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Effect of Distributed Photovoltaic Generation on Short-Circuit Currents and Fault Detection in Distribution Networks: A Practical Case Study

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Abstract: The increase in the installation of renewable energy sources in electrical systems has changed the power distribution networks, and a new scenario regarding protection devices has arisen. Distributed generation (DG) might produce artificial delays regarding the performance of protection devices when acting as a result of short-circuits. In this study, the preliminary research results carried out to analyze the effect of renewable energy sources (photovoltaic, wind generation, etc.) on the protection devices of a power grid are described. In order to study this problem in a well-defined scenario, a quite simple distribution network (similar to the ones present in rural areas) was selected. The distribution network was divided into three protection zones so that each of them had DG. In the Institute of Electrical and Electronic Engineers (IEEE) system 13 bus test feeder, the short-circuits with different levels of penetration were performed from 1 MVA to 3 MVA (that represent 25%, 50%, and 75% of the total load in the network). In the simulations carried out, it was observed that the installation of DG in this distribution network produced significant changes in the short-circuit currents, and the inadequate performance of the protection devices and the delay in their operating times (with differences of up to 180% in relation to the case without DG). The latter, that is, the impacts of photovoltaic DG on the reactions of protection devices in a radial distribution network, is the most relevant outcome of this work. These are the first results obtained from a research collaboration framework established by staff from ETSI Civil and the IDR/UPM Institute, to analyze the effect of renewable energy sources (as DG) on the protection devices of a radial distribution network.

Keywords: coordination protection; distributed generation; photovoltaic resources; DigSILENT

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1. Introduction

The distributed generation (DG) based on renewable energy sources in some distribution networks has caused a major change in the traditional model of power supply. According to the new paradigm of DG, generation of electricity power should come closer to the user, in contradiction to the traditional generation in centralized plants [1,2]. Therefore, it is necessary to implement electrical systems with an infrastructure that allows the energy to be distributed and made available to users in optimal conditions for their use [3].

Although the presence of DG in power networks can be beneficial [4,5], it produces a structural transformation, failing to behave as a classical radial distribution network. Reversed power flows can occur both in steady state and in the presence of faults [6–10]. The impacts that DG may have on these distribution networks will depend, among other aspects, on the type of generation, technology used, installed power, and location in the network [11–15]. Furthermore, these new fault modes resulting from the introduction of DG, based on renewable energy such as photovoltaic (PV) generation, can affect the reliability of these PV systems and decrease the revenues foreseen [16,17].

Among the different problems arising with the increasing of DG within power networks, the protection relays coordination is one of the most relevant (other problems being harmonic distortion, frequency drop, and stability and reliability of the network [18–22]). Protection in traditional networks was designed for unidirectional power distribution. However, this situation has changed with the greater importance of renewable energy [23], and other ways to reduce power production from the traditional energy sources that have a negative impact on the climate (e.g., the use of electric vehicles as power sources [24–29]). Within the networks with DG, such as the ones with photovoltaic generation located in different points of the grid, the coordination between protection devices might fail [30–38]. Additionally, each kind of renewable energy source presents new fault modes in a network. In [39], there is thorough review of the fault modes that a photovoltaic installation can bring to a distribution network.

The management and control of a radial electric distribution network is based on the assumption of the existence of unidirectional flows of power, which is transmitted from the highest levels of transport voltage to the distribution levels. We can assume that the short-circuit currents behave in a similar way. These assumptions allow the implementation of relatively simple and economical protection schemes, in order to achieve selective operation of the protection system (according to the principles of selectivity, only the protection device closest to the defect must function to clear the fault, leaving the rest of the network energized). There are numerous literature reviews on the matter of the protection of power grids with DG; the recent works [40–44] being worthy of mention.

The installation of DG in medium and low voltage levels changes the fundamental basis of the aforementioned unidirectional power flow [45]. Both the power flows and the short-circuit currents can now have upstream addresses, these also being of different values than the ones initially foreseen [6]. As mentioned above, the initial schemes applied (that is, the main feeder protection) might start being less effective or even stop working [46]. This problem being caused as the value of the short-circuit current detected by the main protection of the substation may be altered, and therefore affect the response time of the protection devices that will depend, to a great extent, on the size and location of the DG within the distribution network [15,47,48].

As stated, one of the main problems of the presence of DG in distribution networks is the loss of coordination and untimely triggering of protection devices [49], as short-circuit currents can increase as a result of the contribution from those DG. The fault currents suffer variations that can run the fuse in both directions, which means that it can be traversed by currents generated in points downstream and upstream of its location. Therefore, it is necessary to reconfigure the protection devices of these distribution networks. The loss of sensitivity of the protection devices can then be analyzed according to the location of short-circuits in relation to the DG, differentiating among faults located upstream and downstream of the aforementioned DG.

The aim of this work is to describe the preliminary results obtained from a research collaboration framework established by researchers from ETSI Civil and the IDR/UPM Institute to analyze the effect of renewable energy sources (as DG) on the protection devices of a power grid. The aforementioned framework is based on the work already carried out on protection in power grids with distributed generation [50], and the work carried out in analytical modeling on solar panels and batteries [51–60]. In the present work, photovoltaic energy was selected as the example of DG. It should be underlined that this particular source of energy is associated with some specific problems when considered as DG [61–65], and should be analyzed while taking into account its particular performance in relation to temperature and irradiance [66]. Finally, it should be underlined that although there are many works in the available literature on the effect of DG on distribution grids [6,11,12,14,18,20,24,29,36,67,68], it appears that the effect of DG on the protection coordination of relays curves.

In order to obtain quick results that could lead to general but solid conclusions, a simple distribution network has been analyzed in the present work. This specific power distribution grid was selected as it represents a well-defined scenario in which relevant conclusions can be derived.

As a first work on protection for grids with DG based on renewable energy sources, we chose to analyze a simple distribution network similar to the ones typical of rural areas. With the objective of ensuring the electricity supply in these distribution networks when DG is connected, and maintaining the functionality of the protections, the following aspects were studied:

- How the installation of DG in the studied distribution network can cause significant changes in the fault currents;
- The untimely actuation of the protections; and
- The effect on the protection devices relating to the amount of DG power supplied to the system.

Finally, it is also fair to say that the present work analyzed the effect of photovoltaic distributed generation in a network, leaving aside other possible renewable sources, such as wind power generation. This was a drawback that will be overcome in future works.

The following paper is organized as follows: in Section 2, the distribution network and different cases studied are described, the results being included in Section 3. Finally, conclusions are summarized in Section 4.

2. Materials and Methodology

The protection of the distribution networks studied in this work was guaranteed by main protection relays located at the beginning of the line (that is, at the electric substation (S)), and cut-out fuses (F1, F2) at the laterals. The basic topology of this kind of network is shown in Figure 1, where a distributed generation (DG) source has been added. The main feeder is protected by a relay (R), whereas the laterals supplying the loads are protected by means of fuses.

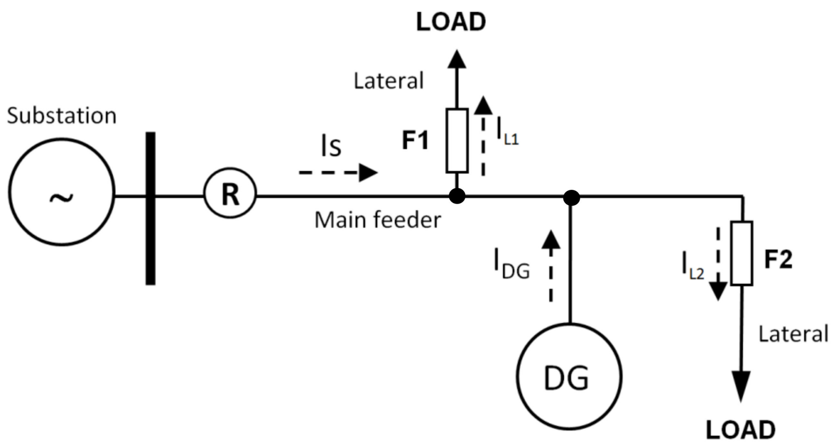

Figure 1. Basic topology of the simple power distribution network studied. A distributed generation (DG) source has been added.

Relays are normally equipped with inverse time overcurrent devices, whose performance is defined by the following equation [67]:

$$t(I) = \frac{a}{\left(\frac{I}{I_{pick-up}}\right)^{b} - 1} \text{TMS} \quad (1)$$

where t is the time of operation of the overcurrent device, I is the fault current detected by the device, $I_{pick\text{-}up}$ is the adjustment current (relay pick-up curve) of the device, a and b are the control parameters of the actuation curve, and TMS is the Time Multiplier Setting (expressed in seconds) [69]. The characteristic values of the relays used in the present work are included in Table 1.

Table 1. Parameters for the different relay characteristics used in the Institute of Electrical and Electronic Engineers (IEEE)-13 bus test feeder system used in the present work (see Equation (1)). These values were selected according to the IEC 60255-51 standard.

Time-Current Curve Type	Settings	
	a	b
Inverse	0.14	0.02
Very inverse	13.5	1
Extremely inverse	80	2

Each relay in a protection system has a set of relay settings that determine the primary and backup protection that the relay will provide. The relay settings for each relay are calculated so that the relay fulfills the primary and backup protection requirements of the network it is protecting. Calculations are based on the maximum load current, the maximum and minimum fault currents, and/or the impedance of feeders that the relay is protecting.

On the other hand, 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. However, it should be underlined that the most interesting part of this curve, in terms of its practical applications, can be approximated by a linear expression [70]. Therefore, it can be assumed that the general equation for the characteristic curve of an expulsion fuse can be expressed as [68,71–74]:

$$\log(t) = m\log(I) + n \tag{2}$$

where t is the actuation time of the ejection fuse, I is the current through it, and m and n are fuse constants to be determined as in [75].

The present work was carried out by using computer simulation of a rural/small grid with 3 possible photovoltaic DG sources, selected as a case study test network. To analyze the effect of the photovoltaic DG on the protection devices of such a distribution network, the IEEE-13 bus test feeder system was used (see Figure 2).

The simulation was performed with DIgSILENT Power Factory software, already used to study the protection of distribution systems with DG [72,76–79]. This distribution network design has been successfully used to study static short-circuit currents [80], the maximum possible photovoltaic power penetration into a network in relation to the demand response [81], voltage regulation strategies in DG [78,82,83], or fault ride-through in power networks related to renewable energy (wind and photovoltaic) [79]. Besides, it should be also said that DIgSILENT Power Factory software is a powerful simulation tool that integrates the following standard methodologies for short-circuit calculations: IEC 60909, IEEE 141/ANSI C37, VDE 0102/0103, G74, and IEC 61363.

The analyzed distribution network was divided into three Zones of Protection (Zones 1, 2, and 3), assigning a specific area for each DG (starting each one of these zones from the beginning of the output feeder from the electrical substation, see Figure 2). The total load of the distribution network was 4 MW, which was considered constant in all simulations. The connection points of the DG were chosen based on their distance from the main substation.

The three different case studies analyzed in the present work are indicated Figure 2 (each of them involves only one photovoltaic DG):

- N1: installation of a photovoltaic DG at bus 646, located at the middle of the distance to the substation (L = 2400 m), within Protection Zone 1;

- N2: installation of a photovoltaic DG at bus 633, closer to the substation (L = 1500 m), within Protection Zone 2;
- N3: installation of a photovoltaic DG at bus 652, farthest from the substation (L = 7000 m), within Protection Zone 3.

These case studies were analyzed with different DG penetration levels (1, 2, and 3 MW, representing 25%, 50%, and 75% of the power load, respectively). These levels represent normal variations in the behavior of the solar panels in relation to irradiance on the solar cells and their temperature (the use of Maximum Power Point Tracking is supposed). In recent works, we have reflected these variations (both measured and calculated by using implicit and explicit models) [59,60,84].

To the authors' knowledge and after a thorough review of the available literature, the present approach to analyze the performance of a protection scheme based on both relays and cut-out fuses in a well-known power distribution grid, and in relation to the power supplied from photovoltaic DG, represents a novelty.

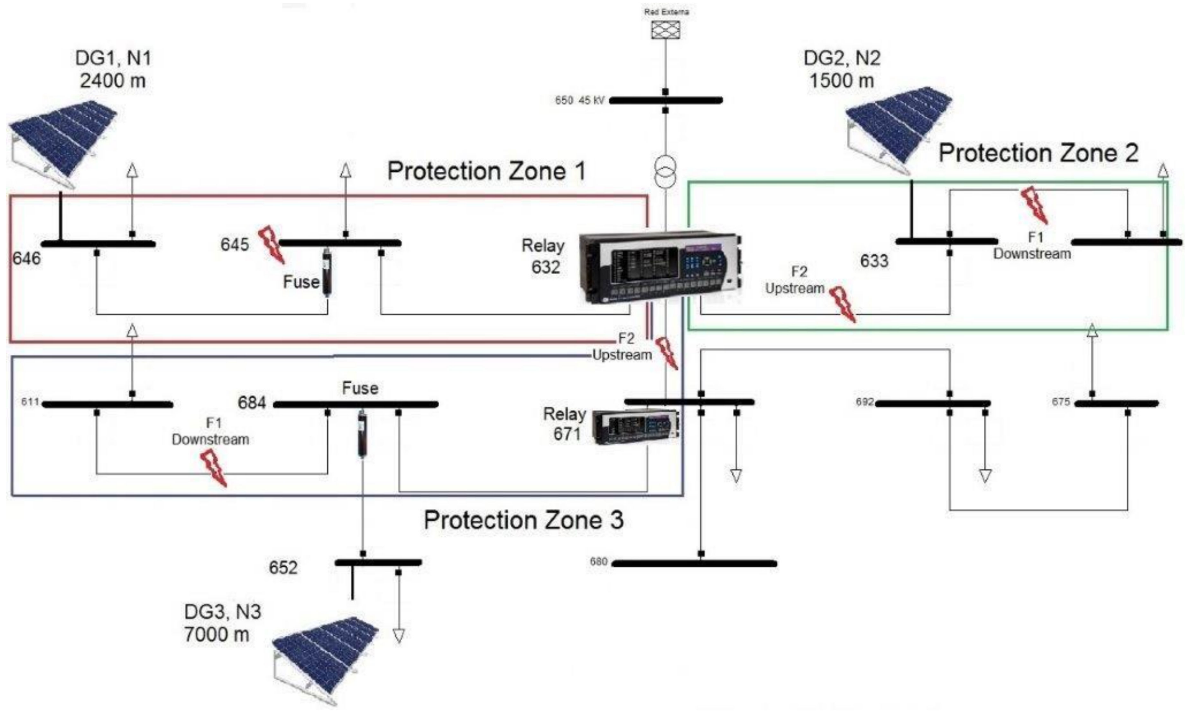

Figure 2. Example of the rural network topology studied in the present work. The position of the three DG included in the topology, N1, N2, and N3 (case studies), is indicated. The different protection zones are also indicated in the figure, together with the simulated short-circuits.

3. Results and Discussion

The results, as presented for all scenarios, show various ranges of DG capacity which provide different values of fault current. Adding distributed generation to the 20 kV distribution network creates a situation where networks that were designed primarily as tail, radial, or open radial networks become looped networks.

As a result, distributed generation can cause relays in a protection system to under-reach or over-reach. This has been illustrated in this paper, by sample calculations and an actual protection review (using DigSILENT PowerFactory software).

In Figure 3, the electric circuit corresponding to Protection Zone 1 with a 1 MW photovoltaic DG source (connected to bus 646) is shown (see also Figure 2). Protection elements in this area include an overcurrent relay at the beginning of the line (bus 632), and a fuse (F645) to protect the line connecting the DG. Only a 1 MW power supply through bus 646 was analyzed, as it represented the maximum power that was able to be injected by the DG in continuous operation (larger installed powers always tripped fuse F645).

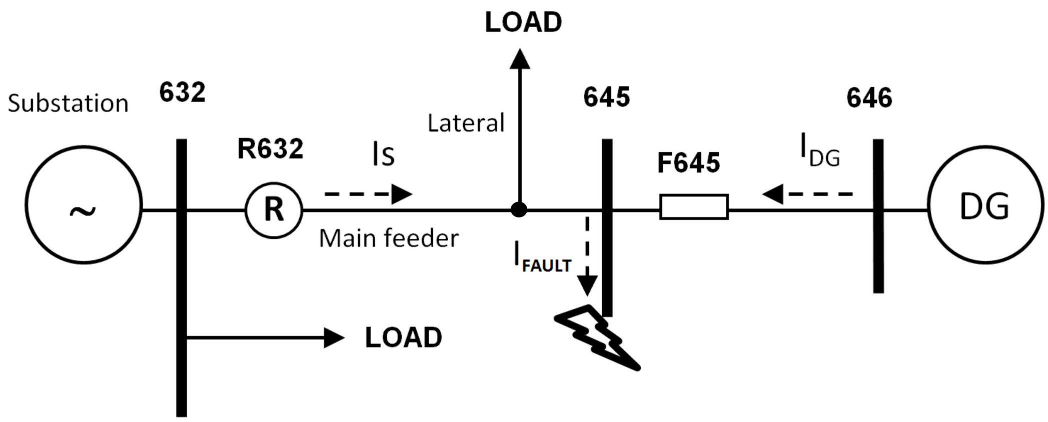

Figure 3. Protection Zone 1 electric circuit (see also Figure 2), in which a short-circuit in bus 645 is indicated.

A three-phase short-circuit at bus 645 was simulated; the characteristic curves being plotted in Figure 4. In the graph, it shows that in the case of a fault between the substation and the DG, the presence of the latter represented a decrease in the value of the short-circuit current detected by the relay (R632 in Figure 3), from 536 A to 513 A. Thus, a loss in relay sensitivity (binding), as relay R632 at the main feeder detected a lower value of the fault current, with the triggering time also being delayed from 0.3 s to 0.35 s. These results are also summarized in Figure 5, and Table 2 at the end of this paper.

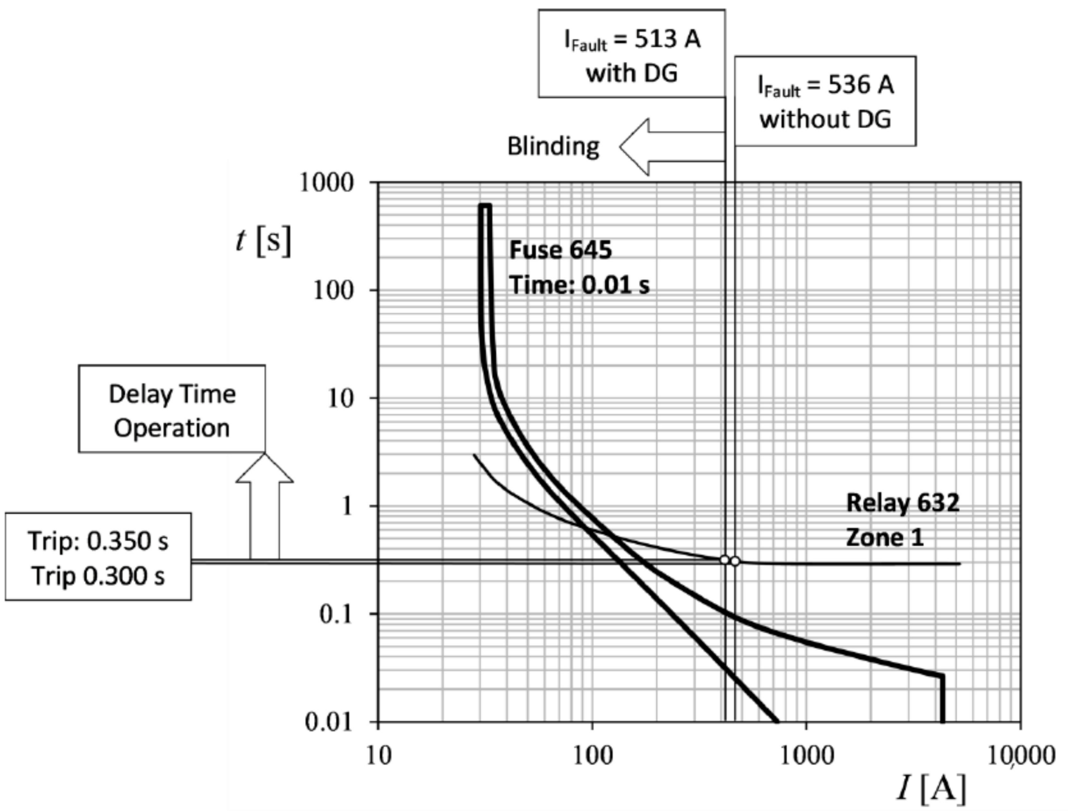

Figure 4. Protection Zone 1 current-time (*I*-*t*) performance in case of a three-phase short-circuit with 25% DG power (1 MW) at bus 645 (see Figure 3).

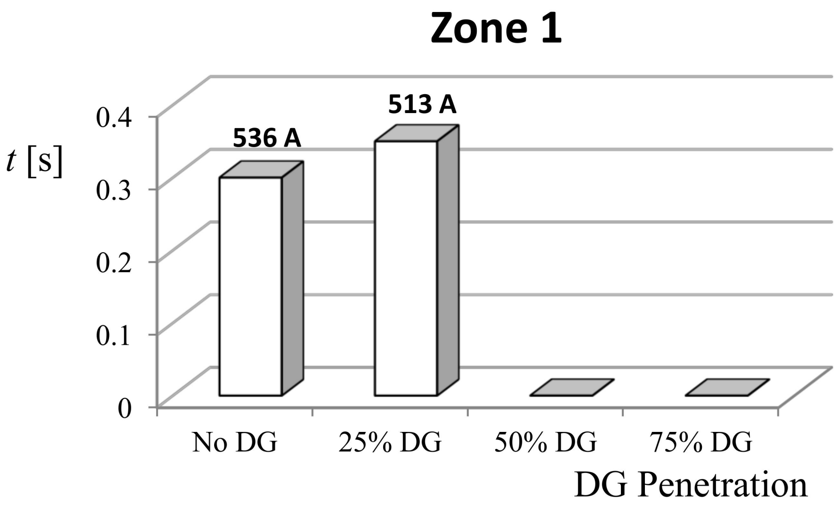

Figure 5. Triggering time, *t*, of protection relay R632 in Protection Zone 1 (see Figures 2 and 3), in relation to the power supply from DG. The currents detected by the relay when triggering were added to the graph in each case.

Table 2. Relay and fuse currents, *I*, and triggering times, *t*, in the protection devices from the defined Protection Zones 1, 2, and 3 (see Figure 2, Figure 3, Figure 6, and Figure 10), in relation to the power supplied by the DG (1, 2, and 3 MW, representing 25%, 50%, and 75% of the photovoltaic installed power).

Protection Zone	Fault	Protection Device	Without DG		25% DG (1 MW)		50% DG (2 MW)		75% DG (3 MW)	
			I_{sc} [A]	*t* [s]	I_{sc} [A]	*t* [s]	I_{sc} [A]	*t* [s]	I_{sc} [A]	*t* [s]
Zone 1	Bus 645	R632	536.3	0.300	513.6	0.350	-	-	-	-
		F645	-	-	726.4	0.010	-	-	-	-
Zone 2	Fault F1	R632	488.3	0.380	465.1	0.389	455.5	0.393	449.3	0.400
	Fault F2	R632	498.1	0.370	477.1	0.384	467.9	0.388	461.2	0.390
Zone 3	Fault F1	R632	1400.1	0.300	490.0	0.800	438.2	0.840	432.5	0.840
		R671	-	-	440.1	0.380	438.2	0.390	432.5	0.380
		F684	-	-	452.3	0.113	440.8	0.112	432.5	0.110
	Fault F2	R632	1113.2	0.560	420.3	0.850	490.3	0.860	438.3	0.870
		R671	1113.2	0.310	420.3	0.390	427.6	0.390	438.3	0.750
		F684	-	-	439.5	0.110	427.6	0.119	438.0	0.120

The Protection Zone 2 analyzed scenario (Figure 2) involved a 1, 2, and 3 MW DG power supply. A protection relay R632 was installed at the substation (see Figure 6), and two faults were studied, at points F1 (downstream from the DG source) and F2 (upstream from the DG source). In case of a short-circuit at point F1, the current detected by the relay decreased from 488 A (without DG) to 455 A (with DG), with a triggering delay of 13 ms (see in Figure 7 the case corresponding to 50% DG power at bus 633). Similarly, in case of a short-circuit at point F2, the currents decreased from 498 A to 467 A, with a triggering delay of 10 ms (see in Figure 8 the case corresponding to 50% DG power at bus 633). The results are summarized in Figure 9 and Table 2.

As performed in relation to the fault analysis carried out in Protection Zone 2, three different DG power supply scenarios (1, 2, and 3 MW) were studied in relation to Protection Zone 3 (Figure 2). The protection devices installed were two overcurrent relays (R671 and R632) within the main distribution line, and a fuse 684 DG protection, see Figure 10. Two three-phase short-circuits were simulated within the corresponding Protection Zone 3: at point F1, located downstream from the DG, and at point F2, upstream from the DG. The results are respectively included in the graphs in Figures 11 and 12. In case of short-circuits at F1, the DG installation implies a decrease of the current detected by the relay, from 1113 A to 420 A, which represents a 62% decrease of the relay sensitivity and a delay of 550 ms in relation to the triggering time (see Figure 11). Similarly, in the case of short-circuit at point F2 (see Figure 12), the connection of the DG source introduced a decrease of the detected current from 1400 A to 490 A, and a delay of the triggering time, from 300 ms to 800 ms. The results are summarized in Figure 13 and Table 2.

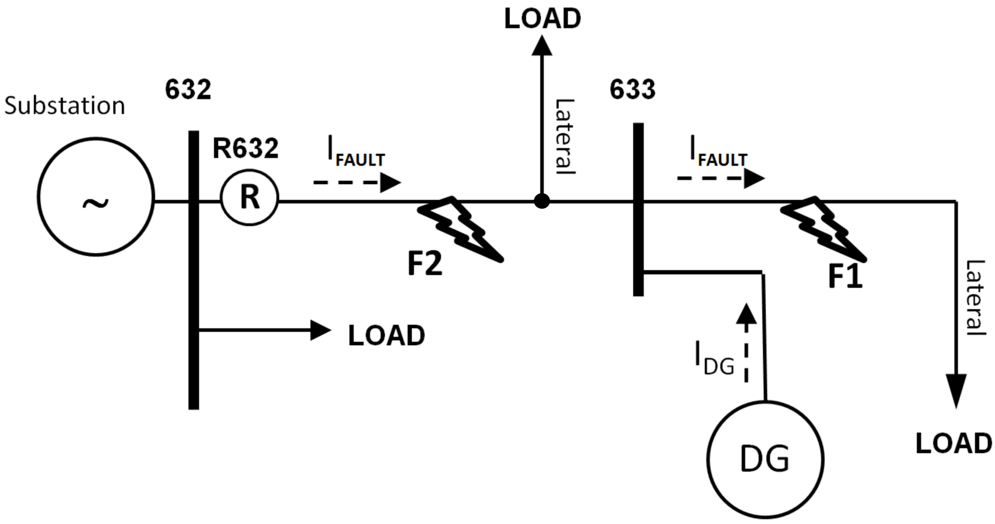

Figure 6. Protection Zone 2 electric circuit (see also Figure 2), in which short-circuits in points F1 and F2 are indicated.

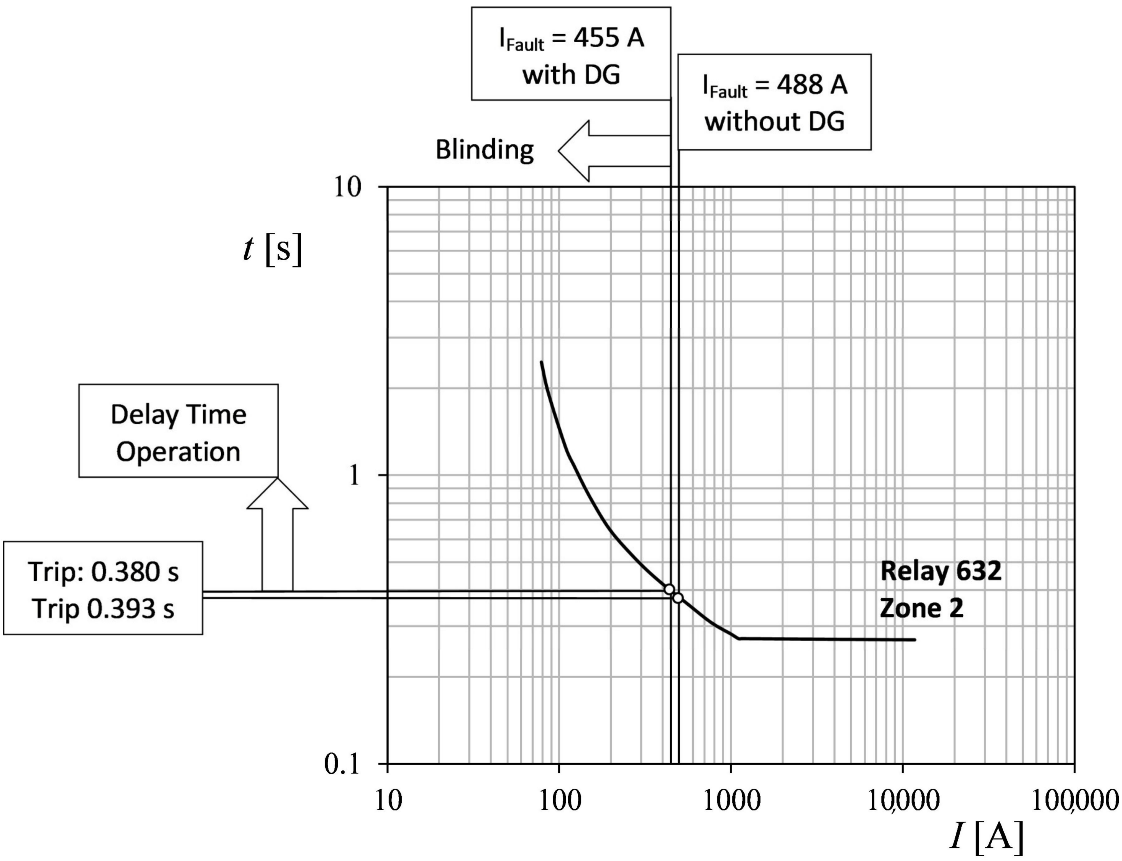

Figure 7. Protection Zone 2 current-time (*I*-*t*) performance of in case of a three-phase short-circuit at point F1, with 50% DG power (2 MW) at bus 633 (see Figure 6).

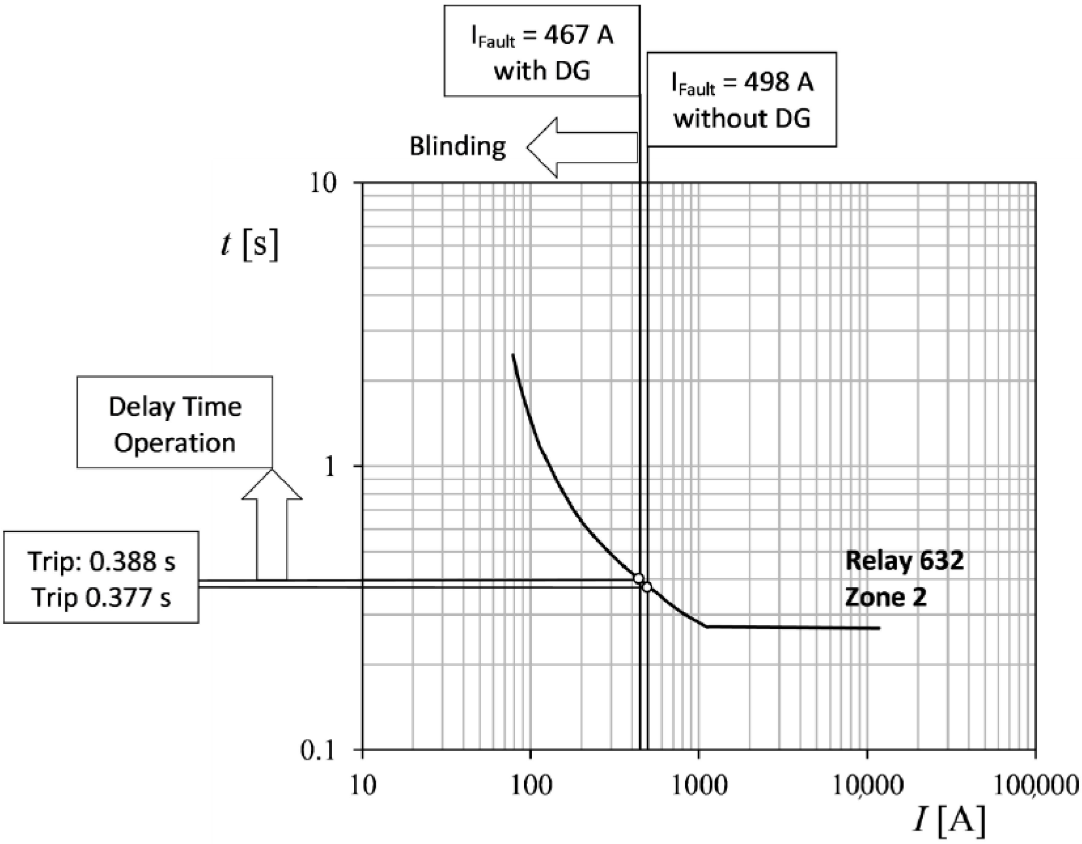

Figure 8. Protection Zone 2 current-time (*I*-*t*) performance in case of a three-phase short-circuit at point F2, with 50% DG power (2 MW) at bus 633 (see Figure 6).

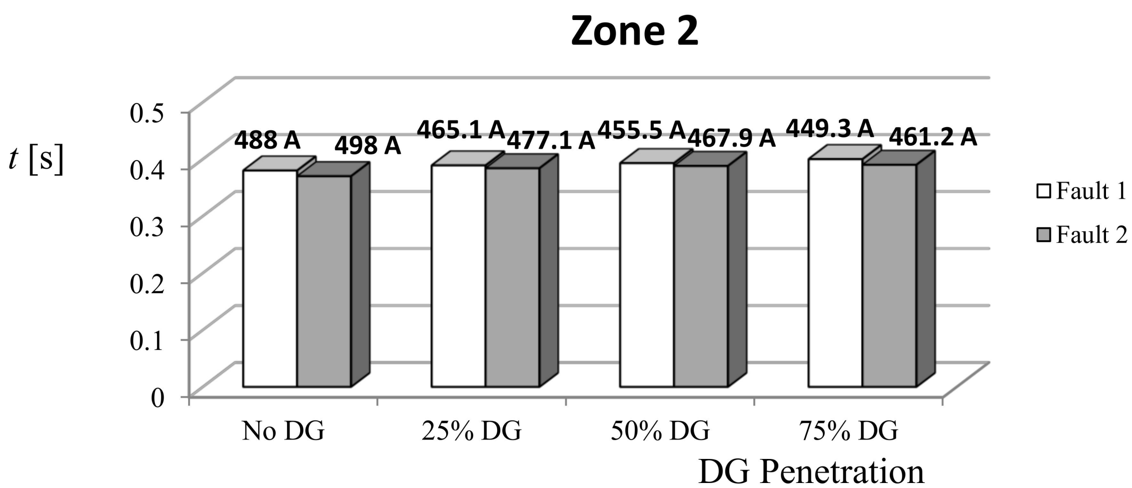

Figure 9. Triggering time, *t*, of the main feeder protection relay R632 in Protection Zone 2 (see Figures 2 and 6) for fault F1 downstream from the DG and fault F2 upstream from the DG, in relation to DG power supply. The currents detected by the relay when triggering were added to the graph in each case.

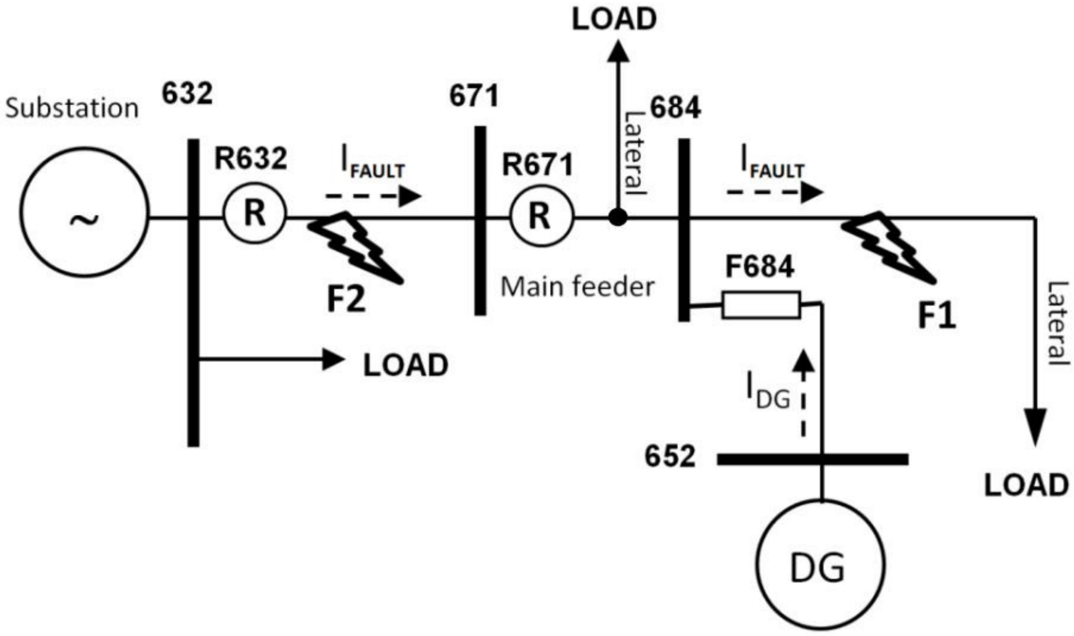

Figure 10. Protection Zone 3 electric circuit (see also Figure 2), in which short-circuits in points F1 and F2 are indicated.

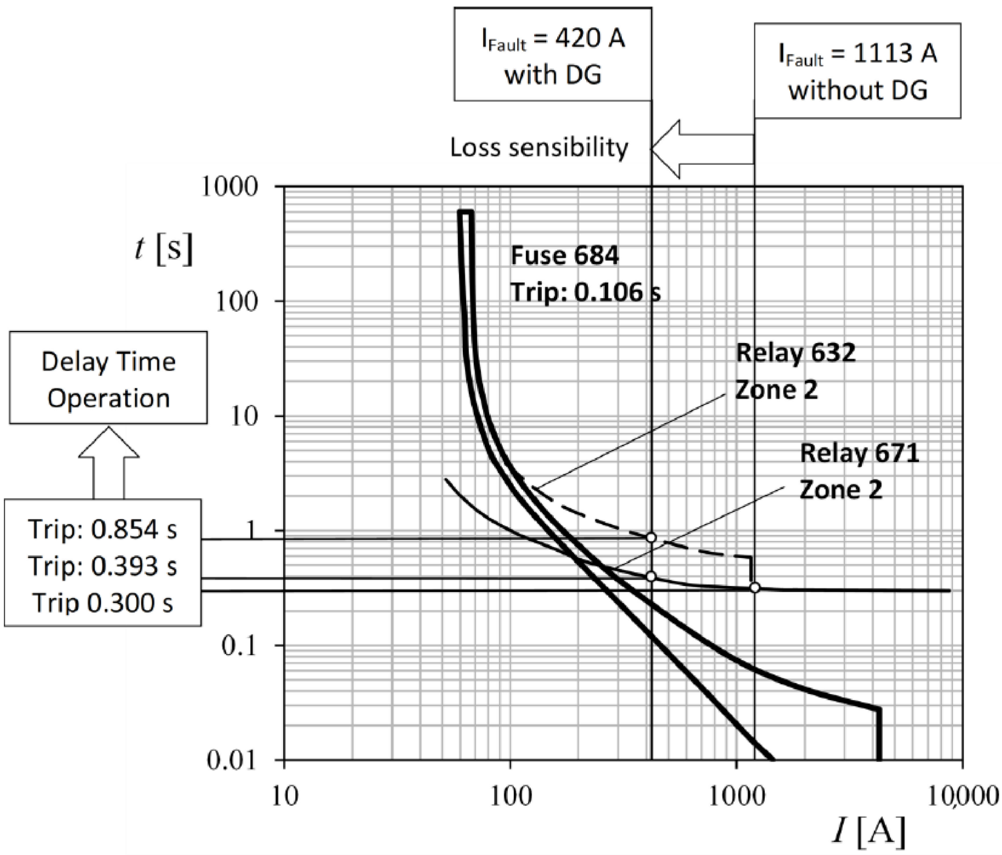

Figure 11. Protection Zone 3 current-time (*I*-*t*) performance in case of a three-phase short-circuit at point F1, with 25% DG power (1 MW) at bus 652 (see Figure 10).

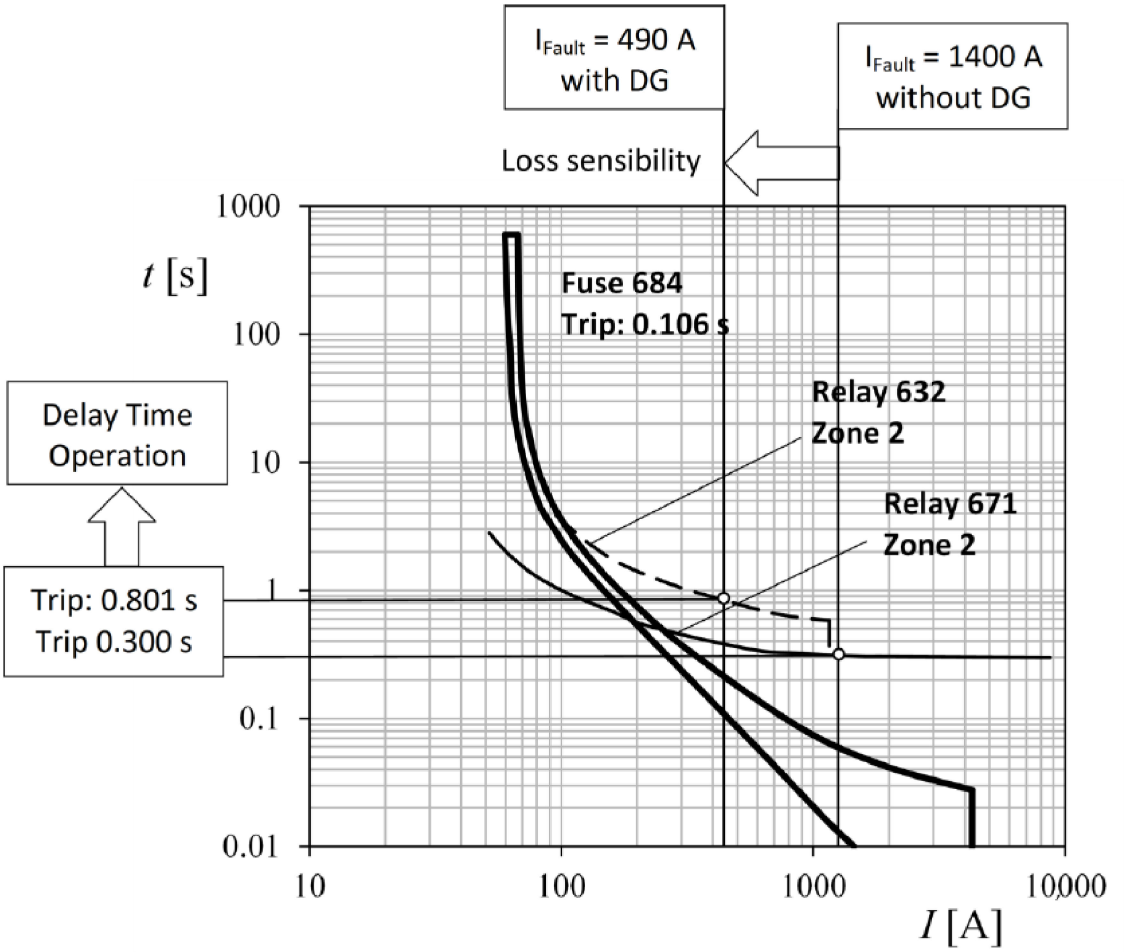

Figure 12. Protection Zone 3 current-time (*I*-*t*) performance in case of a three-phase short-circuit at point F2, with 25% DG power (1 MW) at bus 652 (see Figure 10).

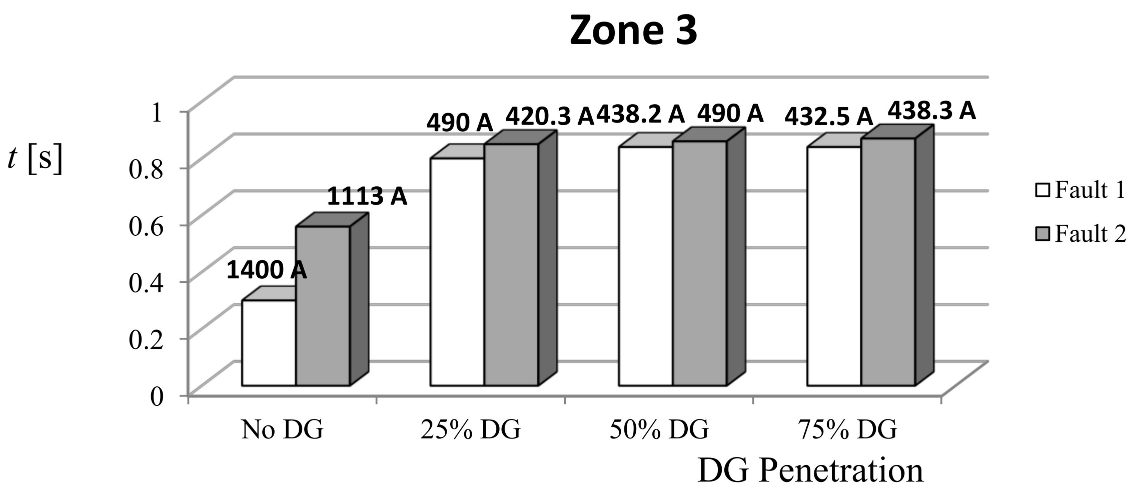

Figure 13. Triggering time, *t*, of the main feeder protection relay R632 in Protection Zone 3 (see Figures 2 and 10) for fault F1 upstream the DG and fault F2 downstream the DG, in relation to DG power supply. The currents detected by the relay when triggering were added to the graph in each case.

In Table 2, the results obtained in relation to each of the analyzed scenarios are included. The fault currents and the protection relay tripping/triggering times are shown with regard to:

- the Zone in which the fault was produced; and
- the penetration level (which is the ratio of the power supplied by the photovoltaic DG to the power demanded by the load, as indicated in the Section 2).

4. Conclusions

A coordination study was presented and applied to the IEEE 13-node test feeder to evaluate the effect of the PV DG penetration on the protection devices coordination. Different cases were studied by changing DG penetration levels and locations for each possible fault location. A protection coordination assessment was carried out by analyzing the location of the faults (devices see fault currents for downstream and upstream faults).

The most relevant conclusions from this work are:

- Faults upstream in relation to the last DG were not seen by the protection devices located downstream from this DG. Even for larger DG penetration these downstream devices did not have coordination problems between them (as they did not see any fault);
- On the other hand, although devices saw fault currents for upstream faults, coordination was lost if they saw the same fault current for a fault downstream as well as for a fault upstream.

Additionally, the present protection procedures need to be revised, as the presence of DG sources might represent a quite serious effect on the current and triggering time reaction of the protection relays. According to the results and depending on the distance to the substation, the tripping time with DG was increased up to 167% (for 25% PV DG penetration) and 180% (for 50% and 75% PV DG penetration).

The results from this work can be reasonably extrapolated to grid networks, bearing in mind the current direction effects on the protection relays, and the DG penetration.

Future works of the research team that carried out the present work are the development of simplified techniques to locate faults in distribution networks with DG, new methods to select the appropriate fuses in these networks (to avoid unexpected fuse tripping), and a procedure to successfully reprogram overcurrent relays.

Finally, it should also be noted that the present work will be followed by others that will include research on the dynamic modeling of power supplies from DG in distribution networks, and simplified methodologies on fault locations in grids with DG.

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