THE NEED FOR ZERO SEQUENCE VOLTAGE PROTECTION IN MV NETWORKS WITH HIGH LEVELS OF DISTRIBUTED GENERATION

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ABSTRACT

Portugal has been one of the European countries where Distributed Generation (DG) has taken a high level of importance for the overall system. In 2015 about 50 % of the Portuguese electrical energy consumption was produced at the distribution network.

This high level of DG has given rise to new challenges for the DSO, one of the latest concerns the protection requirements for DG and the network arising from the ever increasing self-consumption DG. Two major issues are placed upon the DSO: the need to keep DG projects economically feasible without compromising the network safety; and the new exporting mode of MV/LV secondary substations.

One of the issues being raised by the low-power clients wanting to install a self-consumption generation plant is the need for a maximum zero sequence voltage protection (V0>) that requires the installation of a VT in most cases.

The paper performs a new analysis of the network quantities on the LV side (near DG) under a ground fault on the MV feeder. Simulations of multiple scenarios show that the voltage on the LV side can change by a ground fault on the MV side.

The analysis confirm that the V0> protection is the strongest robust way to protect the network against a ground fault on the MV side.

INTRODUCTION

The current Portuguese regulation DR 56/85 [1] does not allow a phase-to-ground fault to remain permanently in the grid. In accordance, the network protection system must assure its elimination in less than 3 s, guaranteeing the selectivity and the reliability of the system.

The increasing of distributed production, as well as self-consumption, obliges to re-analyse the network protection practices, in order to ensure compliance with the current regulation. Specially, regarding MV network protection, where national legislation refers the need to install a maximum zero sequence voltage protection (V0>) at the point of common coupling of DG with the grid, [2]. Delta, or isolated Y, connection at the MV side of transformer is a motivation for this protection function because the zero sequence voltage is not detected on the LV side. In the absence of a MV Voltage Transformer (VT), voltage metering is performed on the LV side. Given the size of the generation plants, there may be an economic viability issue if extra devices are required. One of the issues being raised by the low-power clients who want to install a self-consumption generation plant is whether it is necessary a maximum zero sequence voltage protection (V0>), given the need to install VT in most cases. This has impact on the traditional planning of the protection system.

On the other hand, the growth of low voltage self-consumption levels may lead some of the secondary MV/LV substations to inject power into the MV network. This is a new challenge, which has not been taken into account in traditional network protection plans.

These new challenges have given rise to two questions: Is V0> necessary for all types of DG? What conditions have to be met? The aim of this study is to analyse the need to install the maximum zero sequence voltage protection and in which conditions.

An extensive European benchmarking was conducted on the V0> use and on alternative methods for detecting a ground fault. The current regulations and the national practices regarding the phase-to-ground fault protection required for DG producers have also been analysed. Finally, the network performance, considering DG, in the presence of phase-to-ground faults was characterized by simulation.

BENCHMARKING

The use of maximum zero sequence voltage protection is very dependent on the grounding system used in each country. Maximum zero sequence voltage protection application has been identified in Portugal, Spain, France, Italy and Ireland , [2], [3], [4], [5], [6], [7].

In countries where the MV network is operating in resonant grounding, the use of maximum zero sequence voltage protection is not required given the ability to operate permanently with a phase-to-ground fault and the persistent zero sequence voltage, even without fault, due to the near operation of the resonance point. In these cases, the systems identify the fault and signal it to the network operator.

Concerning the protection of LV networks and, although the characteristics of these networks are very different from country to country, there is also an unanimous requirement on disconnection of producers, in case of fault.

Usually, there are frequency and voltage protection functions installed on the LV distributed generator. However, unintentional islands are not allowed, so the producer must be disconnected from the network by a Loss of Mains protection or due to a network collapse caused by the loss of the balance between generation and load, [8], [9].

The benchmarking conducted for Europe, with the objective of characterizing the use of maximum zero sequence voltage protection, or alternative means of detecting phase-to-ground faults, showed an unanimity on the producers disconnection in case of a network short-circuit, preventing unintentional island operation.

PORTUGUESE LEGISLATION

The Portuguese Technical Guide for DG connection to the grid [2], states that those producers must have their protections coordinated with the network protections, so that faults are properly isolated assuring selectivity.

It also recommends the typical constitution of an interface protection block between the network and the generator, including: maximum and minimum frequency relays; maximum and minimum voltage relays; maximum zero sequence voltage relay (protection against ground faults in MV) and maximum current relays (dispensable in case of connection to a low voltage network).

Recently, the new document applied to Production Units for Self-Consumption, [10] established specific rules applicable to PV installations, in addition to the other specifications established in [2]. This document states that all PV installations must have the legally defined protections for interconnection with the distribution network.

It also states that maximum zero sequence voltage protection is generally used for producers with power ratings above 250 kW.

In cases duly justified by the DSO, due to the on-site network characteristics, it may be necessary to use this protection for producers below 250 kW. However, this protection is not required when the manufacturer installs a system that prevents any power injection into the network.

SYSTEM PERFORMANCE WITH A PHASE-TO-GROUND FAULT

In Portugal, the MV distribution network is grounded by a reactance installed in the HV/MV substations. On the other hand, the power transformers installed in the secondary substations are usually delta-wye connected with the delta connection on the MV side.

When a ground fault occurs on a MV feeder, the zero sequence current relay installed in the HV/MV substation orders the feeder breaker to open. Therefore, this MV feeder becomes isolated from the network and the feeder loses grounding connection leading to an ungrounded system. The presence of power sources in this feeder could create conditions for the system to operate in island mode, since a power balance between generation and load could be achieved.

The zero sequence impedance, observed from the secondary substations, is almost infinite due to the delta-wye transformer connection. Therefore, any I0> and V0> protection relays monitoring the LV power generation cannot detect the upstream fault to ground.

The island mode is only effective if frequency is kept without significant variation, otherwise the frequency variation based relays will operate and the DG will be disconnected.

Frequency variation depends on the balance between generation and load. Therefore, if the available generation is not enough to support the load in the MV feeder, the frequency will tend to decrease. Namely, if the power balance is not restored, either by increasing generation or by dropping off load or even by a combination of both, the grid becomes unstable and collapses. At this time, if existing, the frequency variation based relays will trip. Note that the Loss of Mains protection uses the frequency variation to detect the island mode.

However, if generation and load balance is achieved and simultaneously a fault to ground occurs on the feeder, the frequency variation based relay will not operate. This is more likely to happen in distribution networks with high levels of DG able to support the load. For instance, in Figure 1 it can be observed the power inversion (negative active power), also as long periods of balance between generation and load (when power is nearby zero), measured on a HV/MV substation.

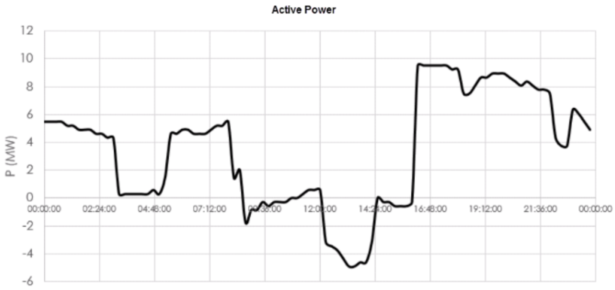

Figure 1- Power Transformer daily diagram from a HV/MV substation (source: EDP Distribuição).

Most of the DG present in the LV is photovoltaic and uses inverters to convert the generated energy. The dynamic analysis of the inverters is not an easy task due to a lack of technical information and a total absence of standards to regulate and model their dynamic operation. In addition, each manufacturer has a different solution and behaviour under the same conditions. More, some of them allow firmware update by the internet, potentially changing the inverter operation. Finally, it is expected that the future will bring some innovation on these devices operation. All these conditions challenge the DSO on understanding this equipment, especially under fault to ground conditions. Given all these reasons, the present work does not consider the inverter's dynamic operation.

These ideas are a starting point on the grid performance analysis with a high level of DG in a faulted to ground MV feeder. The aim is to analyse the voltage (V and V0) and current, with different operating scenarios, in several grid locations, namely HV/MV substation and secondary substations.

Simulation scenarios

The studied network comprehends a 60/15 kV substation with two rural feeders, mostly overhead lines (feeders 1 and 2), and an urban feeder, mostly underground cable (feeder 3), Figure 2.

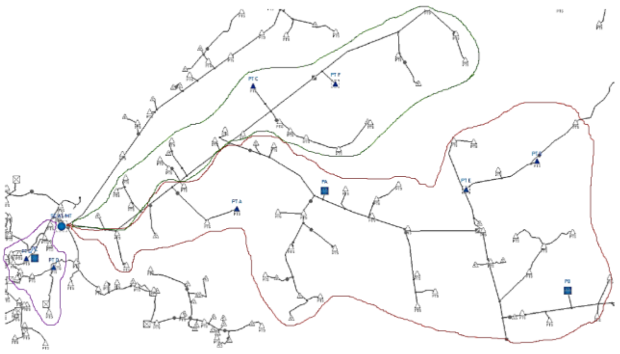

Figure 2 - Simulated MV network scheme: feeder 1 (red), feeder 2 (green) and feeder 3 (magenta) (source: DPlan).

As previously exposed, the analysis focuses on voltage (V and V0) and current in different scenarios namely: DG variation, different fault location and different fault impedances. Phase-to-ground faults were simulated and pre-fault conditions considered.

Simulations were conducted using DPlan software.

Simulation Results

Upon occurrence of a ground fault in a MV feeder, the amplitude of the current flowing into the feeder coming from a LV DG may not change significantly when compared with normal operation. Moreover, a high level of connected DG may cause the MV feeder to operate on island mode, ungrounded. On healthy phases (MV side), voltages will increase to values close to phase-phase. However, on the LV side (near DG) voltages may show an interesting behaviour. Figure 3 shows the behaviour of LV voltage with different installed generation powers, at the LV side of the transformer secondary substation.

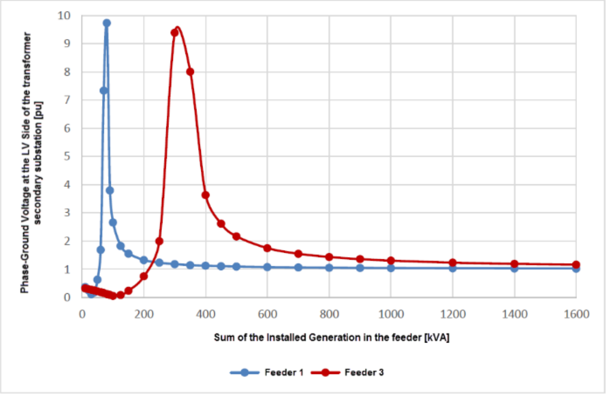

Figure 3 – Single-phase voltage behavior with increasing installed generation in the feeder, secondary substation LV side.

Both curves (feeders 1 and 3) show a similar evolution, although between feeders 1 and 3 there is an offset in power. Feeder 3 needs more installed generation to keep voltage stabilized nearby 1.0 p.u.. Generators models are the same in both feeders, thus positive and negative reactances are assumed to be identical.

However, shunt admittance on feeder 3 is three times higher than on feeder 1. This justifies the offset found in the simulations curves, Figure 3.

Simulations show that the voltage on the LV side can be influenced by two variables: the sum of the installed generation in the feeder (S_G), and the feeder characteristics', such as length, or whether it is an underground cable or an overhead line.

$$S_G = \sum_{i=1}^{N} S_{Gi} \ \ and \ \ B = \sum_{j=1}^{M} B_j$$

N is the number of power facilities in the islanded network
M is the number of line sections (underground cable/ overhead line) in the islanded network

This means that, theoretically, an overvoltage protection relay monitoring the LV side of a secondary substation could detect a fault to ground on the MV feeder after the island formation. For a better comprehension of this situation, the following condition is defined:

$$V_a^{LV} > 1.20 \ [pu]$$

Consider Figure 4 for a ground fault observed from the MV side of a secondary substation, where 1, 2 and 0 correspond, respectively, to positive sequence, negative sequence and zero sequence.

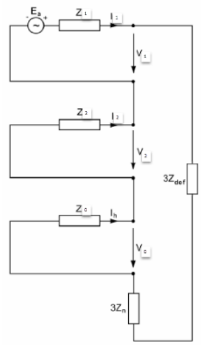

Figure 4 – Equivalent circuit for computation of a ground fault current.

In this case, zero-sequence impedance, Z_0, is infinite and the voltage, V_0, is zero due to the delta-wye transformer connection. Therefore, no zero sequence current will appear on the LV side of a secondary substation when a ground fault occurs on the MV feeder.

As the feeder is islanded, neutral grounding connection on the substation is lost and the system is ungrounded, being system's shunt capacitances the only path for ground fault currents.

Accordingly, it is possible to replace in the equivalent circuit $3Z_n$ by the equivalent impedance representing the lines capacitance, $X_C = -1/B$, where B is the shunt susceptance of the entire connected circuit.

Transformers equivalent impedances were neglected because their values are much smaller than those of generators.

Generator positive and negative impedances depend on the equipment considered. A synchronous machine has a negative reactance close to the sub-transient reactance, which is significantly lower than the positive reactance. According to [12], a three-phase inverter belonging to a photovoltaic system has negative reactance and zero reactance equal to zero, thus only the positive reactance should be considered. However, for three single-phase inverters the correct approach is to consider positive and negative reactances with equal values.

In both cases, the generator resistance is neglected because its value is much smaller than the reactance.

On simulations, generators were modeled considering equal positive and negative impedances, $Z_d = Z_i = jX_G$, where X_G is the equivalent generator reactance. This case reflects the network behavior with photovoltaic producers (single-phase and three-phase) connected through three single-phase inverters. Therefore, by circuit analysis, it is possible to establish that to occur a minimum 20 % distortion in the voltage on LV side it is sufficient that:

$$S_G < 12B \ \ [pu]$$

Simulation confirms this result.

The bound for S_G decreases from 12B down to the limit of 6B, when synchronous generators or three-phase inverters (photovoltaic installations) are used on LV, as the negative-sequence reactance is significantly lower than the corresponding positive-sequence reactance.

Differences between the curves from Figure 3 are related with the circuit shunt admittance, since there is a relationship between the resonance point, the installed power generation in the feeder and the shunt admittance.

Carefully analysing Figure 3, some zones where the condition is not met can be identified. For generation lower values, the condition can be neglected because it is impossible to achieve a stable island. On opposition, for generation higher values no voltage distortion appears, then a fault to ground in the MV feeder could not be detected on the LV side of a secondary substation with a delta-wye transformer connection.

Simulation conclusions

The main goal of this study was to analyse the hypothesis of removing maximum zero sequence voltage protection from DG facilities, conducting several simulations aiming to characterise the grid performance in island mode with high levels of DG under a ground fault.

The study shows that when a ground fault occurs in the MV feeder, the amplitude of the current flowing on the feeder does not change comparing with normal operation, and then there will be no relay trip by the overcurrent protection. It should be noted that the grid is supplied when the substation feeder protection trips because the DG sustain the load, and the MV feeder may operate in island mode.

The current flowing between the power generation facilities and the feeder is not adequate to protect the network against a ground fault. The same idea applies to secondary substation with high level of micro production.

Further, the earth connection shift from impedance to isolated causes a circulation of the fault current through the distributed grid capacitances.

During the fault, on healthy phases (MV side), voltages will increase to values close to phase-phase, that can cause an early aging of equipment's connected to them. Besides, people's safety could be compromised increasing the risk of injury, especially when occurring life works.

Simulations show that the voltage on the LV side can be influenced by two variables: the sum of the installed generation in the feeder (S_G), and the feeder characteristics, such as length, or either if it is an underground cable or an overhead line.

The main results are:

1) If the sum of the generators nominal power on the island is lower than half of the minimal load in the island, then it is expected that the generators will be put out of service by its frequency and over/under voltage relays.

$$S_G < \frac{1}{2}\sum P_{min}$$

2) If the sum of the generators nominal power on the island is lower than twelve times the susceptance of underground and overhead lines that form the island, then it is expected that at least one single phase of the generator will suffer a distortion higher than 20 %.

$$S_G < 12B \ [pu]$$

Condition 2) assumes that the power facility is single-phase and connected on the LV. If the power facility is three-phase or connected using three-phase inverters, the threshold on the nominal power decreases from twelve times to six times the susceptance of underground cables and overhead lines that form the island.

RECOMENDATIONS

The frequency and over/under voltage relays that equip the power facility cannot provide effective protection against a ground fault. The frequency relays are designed to operate in a situation of imbalance between load and generation and not for faults. The voltage relays need an overvoltage or undervoltage condition to operate, which does not necessarily occurs in the LV level due to a phase-to-ground fault in the MV. On the other hand, in Portugal, the secondary substations do not have maximum zero sequence voltage relays and in the presence of high levels of DG (connected in LV) could lead to a situation of feeding a ground fault indefinitely.

Therefore, the HV and MV power facilities, where none of the conditions 1) or 2) are met, should be put out of service under a ground fault, and then ought to be equipped with a protection system to detect a fault on the feeder, as the V0>. Alternatively, a teleprotection scheme could be considered to guarantee that all power generating facilities and relevant secondary substation will be disconnected when in island operation.

Live work must be executed safely. Accordingly, the relays should have a special operation mode for this situation, and trip instantaneously when a fault occurs. As recommended by international regulations, all power sources capable to impose voltage to the grid must be put out of service, regardless their technology, and avoiding the island mode.

CONCLUSIONS

The DSO has concerns about the protection requirements to eliminate ground faults in the presence of DG, due to the risk it could bring to people and equipment safety.

The paper performs a new analysis of the network state on the LV side (near DG) under a ground fault on the MV feeder. Simulations of multiple scenarios show that the voltage on the LV side can significantly change by the ground fault on the MV side under certain conditions. It was found that the voltage on the LV side can be influenced by two variables: the sum of the installed generation in the feeder (S_G), and the feeder characteristics', such as length, or whether it is an underground cable or an overhead line. This condition is sufficient to insure the overvoltage protection trip even at the LV side. If there is a large power unbalance between generation and load at the feeder the frequency protection will also operate.

These conditions, even if met in the present, may not be met in the future, and are, therefore, not future-proof.

The analysis confirm that the V0> protection is still the most robust way to protect the network against a ground fault on the MV side. The secondary substation located in a feeder with growing DG should be equipped with V0> protection, if the system does not meet the identified conditions or if future-proof is required.

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