_{PDf}, C_{fd} \propto \frac{k+R_f}{h+R_f}, \quad C^0_{PDf}, C^0_{fd} \propto \frac{k+3R_f}{h+3R_f}$$

$$C^+_{uPD}, C^-_{uPD}, C^0_{uPD}, C^+_{PDf}, C^-_{PDf}, C^+_{fd}, C^-_{fd} \propto \frac{k}{h+3R_f} \tag{3}$$

where k and h are constants determined by the impedances of the distribution feeders.

Note that in our general case (figure 2), for PD_1, I_{uPD}, I_{PDf}, and I_{fd} are I_1, I_2, and I_3, respectively, and for PD_2, I_{uPD}, I_{PDf}, and I_{fd} are I_1+I_2, 0, and I_3, respectively.

Equations 1 to 3 indicate that for both three-phase and single-phase faults:

1) *Low resistance faults:* The PVs do not considerably affect the PD operation as, for such faults, I_S is much higher than the PVs limited current contributions, I_{uPD}, I_{PDf}, and I_{fd} (As discussed in section II).

2) *High resistance faults:* The PVs upstream of the PD, I_{uPD}, do not considerably affect the PD operation as the corresponding coefficients, C_{uPD}, C^+_{uPD}, C^-_{uPD}, C^0_{uPD}, are inversely related to R_f. However, as the equation 3 indicates, the coefficients corresponding to the PVs downstream of the PD, C_{PDf}, C_{fd}, C^0_{PDf}, C^0_{fd}, contain R_f in both numerators and denominators which imply that current contributions by such PVs, I_{PDf}, I_{fd}, become relatively noticeable as I_S is low for high resistance faults.

In the next sections, the above-mentioned conclusions will be used to analyze the impact of each group of PVs, shown in figure 2, on the coordination between PD_1 and PD_2.

B. Impact of PVs Downstream of PD_2 on the Coordination

As discussed in the previous section, for low resistance fault, the PVs do not have considerable effect on the PD operation. This is also shown on figure 3 where the PDs' operating points remain still when the fault resistance, R_f, is close to zero.

However, for high fault resistances, PVs located downstream of PD_2 reduce the fault currents measured by both PD_1 and PD_2, leading to an increase in the trip times of both PDs. As shown in figure 3, the time difference between the

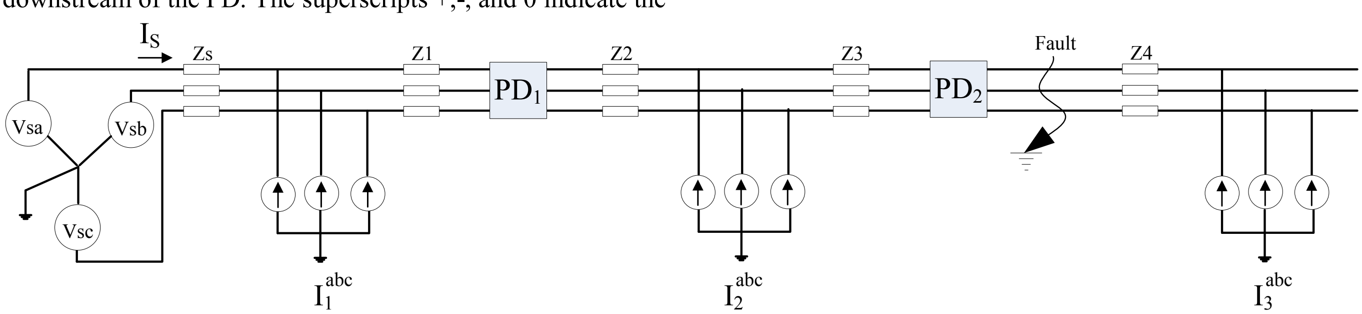

Fig. 2. A generic three-phase case showing the PVs in different locations.

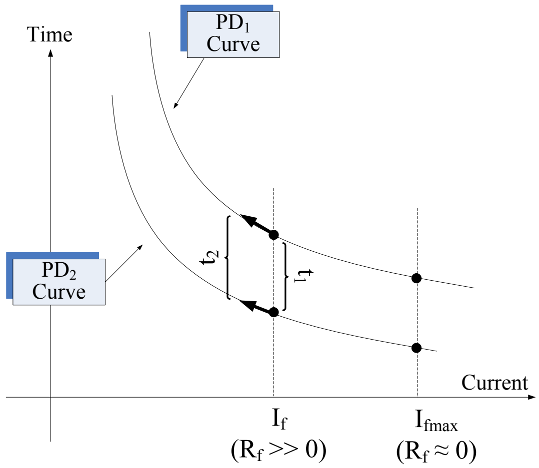

Fig. 3. Impact of PVs downstream of PD_2 on the coordination.

PDs trip times increases from t_1 to t_2. Note that the curve scale is logarithmic so t_2 is bigger than t_1. This means that not only this group of PVs does not hinder the coordination, but also it improves the coordination by increasing the time difference between the PDs trip times.

C. *Impact of PVs Between PD_1 and PD_2 on the Coordination*

As discussed, the operating points of PDs remain still for low resistance faults.

However, as shown in figure 4, this group of PVs reduces the fault current measured by PD_1 leading to an increase in PD_1 trip time, but it does not have considerable effect on the operating point of PD_2. This is because the PVs between PD_1 and PD_2 are located downstream of PD_1 but upstream of PD_2. As concluded before, the PVs upstream of a PD do not affect the operating point of the PD considerably, however they increase the PD trip time if they are located downstream of the PD. This indicates that this group of PVs improves the coordination by increasing the difference between PDs trip times from t_1 to t_2.

D. *Impact of PVs Upstream of PD_1 on the Coordination*

As shown in figure 5, this group of PVs does not have considerable effect on the operating points of both PDs even

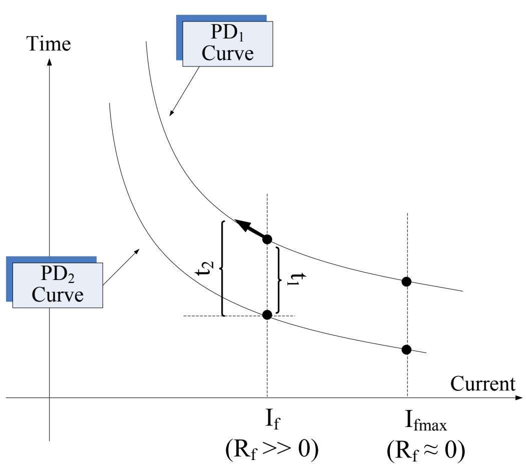

Fig. 4. Impact of PVs between PD_1 and PD_2 on the coordination.

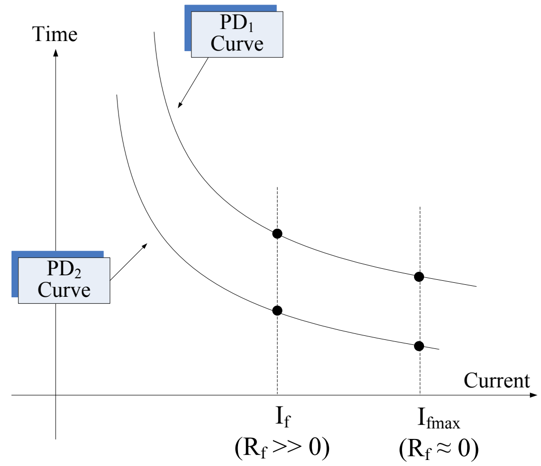

Fig. 5. Impact of PVs upstream of PD_1 on the coordination.

for high resistance faults. This is because they are located upstream of both PDs. Therefore, this group of PVs does not affect the coordination.

E. *One Exception*

As discussed in the previous sections, the PVs either improve the coordination by increasing the time difference between the PDs trip times or do not affect it considerably.

However there is one exception to this conclusion and that happens when a high resistance single-phase fault occurs at the end of a long feeder where the feeder voltage becomes relatively low for high resistance faults. In this case, most of the PVs on the faulty phase shut down (due to their voltage-based self protection – discussed in section II) <u>before</u> the PD ground relay trips, while the PVs on the other phases are operating normally. This PV unbalance, located downstream of the PD, generates a negative zero sequence current which, according to equation 2, increases the zero sequence current that the PD ground relay measures which, in turn, leads to a reduction in the PD trip time. As shown in figure 6, this reduction may be more significant for PD_1 than for PD_2, as PD_1 is located upstream of PD_2 and therefore sees a larger PV unbalance. Hence the time difference between the PDs trip times decreases from t_1 to t_2. Note that, as indicated in the

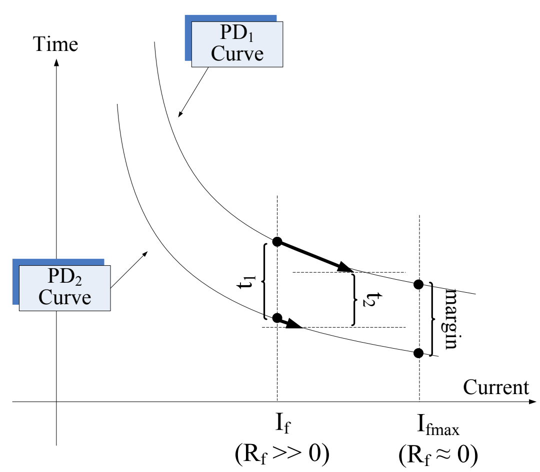

Fig. 6. Impact of PVs downstream of PD_1 and PD_2 on the coordination, while a high resistance single-phase fault occurs at the end of a long feeder.

figure, t_2 may become even less than the margin required for preserving the coordination.

IV. Numerical Assessment of PV Penetration Impact on Coordination between Overcurrent Relays

A. Basics

In conventional distribution feeders, the coordination between overcurrent relays is evaluated by comparing the relays trip times versus the fault current flowing through them simultaneously. This is typically done on the relays time-current curves [10]. However, as discussed in the previous sections, the time-current curves of the relays, utilized in the PV-dominated distribution feeders, do not correctly provide the trip times, as the PVs contribution to the fault current make the currents, flowing through the PDs, different from each other also from the fault current at the fault location.

Hence a new short-circuit analysis has to be performed on such feeders to calculate the correct currents of the PDs during a fault. Fault current profile on a PV-dominated distribution feeder is rather different than a conventional feeder: first because of the PVs contribution, and second because of the varying nature of the fault current due to PVs disconnecting at different times caused by their voltage-based self protection. As the conventional short-circuit analysis methods are inadequate to analyze the fault current in such feeders, a new approach proposed in [11] will be used in this study. Figure 7 shows the approach. Since, PV current depends on its terminal voltage, an iterative procedure is used to obtain the solution, as the figure illustrates. The response of the PV protection is emulated in each iteration in order to determine the PVs that will be disconnected by their protection system, and how long it will take for the protection system to disconnect them. This loop is repeated until the PV protection does not disconnect any more PV.

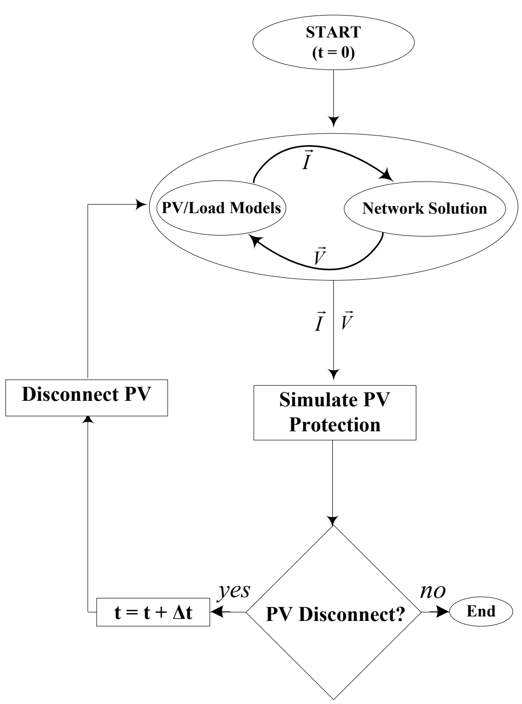

Fig. 7. Short-circuit analysis method for a PV-dominated distribution feeder.

Also, since the fault current varies in such feeders, it becomes more challenging to estimate the time taken for an overcurrent relay, which will see this fault, to trip. Therefore a method has been developed for this purpose in [11] that will be used in this paper. Figure 8 shows the method for estimating the trip time of an overcurrent relay while the fault current changes n times from I_1 to I_n at t_1 to t_{n-1}.

In order to assess the coordination in PV-dominated feeders, a new time-current curve, showing the trip times versus the fault current at the fault location, for each PD relay has to be obtained by using the above-mentioned methods for short-circuit analysis and trip time estimation of overcurrent relays. Details will be discussed in the next section.

B. Assessment of Coordination

As discussed in section III, the PVs either improve the coordination or do not affect it considerably except for high resistance single-phase fault, occurring at the end of long feeder, that the PVs may hinder the coordination. Therefore, the new time-current curves have to be obtained for:

1) *Single-phase and three-phase faults occurring at the beginning of the protection zone of the downstream PD:* These two sets of curves show how much the PVs improve the coordination.

2) *Single-phase fault occurring at the end of the protection zone of the downstream PD:* This set of curves shows if the PVs hinder the coordination.

Note that these curves show the trip time of the PD relay versus the fault current at the fault location while the conventional relay time-current curves show the trip time of the PD relay versus the fault current flowing through the own PD. The conventional curves cannot be used to assess the coordination in PV-dominated feeders as, due to the PVs contributions, the fault currents flowing through the PDs are different from the fault current at the fault location in such feeders.

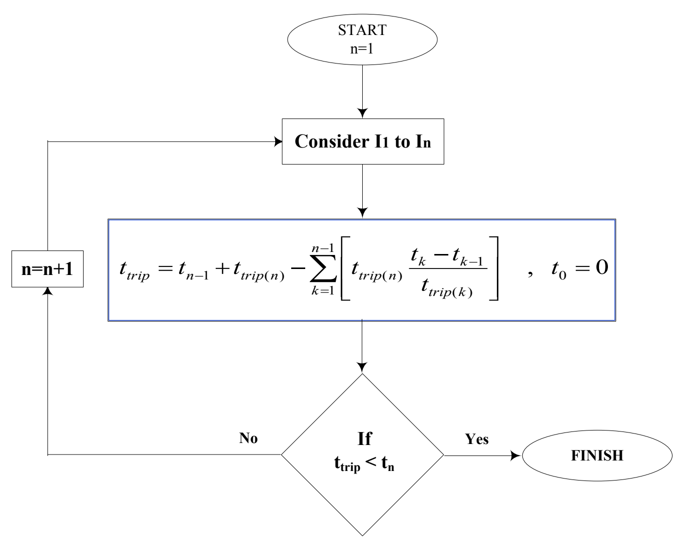

Fig. 8. Trip time estimation for an overcurrent relay in a PV-dominated distribution feeder.

To evaluate the performance of the proposed method on a PV-dominated feeder, an actual 22 kV distribution system serving mostly residential loads in a suburb of Raleigh NC is considered as the test case in this study. The feeder has three-phase primary with several single-phase underground cables tapped off from the main circuit to feed the customers within the same neighborhood. For this study, this system is simulated using PSCAD in order to get detailed time domain simulations and to use them for comparison with the proposed method. Since it was not practical to include all the loads and PV systems individually in the simulation, the loads and the PV systems on the single-phase laterals served off the main line sections have been aggregated as one lumped load and PV system as shown in figure 9. Hence, the simulated system is a three phase circuit with unbalanced loads and PVs represented on a phase basis.

Figures 10 and 11 show how the PV penetration affects the coordination between the breaker (CB1) and the recloser (RCL1) of the test feeder for phase and ground relays, respectively. As shown in the figures, the PVs do not have considerable effect when the fault current is high (the fault resistance is low). However as the fault current decreases (the fault resistance increases), the PVs increase the trip times of both breaker and the recloser and also the time difference between them, hence the coordination improves. Note that these time-current trajectories do not follow the original ones. This is because any change in the fault resistance impacts the nodes voltages which, in turn, affect the current contribution from each PV and the time period it remains online after the fault occurrence.

The figures compare the results from the proposed method with the results obtained from PSCAD simulations. These results show that the proposed method estimates are very close to the ones from simulations.

To check if the coordination between the ground relays is preserved at the end of the feeder (as discussed in section III.E), the new time-current curves of the ground relays of the breaker and the recloser have been obtained and verified by PSCAD simulations, as illustrated in figure 12. As shown in the figure, the time difference between the trip times of the breaker and the relcoser becomes as low as 0.125s which is much lower than the margin, 0.4s, required for preserving the coordination. Note that this reduction in coordination time occurs only for high resistance faults.

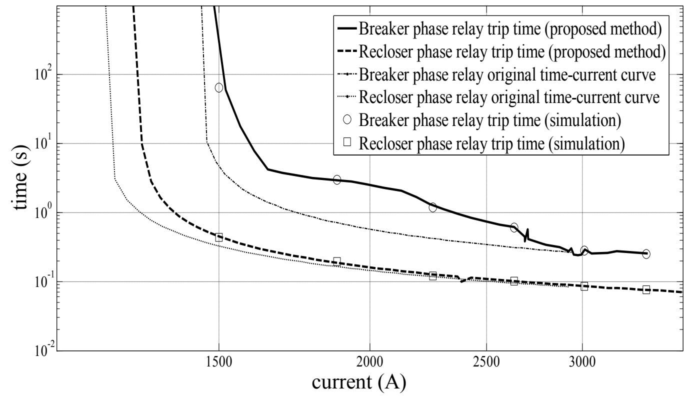

Fig. 10. Breaker and recloser trip times versus the fault current, for a three-phase fault occurring at node 3, in the test feeder.

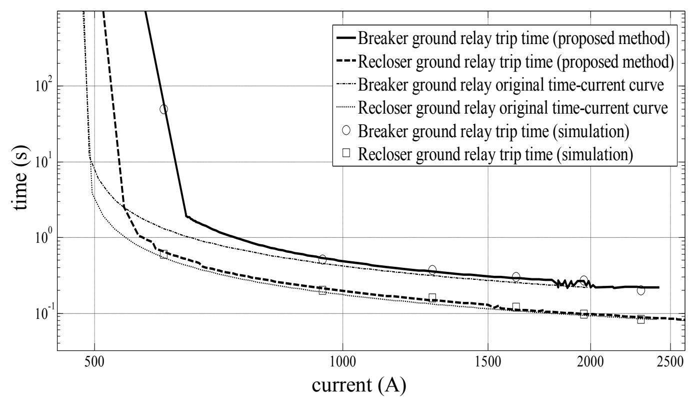

Fig. 11. Breaker and recloser trip times versus the fault current, for a single-phase fault occurring at node 3, in the test feeder.

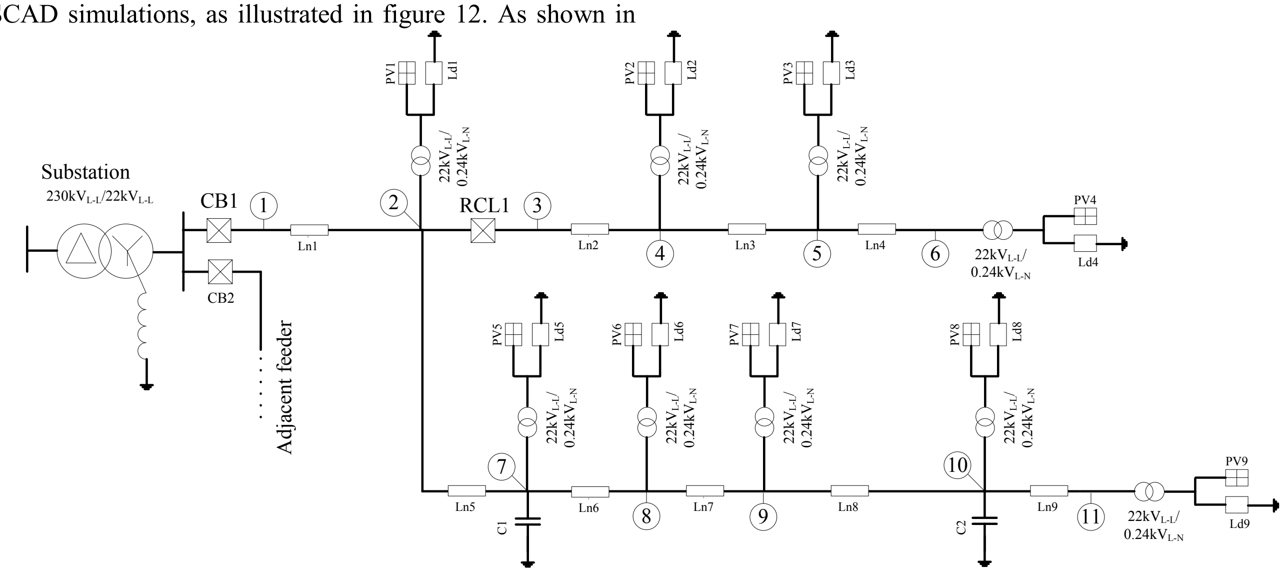

Fig. 9. Test feeder - a sample PV-dominated feeder (circles indicate the node numbers).

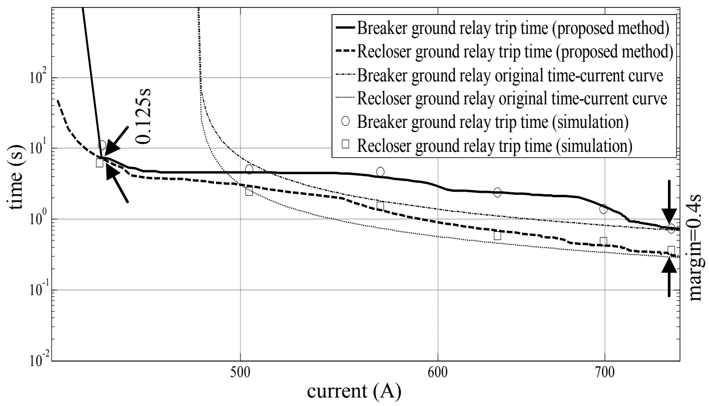

Fig. 12. Breaker and recloser trip times versus the fault current, for a single-phase fault occurring at node 6, in the test feeder.

V. CONCLUSION

This paper showed that how and under what conditions the coordination between overcurrent relays in a PV-dominated distribution feeder is affected by the PV systems. The presence of PVs improves the coordination except for long feeders where mis-coordination may happen between the overcurrent ground relays for high resistance faults occurring at remote points.

The paper proposed a new method that extends the conventional time-current curves and provides an assessment of the coordination for PV-dominated distribution feeders. The simulation based test results indicate that the method provides quite accurate results.

Given that PV penetration on distribution level will increase in near future, the proposed method is much needed tool for a practicing engineer in assessing the impact of PV penetration on system protection and developing mitigating strategies, such as revising relay settings for relay coordination.

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