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Disconnection of Single-Phase Rooftop PVs after Short-Circuit Faults in Residential Feeders

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Abstract—This paper presents an analysis on the disconnection time of single-phase rooftop photovoltaic systems (PVs), located in a three-phase four-wire low voltage distribution feeder, after a single-phase and a three-phase short-circuit fault on the low voltage feeder. The paper aims to evaluate and discuss the disconnection time and disconnection sequence of PVs in a network with 100% PV penetration level to evaluate the islanding issues that are related to the safety of people and the damage of electrical apparatus. The impact of different parameters such as the location of the fault, impedance of the fault and the ratio of PVs generation capacity to the load demand are contemplated in the analysis. Furthermore, the influence of the network earthing in the form of multiple earthed neutral and non-effectively grounded systems are evaluated on the PVs disconnection time. This research intends to figure out the conditions under which the PVs in the feeder may fail to disconnect after a single-phase or three-phase fault and continue to feed the fault.

Index Terms—Distribution network, Rooftop PVs, Short-circuit faults, PV disconnection time, Voltage profile.

1. Introduction

During the last decade, a vast effort has been made towards the expansion and increase in the penetration level of distributed generation units within the electric distribution networks. Single-phase rooftop photovoltaics systems (PVs) are the most commonly utilized type of distributed generation that are installed in distribution networks of many countries. As an example, in the last 6 years, over one million rooftop PVs have been installed in Australia of which over 90% is single-phase PVs in the residential premises [1]. However, the increasing penetration level of these units in low voltage (LV) distribution networks has imposed several technical problems such voltage rise issues [2, 3] and power quality problems [4, 5]. The technical and economic impacts of imposed over-voltages by rooftop PVs in PV dominated distribution feeders is assessed in [2-5] and several improvement techniques are proposed in [6] to mitigate or minimize these problems. Furthermore, the sudden variations of voltage in PV dominated feeders, as the result of clouding, has been studied in [7] where some improvement methods are proposed in [8] to overcome rapid voltage fluctuations.

In addition to voltage rise and fluctuation and power quality problems, the utilities worldwide are concerned with the influence of high penetration of rooftop PVs on the mis-coordination among the protective devices in those networks [9-13]. As an example, reference [14] has discussed the protection problems related to the high penetration of rooftop PVs in distribution networks. For medium voltage (MV) networks with high penetration of rooftop PVs in their LV feeders, reference [15] proposes a new technique to define and update the settings of the network protective devices to maintain a proper coordination among them. In addition, reference [16] proposes a new technique based on current phase comparison at different points along MV feeders to detect the contribution of rooftop PVs on the short circuit faults.

The above references have focused on the impact of rooftop PVs on MV feeders but have not discussed the effects of PVs on the LV feeders to which they are connected. In addition, they have not examined the distribution of PVs along the LV feeder neither the different nominal ratings of the PVs.

These points need to be considered in protection-related studies of networks with high penetration of PVs.

On the other hand, the utilities try to minimize the possible negative outcomes of rooftop PVs by limiting their penetration in the networks. As an example, majority of electrical utilities in Australia, have developed a 25 or 30% maximum penetration limit for the single-phase rooftop PVs in each LV feeder [17, 19] because of harmonic saturation, voltage rise, reverse power flow and protection issues. This limit prevents newer householders to install rooftop PVs. From protection side, the utilities are worried that due to high penetration of rooftop PVs, there is a possibility that the rooftop PVs will not allow the voltage along the feeder to drop during short-circuit faults, resulting in the continuous supply of the fault through the rooftop PVs, even if the upstream circuit breakers have operated. It is stated in [18] that one important issue to be investigated about the networks with rooftop PVs is that whether it is possible for some PVs to continue to supply power to the feeder when the upstream network is lost, particularly in a situation where there are many PV systems on the feeder. The report states that such an issue should not occur due to design requirements of PV systems but it is still an issue to be discussed and investigated. This is the research gap that this paper focuses on.

To facilitate higher penetration of single-phase rooftop PVs in electric networks, the protection issues of these networks should be evaluated in more details. In this regard, this paper concentrates on the LV feeders to which the single-phase rooftop PVs are connected. The voltage profile along the feeder after a short-circuit fault in the LV feeder is analysed carefully. Within this period, the disconnection time and disconnection sequence of the rooftop PVs are also scrutinized. Several parameters such as the impedance of fault (IoF), location of fault (LoF) and PV generation capacity to residential load demand ratio (GDR) are contemplated within the studies. The voltages of nodes along the feeder are observed during the first few cycles after fault-occurrence on the LV feeders. Another aim of this research is to compare the footprint of network earthing on the disconnection time of PVs. The paper will present a comparison on the voltage profile along the feeder in multiple earthed neutral (MEN) [18] and non-effectively grounded (NEG) [20] systems after a short-circuit fault. The single-

phase (1Φ) faults, which are the most common type of faults in distribution networks [21] as well as three-phase (3Φ) faults are considered in the analyses of this paper. The open-conductor fault is also briefly discussed. The main contributions of this research are:

- to evaluate and discuss the disconnection time and sequence of single-phase rooftop PVs distributed in different phases during 1Φ and 3Φ faults,
- to investigate the importance of IoF and LoF on the disconnection time of rooftop PVs after a 1Φ and 3Φ faults,
- to investigate the correlation between the disconnection time of PVs and a high GDR under short-circuit scenarios,
- to compare the consequence of NEG and MEN systems on the disconnection time of rooftop PVs in an LV feeder with 100% penetration of rooftop PVs,
- to define the conditions under which rooftop PVs may not be disconnected after a 1Φ or 3Φ fault in LV feeders.

The rest of the paper is organized as follows: Section II introduces the network under consideration. The research methodology is discussed in Section III and the results of the analyses are presented in Section IV and V. Section VI presents a discussion on the findings of the research. The general conclusions of the paper are highlighted in the last section.

2. Network under Consideration

Let us consider the network of Figure 1 which schematically represents a typical Australian urban LV distribution network, used for supplying residential loads. This network is selected as the study case in this research. It is assumed that a three-phase, three-wire MV feeder supplies a three-phase, four-wire LV feeder through a three-phase Dyn distribution transformer [22]. The residential houses are assumed to be single-phase loads, connected to the LV feeder. The considered network in this paper is composed of 30 houses, equally distributed among the three phases. In this research, to

consider a worst case scenario, it is assumed that the penetration of single-phase rooftop PVs is 100%. It is to be noted that the PV penetration level is defined as the ratio of the output AC power of the PV systems versus the network peak load [23]. A similar network is used by majority of the European and Asian utilities to supply the urban residential loads. It is to be noted that this network is different from the networks of North American countries [24]. The new and properly designed LV feeders are in the form of MEN type where the neutral wire is earthed at the secondary of the distribution transformer as well as at the premises of each load [25], as seen from Figure 2(a). However, old LV feeders or LV feeders developed without proper engineering supervisions may be in the form of an NEG system. Thus, the neutral wire in the LV feeder is assumed to be grounded only at the distribution transformer but not at every residential load premises, as seen from Figure 2(b), when considering an NEG system; while it is also grounded at each residential premises (through an earthing resistance) when considering an MEN system.

The rooftop PVs are assumed as constant single-phase power sources, operating at unity power factor, based on IEEE Recommended Practice for Utility Interface of PV Systems [26]. Furthermore, the maximum current output of the PVs are limited to 150% of the nominal value [27], during the faults. Each PV is assumed to be 4.4 kW, which is approximately the median of the most common rooftop PVs sizes in Perth, Western Australia [28]. In addition, in this research it is assumed that the protection system of the PV systems are based on under/over voltage scheme, as highlighted in the datasheet of PV systems that are commercially available in Australian market [27, 29-30].

The loads of the network are assumed as single-phase constant impedance type, distributed equally among the phases. Each load is assumed to be 4.4 kVA with a power factor of 0.95 lagging, which is equal to the after diversity maximum demand (ADMD) of townhouses and villas in Perth, Western Australia [31].

It is to be noted that the considered LV feeder is composed of 30 houses and is supplied by a 150 kVA distribution transformer. Three houses are assumed to be supplied from each pole, where the poles are located with a distance of 40 meters from each other.

3. PV Disconnection after a Fault and Effectual Parameters

PV systems should isolate from the LV feeders if a short-circuit fault occurs in the network. If they are not isolated, the LV feeder may remain energized by the PV systems, even if the upstream circuit breaker has operated. Under such a scenario, if the output power of the PV systems is potentially equal to or greater than the minimum load of the network, a risk of islanding exists; although no national or international records are available on that based on [13]. Islanding can lead to the damage of the electrical equipment and hazards for the utility personnel. Although this can be a rare situation but proper protection schemes should be utilized to prevent such cases. IEEE Recommended Practice for Utility Interface of PV Systems [26] defines the normal operating voltage boundaries for the rooftop PVs of smaller than 10 kW. Based on [26], the rooftop PVs should be isolated and disconnected from the LV feeder and do not energize it, if the voltage of the feeder drops below 88% of the nominal value. In a similar fashion, the PVs should also get isolated if the voltage of the feeder rises above 110% of the nominal value. This standard also highlights that the PV systems should disconnect if frequency variations are observed in the LV feeder. Australian standard on grid connection of energy systems via inverters [32] provides a similar guideline for the disconnection of PV systems in case of abnormal voltage and frequency deviations in the network. The maximum allowed time for disconnection of the PVs depends on the level of the voltage drop, as given in Table 1 for both of these standards. In the rest of this research, the levels defined by [26] are considered only.

Table 1. Maximum disconnection time of rooftop PV in response to feeder abnormal voltages [26, 32]

IEEE Recommendation (IEEE Std 929-2000)		Australian Standard (AS4777-2013)	
Condition (%)	Maximum tripping time (cycle)	Condition (%)	Maximum tripping time (cycle)
$50\% < V < 88\%$ or $110\% < V < 137\%$	120	$V < 78\%$ or $V > 113\%$	100
$V < 50\%$	6		
$V > 137\%$	2		
$59.3 < f < 60.5 \text{ Hz}$		$47.5 < f < 52 \text{ Hz}$	100

Figure 3. Schematic internal structure of a rooftop single-phase PV system.

Table 2. Protection functions available in some of the PV systems in Australia [27, 29-30, 33]

Protection Function	Schneider (Clipsal)	ABB (PVS300)	C1energy Catalyst (SPH40)	EATON (SG00210)
Overcurrent (Overload, Short-circuit)	✓	✓	✓	✓
Under/over voltage	✓	✗	✓	✓
Reverse current	✓	✗	✓	✗
Over temperature	✗	✓	✗	✗
Deep discharge	✗	✗	✓	✗

Figure 3 illustrates schematically the internal structure of a typical single-phase rooftop PV system that are available in Australian market [30]. These PV systems are usually equipped with different types of protection functions such as surge protection, overvoltage protection, deep discharge protection, reverse current protection and short circuit protection of the module and overcurrent and over temperature protection for their PV array and dc sides. On the other hand, they are required to be equipped with techniques to prevent islanding in the LV feeders. Thus, the PV systems usually have passive anti-islanding protection functions such as under/over voltage, under/over frequency, rate of change of frequency, voltage phase jump and harmonics [34]. Among these, under/over voltage and under/over frequency are the most common protection functions for the PV systems that are commercially available in Australian market [27, 29-30, 33]. Table 2 illustrates a comparison among the available protection functions of different PV systems that are available in Australian market. On top of the passive anti-islanding protection functions, active islanding protection functions such as

frequency shift, frequency instability, power variation, negative sequence current or impedance monitoring can also be utilized [33].

On the other hand, PV systems are usually equipped with low voltage ride through (LVRT) capability [35-36], based on which the PV systems continue to supply power if the voltage in the LV feeder drops below the nominal value, especially in case of temporary short-circuit faults. It is been cited in [36] that a delay time of 0.2 or 0.5 second is used to avoid unnecessary disconnection of the PV systems in such cases in the grid codes of different countries. If the fault is not cleared and the voltage drop is not recovered within this period, the PV system then disconnects from the LV feeder.

It is expected that following a 1Φ short-circuit fault in the LV feeder, the voltage along the feeder in the faulty-phase will drop quickly while the voltage in the other (healthy) phases will rise. The level of voltage drop in the faulty phase mainly depends on the fault impedance. The present-day concern of utilities is that the high PV generation to load demand ratio, network earthing as well as the fault impedance and location may cause the voltage drop not to be below 88% of the nominal voltage. If it happens so, the rooftop PVs will not detect any abnormal voltage in the feeder and will not disconnect. This will allow the PVs to continue to feed the fault. Under such scenarios, the voltage in the healthy phases may also not rise above the threshold of 110%; hence the PVs on the healthy phase(s) may continue to supply the fault via the distribution transformer. The above-mentioned scenario will continue until the upstream circuit breaker, which is usually controlled by an inverse definite minimum time (IDMT) over current relay, trips. After circuit breaker tripping, the voltages in both faulty and healthy phases will significantly drop, leading to the disconnection of the PVs that are still connected. It is worth mentioning that there is a possibility that the fault current to be very small, resulting in being non-detectable with normal overcurrent relays. Thus, the fault will continue to be fed by the upstream network and PVs. These scenarios and situations will be investigated in Sections IV.

In case of 3Φ faults, it is expected that all three phases show a similar trend to the faulty phase of the feeder under 1Φ fault. This scenario and the PVs disconnection following a 3Φ fault are investigated in Section V.

It is to be noted that although recently developed LV feeders are usually in the form of MEN, the old LV feeders may be NEG. Each of these earthing systems, might have a strong footprint on the voltage profile along the feeder, during 1 Φ or 3 Φ short-circuit faults.

To understand the network situation during a 1 Φ or 3 Φ short-circuit fault, this research considers the network of Figure 1 and evaluates the voltage along the feeder and the disconnection time of the PVs based on the following 4 parameters:

- PV generation capacity to load demand ratio (GDR),
- impedance of fault (IoF),
- location of fault (LoF) along the feeder,
- network earthing system.

Several simulation study cases are developed and examined in PSCAD/EMTDC to evaluate the network performance, a few of which provided in Sections IV and V. To analyse each parameter, the selected cases are re-examined assuming the other parameters as constant and the results (i.e. the voltage along the feeder following a 1 Φ or 3 Φ short-circuit fault as well as the disconnection time and sequence of the PVs) are recorded. At the end, the results are tabulated and evaluated.

4. Disconnection of PVs during Single-Phase Faults

This section focuses on the disconnection time and sequence of single-phase rooftop PVs after a 1 Φ short-circuit fault in the LV feeder.

Let us consider the network of Figure 1 with the GDR of unity. A 1 Φ short-circuit fault is applied at the middle of the feeder (i.e. LoF = node 5 can a range from 1 to 10) on phase-a where the IoF is assumed to be (e.g. IoF = 2 Ω). The disconnection time of the PVs depends on the time that the voltage of their point of common coupling (PCC) drops below 88% or rises above 110% of the nominal voltage. Assuming the network at steady-state condition, the fault occurs at $t = 0$. The voltages of the faulty phase drop below 88% of the nominal value immediately; hence, all of the PVs within phase-a

disconnect simultaneously at $t = 0.0048$ s. Immediately after fault-occurrence, the voltages of the healthy phases increase. As an example, in the considered study, the voltage of node 1 in phase-b and nodes 1-4 in phase-c increase above 110% of their nominal value at $t = 0.0060$ and 0.0075 s; thereby the PVs connected to these nodes disconnect at these times. The rest of the PVs connected to phase-b and c disconnect in the same fashion before 0.0137 . Thus, all PVs disconnect in less than a cycle after fault-occurrence. It is to be noted that no LVRT was considered in this analysis. However, if the PVs have the LVRT feature, the PVs will disconnect in one cycle after the delay time of the LVRT (i.e. 0.2 or 0.5 s based on the grid codes of different countries [36]). The upstream circuit breaker, which has an extremely inverse characteristic and a time multiplier setting (TMS) of 0.02 opens at $t = 1.306$ s. The schematic disconnection time of the PVs for the considered study case is shown in Figure 4. This network is now analysed in detail considering different IoFs, LoFs and GDRs, as discussed below:

Figure 4. Disconnection time and sequence of PVs and upstream circuit breaker after a 1 Φ fault.

4.1. Impact of Impedance of Fault

Let us consider the network of Figure 1 with the GDR of unity. A 1Φ short-circuit fault is applied at the middle of phase-a (i.e. LoF = node 5). In this study, the IoF is varied from a very small (e.g. 0.002 and 0.2 Ω) to small (e.g. 1 and 2 Ω) and high (e.g. 20 Ω) values. The voltage profile along the feeder between fault-occurrence and the disconnection time of PVs or the opening time of the upstream circuit breaker is shown in Figure 5. The results are recorded for the MEN and NEG systems, separately. The left hand graphs of Figure 5 show the voltages in an NEG system while the right hand graphs show the voltages in an MEN system. From this figure, it can be seen that the voltage of all nodes of the faulty phase drop below the limit of 88% for all IoFs except IoF = 20 Ω . Hence, all of the PVs in the faulty phase disconnect after fault-occurrence. This is valid for both MEN and NEG systems; however, the voltages of the NEG system remain slightly higher than those for the MEN system. This figure also shows that for high impedances IoFs (e.g. 20 Ω) in the MEN system, the voltage of the healthy phases (phase-b and c in this case) rest within the normal operation bandwidth of 88% to 110%; Thus, the PVs connected to the healthy phases will not disconnect and will continue to feed the fault. This is true for the IoFs larger than 1 Ω in the NEG system. In case of high impedance 1Φ short-circuit faults (e.g. 20 Ω), the PVs in both healthy and faulty phases remain connected to the LV feeder and keep feeding the fault until the upstream circuit breaker trips.

It is worth mentioning that the voltages shown in Figure 5 are recorded at one specific moment (i.e. between fault-occurrence and the first disconnection time of PVs or the upstream circuit breaker). Thus, this figure does not illustrate the voltages after the disconnection of the first set(s) of PVs. Thereby, even if the voltages of some nodes is within the nominal bandwidth of 88% to 110% in Figure 5, their voltages may exit this bandwidth after the disconnection of the other PVs. Hence, the disconnection time and sequence of the PVs should also be studied. Comprehend

To study the disconnection time of PVs and their sequence in presence of different IoFs, the recorded results are represented in radar charts of Figure 6. In this type of charts, the radius of circles

represent the disconnection time while the numbers around the circles refer to the node numbers. It is to be noted that the considered LV feeders are radial, as illustrated in Figure 1(b) and the circular alignment of the nodes should not be interpreted as a loop topology. The top row of this figure represents the NEG system while the bottom row represents the MEN system. It can be seen from this figure that the PVs connected to both healthy and faulty phases do not sense the fault and do not disconnect when the IoF is higher than 2Ω for both MEN and NEG systems. The radar charts of Figure 6 also show that for each IoF, all of the PVs in one phase operate at the same time roughly (i.e. in less than half a cycle difference). The disconnection time increases as the IoF becomes larger. This figure also shows that for the MEN system, the disconnection time is almost same for both faulty and healthy phases. It is noteworthy that this time is larger for the NEG system versus the MEN system.

4.2. Impact of Location of Fault

To investigate the influence of the LoF on the voltage profile along the feeder and also the disconnection time and sequence of the rooftop PVs, the previous evaluation is repeated (i.e. a short-circuit fault is applied on phase-a where the GDR is unity) assuming that the IoF is very small (i.e. $2 \text{ m}\Omega$) while the LoF is varied from the beginning of the feeder towards its end. In the rest of this paper, LoF = 1, 5 and 10 respectively represents the fault at the beginning (i.e. node-1), middle (i.e. node-5) and the end (i.e. node-10) of the LV feeder.

The voltage profile along the feeder in this case is shown in Figure 6. This figure shows that for all cases of LoF = 1, 5 and 10, the voltage of the nodes in the faulty phase are very close to each other and all are lower than 20% of the nominal value in the MEN and less than 40% of the nominal value in the NEG system. Hence, it is expected that the PVs within the faulty phase will disconnect regardless of the fault location along the feeder. Following fault-occurrence, the voltages of the nodes in the healthy phases rise above the threshold of 110% and thus their PVs will also disconnect.

Figure 5. Voltage profile along the feeder during 1Φ fault between fault-occurrence and the PV/upstream circuit breaker tripping for different IoFs.

Figure 6. Disconnection time and sequence of PVs after 1Φ fault for different IoFs.

An interesting issue can be observed in the results of the NEG system. As it can be seen from Figure 7, the voltage of some of the nodes in phase-b in the NEG system do not rise above the 110% threshold even for a very small IoF of 2 m Ω . Thus, the PVs connected to the middle and end nodes of this phase will not be disconnected under such conditions. The situation will be even worse when the IoF is larger. Figure 8 presents the disconnection time of the PVs in radar charts. This figure shows that all of the PVs in both healthy and faulty phase disconnect almost at the same time (i.e. within few millisecond differences but within the same cycle) and this time is not affected strongly with the LoF. This is valid for both of the MEN and NEG systems.

4.3. Impact of Generation to Demand Ratio

To analyse the importance of the GDR on the voltage profile along the feeder as well as the disconnection time and sequence of the rooftop PVs, the previous study is repeated (i.e a short-circuit fault is applied on phase-a with IoF = 2 m Ω and LoF = 5) where the GDR is varied from 50% to 200% in steps of 50.

The voltage profile along the feeder for this case is shown in Figure 9. This figure shows that for all different considered GDRs, the voltages of all nodes in the faulty phase are very close to each other and all are lower than 10% of the nominal value in the MEN and less than 25% of the nominal value in the NEG system. Hence, it is expected that the PVs within the faulty phase will disconnect regardless of the GDR level. Following fault-occurrence, the voltages of the nodes in the healthy phases rise above the threshold of 110%. These voltages are also very close to each other and the PVs connected to these nodes will disconnect.

Figure 10 presents the disconnection time of the PVs in radar charts. It is seen from this figure that as the GDR level increases, the disconnection time of the PVs connected to the healthy phases reduces. This is valid for both of the MEN and NEG systems. The disconnection time of the PVs connected to the faulty phase does not illustrate a specific trend as the GDR level varies; however, all of the PVs disconnect in less than a cycle after fault-occurrence.

Figure 7. Voltage profile along the feeder during 1Φ fault between fault-occurrence and the PV/upstream circuit breaker tripping for different LoFs.

Figure 8. Disconnection time and sequence of PVs after 1Φ fault for different LoFs.

Figure 9. Voltage profile along the feeder during 1 Φ fault between fault-occurrence and the PV/upstream circuit breaker tripping for different GDRs.

Figure 10. Disconnection time and sequence of PVs after a 1 Φ fault for different GDRs.

5. Disconnection of PVs during Three-Phase Faults

This section focuses on the disconnection time and sequence of single-phase rooftop PVs after a 3 Φ fault in the network. Let us consider the network of Figure 1 with the GDR of unity. A 3 Φ short-circuit fault is applied at LoF = 5 with an IoF = 2 m Ω . The disconnection time of the PVs depends on the time that the voltage of their PCC drops below 88% of the nominal voltage. Immediately after fault-occurrence, the voltages of all nodes along all phases drop below 88% of the nominal value; hence, all of the PVs disconnect almost simultaneously in less than a cycle. The upstream circuit breaker opens within 2 cycles after fault-occurrence. The schematic disconnection time of the PVs in the considered study case are shown in Figure 11.

This network is now analysed in details considering different IoFs, LoFs and GDRs. A study similar to Section IV is repeated for this type of fault, as discussed below:

Figure 11. Disconnection time of PVs and upstream circuit breaker during a 3 Φ fault.

5.1. Impact of Impedance of Fault

Let us consider again the network of Figure 1 with the GDR of unity. A 3Φ short-circuit fault is applied at the middle of the feeder (i.e. $LoF = 5$) where the IoF is varied from 0.002 to 20Ω . The voltage profile along the feeder between fault-occurrence and the disconnection time of PVs or the opening time of the upstream circuit breaker is shown in Figure 11(a). From this figure, it can be seen that the voltage of all nodes in all phases drop below the limit of 88% for all $IoFs$ except $IoF = 20 \Omega$. Hence, all of the PVs in the feeder disconnect after fault-occurrence except the conditions that the IoF is very large. This is valid for both MEN and NEG systems.

To examine the disconnection time of PVs and their sequence in presence of different $IoFs$, the recorded results are represented in the radar chart of Figure 12(a). It can be seen from this figure that none of the PVs disconnect when the IoF is higher than 2Ω . This figure also shows that for each IoF , all PVs in one phase disconnect at the same time roughly (i.e. with almost less than half a cycle difference). Note that Figure 12 illustrates the results for phase-A only but the results are identical for all three phases. It is also worth mentioning that the PVs that are connected to the very first nodes (e.g. node-1 to 2) of the LV feeder may not sense the fault and thus may remain connected even for an $IoF = 2 \Omega$ since their PCC voltage does not drop below the 88% limit (see Figure 11a).

5.2. Impact of Location of Fault

The previous examination is repeated to analyse the significance of the LoF assuming the GDR is unity and $IoF = 2 \text{ m}\Omega$. The LoF is varied from the beginning of the feeder towards its end. The voltage profile along the feeder for this case is shown in Figure 12(b). This figure shows that the voltage of all nodes of the feeder are below the 88% limit for all different $LoFs$. Hence, all of the PVs in the LV feeder disconnect within less than half a cycle after fault-occurrence, as seen from the radar chart of Figure 13(b). This is valid for both MEN and NEG systems.

Figure 12. Voltage profile along the feeder during a 3Φ fault between fault-occurrence and the PV/upstream circuit breaker tripping time for different: (a) IoFs, (b) LoFs, (c) GDRs.

5.3. Impact of Generation to Demand Ratio

To analyse the consequence of the GDR on the voltage profile along the feeder as well as the disconnection time and sequence of the rooftop PVs, the previous work is repeated assuming an IoF of 2 mΩ and LoF = 5 where the GDR is varied from 50% to 200% in steps of 50. The voltage profile along the feeder for this case is shown in Figure 12(c). This figure shows that for all different considered GDRs, the voltage of all feeder nodes fall below the 88% limit and thus all PVs disconnect within less than half a cycle after fault-occurrence, as seen from the radar chart of Figure 13(c). It is to be noted that in this case, the voltage of the nodes is slightly higher for the NEG system, when compared with the MEN system. However, it does not affect the disconnection time of the PVs.

Figure 13. Disconnection time and sequence of PVs during a 3 Φ fault for different:
(a) IoFs, (b) LoFs, (c) GDRs.

6. Extreme Conditions

To expand the studies for extreme conditions, the previously studied cases are re-examined under extreme conditions. The objective of this analysis is to determine whether the PVs will be disconnected even under the extreme conditions.

Section 4.2 shows that when the LoF is at node 10, the results are more extreme than when the LoF is at node 1 and 5. This analysis was conducted with an IoF of 2 m Ω . This case is re-examined when the IoF is increased to 2 Ω . The results of this analysis are illustrated in Fig. 14(a). This figure shows that in such an extreme condition, all PVs disconnect successfully in an MEN system while the PVs that are connected to the end nodes of the healthy phases in an NEG system remain connected until the upstream circuit breaker operates. It is only at this time that those PVs disconnect.

Section 4.3 illustrated that when the GDR is 2, the results are more extreme. This analysis was also conducted with an IoF of $2 \text{ m}\Omega$. This case is re-examined when the IoF is increased to 2Ω . The results of this analysis are illustrated in Fig. 14(b). This figure shows that in such an extreme condition, all PVs disconnect successfully in an MEN system while only the PVs that are connected to the far end nodes of the healthy phases of an NEG system disconnect successfully. Thus, all of the PVs connected to the faulty phase and the beginning and middle nodes of the healthy phases remain connected until the upstream circuit breaker operates, after which they disconnect.

To consider the worst case scenario, another study is carried out which is a combination of all extreme conditions, i.e. the IoF is 2Ω , GDR is 2 and the LoF is at node 10. The results of this case is illustrated in Fig. 14(c). This figure shows that all of the PVs in the MEN system disconnect successfully while almost all of the PVs in the NEG system fail to disconnect until the operation of the upstream circuit breaker.

The case of Section 5.2 is re-analysed when the LoF is at node 10 while the IoF of is increased from $2 \text{ m}\Omega$ to 2Ω . The results of this analysis are illustrated in Fig. 15(a). This figure shows that in both MEN and NEG systems, only the PVs that are connected to the far beginning nodes of the system disconnect successfully and all other PVs remain connected until the upstream circuit breaker operates.

The case of Section 5.3 is also re-analysed when the GDR is 2 and the IoF of is increased from $2 \text{ m}\Omega$ to 2Ω . The results of this analysis are illustrated in Fig. 15(b). This figure shows that in both MEN and NEG systems, none of the PVs in the system disconnect before the operation of the upstream circuit breaker.

Figure 14. Disconnection time and sequence of PVs during a 1 Φ fault for some extreme cases:

(a) LoF extreme case, (b) GDR extreme case, (c) worst case scenario.

Figure 15. Disconnection time and sequence of PVs during a 3 Φ fault for some extreme cases:

(a) LoF extreme case, (b) GDR extreme case.

7. Findings and Discussions

The carried out study demonstrates that following a 1Φ short-circuit fault, all of the PVs that are connected to the faulty phase sense the fault and disconnect in an MEN system since their voltages drop below 88% of the nominal voltage immediately, except the cases with large IoFs (e.g. $\text{IoF} = 20 \Omega$). However, these PVs may fail to disconnect before the operation of the upstream circuit breaker for an $\text{IoF} \geq 2 \Omega$, if the GDR is high (e.g. $\text{GDR} = 2$) or when the fault is at the end of feeder (e.g. $\text{LoF} = 10$).

The results show that except the cases that a 1Φ short-circuit fault is at the beginning nodes of the feeder (e.g. $\text{LoF} = 1$), the level of voltage drop in the MEN systems is much larger than the NEG system. In MEN systems, the PVs of the faulty phase disconnect in less than two cycles after the fault or after the delay time allowed for LVRT, if the fault impedance is small (i.e. less than 2Ω). It was also revealed that the location of the fault, when varied from the beginning of the feeder towards its end as well as the ratio of the generation capacity of PVs versus the load demand, when varied from 50% to 200%, does not have a significant effect on the disconnection of the PVs in MEN systems. However, they have some effects in the NEG systems and lead to unsuccessful disconnection of the PVs. Moreover, it was revealed that there is a possibility for the PVs that are connected to the faulty phase not to disconnect, if the network is NEG or if the IoF is high (e.g. 20Ω).

The conducted analysis also demonstrates that the voltages of all nodes along the healthy phases, in case of a 1Φ short-circuit fault, rise above the nominal voltage immediately after fault-occurrence. The level of voltage rise is higher for the MEN systems compared to the NEG system. Once the voltage magnitude rises above 110% of the nominal voltage, the PVs connected to the healthy phases disconnect. The examinations show that this usually happens in less than a cycle after fault-occurrence or after the delay time allowed for LVRT. For the healthy phases, it was noticed that the fault impedance has a significant effect on the PVs disconnection. As an example, the results revealed that for fault impedances larger than 2Ω for the MEN system and larger than 0.2Ω for the NEG system,

the voltage profile along the healthy phases does not rise above 110%. In addition, it is revealed that the location of the fault and the ratio of PVs generation to load demand do not have a strong effect on the disconnection of PVs in MEN systems.

It is to be reminded that the analysis carried out in Section 4 assumed a solid grounded system (i.e. an earthing resistance of zero ohm) for the MEN system. When the analysis was repeated assuming a 2 Ω earthing resistance at every earthing point, the variations in the voltage profiles along the feeder did not exceed 3.28 % compared to the zero ohm earthing resistance. Thus, the maximum deviation in the disconnection time of the PVs was less than 10% of a cycle.

The analysis revealed that in case of a 3 Φ short-circuit fault, the PVs in all phases disconnect in MEN systems in less than a cycle after fault-occurrence or after the delay time of LVRT, since their voltages drop below the 88% limit. However, there are a few exceptions such as when the fault impedance is very large (e.g. 20 Ω), or when GDR is high (i.e., 2) even for an IoF of 2 Ω . It was also revealed that there is a possibility for the PVs not to disconnect in NEG systems.

It is to be noted that the analyses carried out in Section 5 assumed a 3 Φ short-circuit fault. When these analyses were repeated for a 3 Φ -to-ground fault, the variations in the voltage profiles along the feeder did not exceed 25% compared to the 3 Φ faults. Thus, the maximum deviation in the disconnection time of the PVs was less than 40% of a cycle.

The extreme cases of Section 6 illustrate that using PV systems with only under/over voltage protection function may lead to a failure in the disconnection of PV systems from the LV feeder in case of both MEN and NEG systems during 3 Φ short-circuit faults.

It was noticed that the PVs that had failed to disconnect based on the under/over voltage protection function, will disconnect only when the upstream circuit breaker operates. It was seen that after the operation of the upstream circuit breaker all PVs are disconnected and no islanding issue was observed.

It is worth mentioning that the open-conductor faults were also examined in this research. The studies exposed that the voltage of all the nodes in the downstream of the open conductor point

immediately drop below the 88% limit after fault-occurrence; thus all of the PVs that are connected to those nodes disconnect. This is only observed for the faulty phase and no problem rises in the healthy phases or in the upstream of the fault point of the faulty phase.

8. Conclusion

A research has been carried out to investigate the disconnection time of single-phase rooftop PVs following a single-phase or a three-phase short-circuit fault on the low voltage feeders. The research focuses on a three-phase, four-wire low voltage feeder, with 100% PV penetration. Several parameters are contemplated including the location of the fault, the impedance of the fault and the ratio of the PVs generation capacity to the load demand. Moreover, the influence of the network earthing system is also investigated.

The analysis reveals that for an MEN system, during a single-phase short-circuit fault, the PVs in the faulty phase sense the fault and disconnect immediately in less than a cycle after fault-occurrence or after the required delay time for LVRT since the voltage of their PCC drops below the limit of 88%. Similarly, the PVs located in the healthy phases sense the fault and disconnect as the voltage of their PCC rises above the 110% threshold. An exception is when the fault impedance is relatively large (e.g. 20 ohms or more). However, if the LV feeder is not-effectively grounded, there are situations in which the PVs may not disconnect.

The study also discovered that in case of three-phase and three-phase-to-ground faults, depending on the system earthing type, the location and impedance of the fault and the ratio of the PVs generation capacity versus the load demand, there are situations in which the PVs do not disconnect following the fault. These PVs remain connected until the upstream circuit breaker operates, after which they disconnect successfully.

The research concludes that there may be situations in which the PVs fail to disconnect and continue to feed the fault, until the upstream circuit breaker operates. These situations are more probable in

NEG systems or when the fault impedance is high in MEN systems. Thus, only utilizing the under/over voltage protection function will not guarantee the successful disconnection of PVs in such situations. Hence, newer fault detection algorithms should be developed and evaluated for rooftop PVs which can sense the fault and disconnect the PVs, irrespective of the fault impedance, network earthing type and the PV penetration level, before allowing higher PV penetration levels in LV feeders.

Appendix

The parameters of the network under consideration in Figure 1 are given in Table A1.

Table A1. Technical data of the network under consideration.

Distribution Transformer: 150 kVA, 11 kV/ 415 V, 50 Hz, Dyn-type, $Z = 5\%$
MV feeder: 11 kV L-L rms, 2 km, ACSR 50 mm ² bare conductor, three-phase three-wire system, $R = 2.16 \text{ } \Omega/\text{km}$, $X = 2.85 \text{ } \Omega/\text{km}$ [37]
LV feeder: 415 V, 400 m, AAC 75 mm ² bare conductor, three-phase four-wire system with ABCN horizontal configuration on 120 cm crossarms [22] and a total of 400 meter length, 10 nodes with a distance of 40 meter from each other, $R = 0.452 \text{ } \Omega/\text{km}$, $X = 0.27 \text{ } \Omega/\text{km}$ [37]
PV systems: $\text{PF} = 1$, $\eta = 100\%$, $I_{\text{max at Fault}} = 150\% I_{\text{rated}}$
Residential Demand: Single-phase constant-impedance loads, $S = 4.4 \text{ kVA}$, $\text{PF} = 0.95$ lagging

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