ANALYSIS OF PROTECTION ISSUES IN AUTONOMOUS MV MICRO-GRIDS

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ABSTRACT

The paper focuses on the study of the protection problems arising in a MV autonomous micro-grid starting from the analysis of its physical and electrical characteristics in order to assess through numerical simulations how they influence the design of suitable protection schemes. From the viewpoint of distribution operators, it is advisable for technical and economical reasons to consider as far as possible protection devices based on the same principles used for fault clearing and isolation in a traditional distribution network, bearing in mind that any micro-grid protection scheme has to be compatible with the general scheme implemented in the main MV distribution system to which the micro-grid is connected.

INTRODUCTION

Among the innovative management philosophies currently investigated for distribution systems in the framework of active networks development [1], the concept of micro-grids is a promising perspective in order to exploit the potential benefits (ancillary services provision, service continuity enhancement [2], etc.) of distributed generation (DG) in distribution networks. Generally speaking, micro-grids can be regarded as LV or MV portions of public distribution networks as well as small networks designed for specific applications with ad hoc characteristics in terms of topology and generators/loads technology, etc. (some examples of different micro-grid structures are given in [3]-[7]). Micro-grids may be autonomous or not [8]. Typically they have to be able to operate in both configurations and can be electrically isolated from the remainder of the power system at a specific point (usually called Point of Common Coupling – PCC) and locally controlled by management systems able to ensure appropriate operation and protection, even in presence of distributed primary controls. Micro-grids correct and safe operation is technically possible only if local DG is able to ensure stability by controlling network voltage and frequency, and to resynchronize itself with the main system (useful references to this topic, which, however, is covered by a very large amounts of papers, can be found in [9]).

When micro-grids are to be implemented in order to improve service continuity, distribution network protections will have to be modified in order to introduce automation and fast protection devices to detect the faulty portion of the network, to disconnect it rapidly and to automatically reconfigure the network, if necessary, allowing for autonomous operation of micro-grids [10], [11].

In the present paper we will not deal with the control problems of a micro-grid but we assume the possibility that a portion of public network can be appropriately controlled to operate as an island in order to serve customers which can be considered “critical” from the service continuity viewpoint. We will focus on the study of the protection schemes required in a micro-grid in its autonomous operation, starting from the assumption that islanding may not be simply to be intended as a short duration operating mode required to cope with the consequences of a fault in the main system. This implies that solutions different from simply shutting down all generators when a second fault occurs in the island (assuming the first one has caused micro-grid islanding) have to be investigated.

Then, a suitable protection scheme for a microgrid operating in islanding mode for a long time duration (e.g. during system maintenance or, in general, as long as technical/economic issues creates a need for it) should be developed in order to ensure that faults inside the island can be rapidly and clearly isolated. Generally speaking, it could be advisable for both technical and economical reasons that the devices used to detect and isolate a fault inside an autonomous micro-grid were based on the same protection principles used for fault location in a traditional distribution network. Then we will discuss this problem and the main difficulties related to correctly protect a distribution island by using the protections “inherited” from its previous grid-connected operating mode with specific reference to Italian distribution networks (shortly described in [10]) managed by ENEL Distribuzione S.p.A. Practical examples and results of numerical simulations, carried out by DlgSILENT Power Factory® will be reported to show the potential lack of sensitivity and selectivity with the existing protective devices. The influence of the topological and electrical characteristics of a micro-grid on protections design will be discussed. The results of the presented analysis provide useful information to support the design of a suitable protection scheme for multi-phase and phase-to-ground faults in a micro-grid. Such a protection scheme has to be compatible with the general scheme implemented in the main MV distribution system to which the micro-grid is connected.

MICROGRIDS CHARACTERISTICS AND PROTECTION ISSUES

The micro-grid considered in the present paper is characterized by the realistic structure of a portion of public Italian distribution network supplied by a primary substation (PS), not by an ad hoc structure as often reported by scientific literature. As shown in Fig. 1, we consider a micro-grid able to start its autonomous operation after opening a switch at the PCC. The main characteristics examined to discuss micro-grids protection issues are: network extension, neutral grounding, presence of overhead lines or cables, bi-directional power fluxes and fault currents, DG technology.
Micro-grid extension can heavily affect network protection, also depending on neutral grounding. In fact, in case of line-to-ground faults, in neutral isolated networks the zero-sequence currents are directly influenced by lines length because lines contribute to the fault current through their line-to-earth capacitances. Then, reduced size networks, especially in presence of overhead lines, may have very small zero-sequence currents, such that traditional zero-sequence relays (and, consequently, earth-directional relays) might be not sensitive enough. On the other hand, such relays could have sufficient sensitivity in case of cable lines with an overall extension of a few kilometres, as cables determine a higher phase-to-ground fault current due to their greater transversal capacitance.

Network extension has little influence on fault currents in case of resonant earthing. However, this type of connection is typically used in traditional distribution networks to reduce fault currents and the potential sensitivity and selectivity problems of earth-directional relays are solved by introducing a shunt resistance so that directional wattmetric relays can be used. The possibility to reduce overvoltages and interruptions duration are typical advantages, which, however, should be accurately assessed in micro-grids with respect to the opportunity of changing the neutral grounding solution.

If we consider three-phase faults, the problem of micro-grid extension (and the lack of very high three-phase short-circuit power sources) has different consequences. The fault current may change by relatively small amounts as the fault moves along a feeder from one end to the other or from the MV network into the LV system. This makes it difficult to realize traditional over-current coordination [12].

The typical presence of multiple generators in a micro-grid makes non-unidirectional both normal power and fault current flows. This is a hindrance to the realisation of selective protection schemes unless directional relays are used [10].

The path of fault currents not only depends on the number of generators, but also on their reciprocal position (from this viewpoint, the presence of multiple generators connected at the same bus can be considered equivalent to the presence of a single generation unit of larger capacity). Generally speaking, different connection points of the generators may bring about different contributions to fault currents. DG technology is also related to the aforementioned issues. In particular, it is necessary to consider generators interface (“rotating” or “static”) with the network. In fact, there is a potential loss of protections selectivity and sensitivity in presence of DG with static interface (or inverter-based interface).

This is due to the fact that traditional protection against multi-phase faults is based on current sensing relays. It is known that rotating generators (synchronous and asynchronous generators) provide a relatively large contribution to multi-phase fault currents and traditional over current relays are likely to be always adequate in MV autonomous micro-grid as well. On the other hand, the presence of inverter-based generators leads to much lower fault current levels (typically, up to two or three times the inverter rated current [13], [14]), which makes the use of maximum current relays ineffective.
ANALYSIS OF A TEST MICRO-GRID AND SIMULATION RESULTS

This Section discusses some general considerations but also the results of specific numerical simulations of different fault conditions (three-phase and phase-to-ground faults) for the test micro-grid shown in Fig. 1. The simulations have been performed by means of DlgSILENT PowerFactory, version 13.1. As introduced before, the considered micro-grid is conceived as a portion of an Italian distribution network whose general main characteristics are described in [10]. With reference to them, in the test micro-grid we assume the presence of a satellite centre (SC) with three feeders (cable lines), to which three synchronous generators belonging to different APPs are connected (G-1, G-2 and G-3, with a rated power of 3.5 MVA). Twelve secondary substations represent the micro-grid loads, whose rated power is 200 or 400 kVA with PF=0.9. The lines length is relatively short and their main parameters are reported in Table 1.

In the performed analysis we assume the presence of the protections inherited from the grid-connected operating mode (i.e. connected to the main distribution network). The SC protection devices are specified in ENEL DK4451 ("Titled: Protection criteria for MV distribution networks"), while the protections installed at the auto-producers’ plants (APPs), referred to as “general protections” (GPs) and “Interface protections” (IPs), are indicated by the Italian standard CEI 0-16 (titled: “Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company”), as recalled subsequently.

The effect of the different fault types on the inherited protection system will be analysed with reference to:
• Phase-to-ground faults in neutral isolated microgrid;
• Three-phase fault in presence of “rotating” generators.

Phase-to-ground faults

The consequences of phase-to-ground faults are analysed considering a neutral isolated micro-grid as this condition appears to be the “natural” one after the transition from the grid-connected to the autonomous operation. In fact, the generators are typically neutral-isolated when the micro-grid is non-autonomous from the main network.

The SC protections affected by a phase-to-ground fault are the earth-fault directional relays (67N), i.e. 67N.S1, for resonant-earthed systems and 67N.S2, for earth-isolated systems.

The minimum values for current and voltage settings for protection 67N.S2 implemented in the SC of the simulated micro-grid are reported in Table 2. Earth-directional relays are installed in the SC at the sending-end of the supplied feeders.

| Table 2. Settings for SC protection 67N.S2 |
|-------------------------------|---------------|
| Io                            | 0.005-0.05A   |
| Uo                            | 0.4-20 V      |
| Angle Sector                  | 60°-120°      |
| Tripping time                 | 400ms         |

The APP GPs for phase-to-ground faults are a maximum zero-sequence current relay (51N) or an earth-fault directional relay (67N). The latter replaces the former when the contribution to the capacitive current for phase-to-ground faults in the APP MV network exceeds the 80% of the current setting established by the distribution operator for protection 51N.

The minimum values for current and voltage settings for protection 67N.S2 implemented in the APPs of the simulated micro-grid are reported in Table 3.

| Table 3. Settings for APP protection 67N.S2 |
|-------------------------------|---------------|
| Io                            | 2A             |
| Uo                            | 2V             |
| Angle Sector                  | 60°-120°      |
| Clearing time                 | 170ms          |

Fault inside the APP
If the phase-to-ground fault is inside an APP, normally the SC protection will not trip due to its time coordination with the APP protection. The APP protective device trips and clears the fault before the SC protection acts. However, if the micro-grid is not much extended the earth fault current could be excessively small, preventing the protective relay to sense it.

Consider, for example, that a zero-impedance phase-to-ground fault occurs on Line G-3. The simulation indicates that the APP earth directional protection trips in less than 170 ms (as required by standard CEI 0-16) since the local zero-sequence current is 3.73A and falls within the tripping angle sector. Consequently, the SC earth directional protection does not trip.

If we replace cable lines with overhead conductors, we obtain that APP protection 67N in Line G-3 is not sensitive to the zero-sequence current, which is 93mA. On the other hand the SC protection trips in 400ms. In such a case the only local device able to sense the fault condition is the maximum zero-sequence voltage protection, which trips in 5s.

Fault outside the APP
If the fault occurred outside of an APP, the local earth directional protection would not trip as the zero-sequence current would fall out of the tripping angle sector. Further
the current could be so small that it would not reach the tripping threshold. This would prevent protection 51N to trip, in case it was replacing protection 67N. CS 67N, i.e. the earth directional protection installed at the sending-end of the feeder in which the fault occurred, could sense the fault and trip (provided that there are not sensitivity problems). This device would disconnect the whole feeder from the SC. The APPs would disconnect themselves from the feeder after the action of their IPs.

Let us consider a zero-impedance fault in Branch 1.3. All APPs 67N protections can not operate for external faults as they “see” a zero-sequence current which is too small (10mA) and out of their tripping angle sector. On the contrary, SC 67N protection installed on Branch 1.1 senses a zero-sequence current of 2.6A (which falls within the angle sector) and trips in 400ms. This allows to identify the faulted feeder (but not the branch).

Simulations of the micro-grid with overhead lines have shown that the zero-sequence current of 65mA sensed by the SC 67N protection is very low, even though it may still cause the protection tripping. In both cases of phase-to-ground faults inside or outside of an APP, should local protections 51N or 67N not operate due to a lack of sensitivity, maximum zero-sequence voltage protections (59N) belonging to all the APP IPs, could trip. This could cause the disconnection of all micro-grid generators.

Three-phase faults
The SC protection affected by an overcurrents multi-phase faults is a maximum current protection, with one only tripping threshold. It should be as fast as possible and have a current setting suitable to allow selectivity with the upstream protection (installed at the primary substation, when the micro-grid is connected to the main distribution network, on the sending-ends of MV feeders) and the downstream protections for faults in the LV system. The APP GWs for overcurrents require a maximum current protection with different tripping thresholds. For the sake of brevity Tables 4 and 5 indicate only the settings of the protection tripping thresholds involved in the analysis of the simulation results referred to short-circuits events, reported in the following.

<table>
<thead>
<tr>
<th>Table 4. Settings for APP protection 51</th>
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<tr>
<td>Zero fault impedance</td>
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<tr>
<td>Current</td>
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<tr>
<td>Clearing time</td>
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<th>Table 5. Settings for SC protection 51</th>
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<tbody>
<tr>
<td>Current</td>
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<tr>
<td>Tripping time</td>
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Fault inside the APP
In case of a three-phase short circuit inside an APP, local GP 51 would trip. Further, due to the absence of an intentional delay the SC protection, which would sense almost the same fault current, would also trip. In practice, there would not be selectivity between the two protective devices. In particular, the APP protection trips later than the SC device (which is instantaneous), especially for low impedance faults. High impedance faults could lead to lower fault currents which could not reach the SC protection tripping threshold.

Consider, for example, a zero-impedance fault on Line G-3. SC protection installed in Branch 3.1 trips instantaneously, as it senses a fault current of 1.57kA, thus identifying the faulted feeder. Line G-3 protection will trip in less than 120 ms. After that the fault is cleared but all the customers connected to feeder 3 are left unsupplied.

Fault outside of the APP
As for a three-phase short circuit occurring outside of an APP, the SC protection would trip. However, the fault would be sensed by the APPs protections, which are not directional and, consequently, might trip as well.

Let us consider a zero-impedance fault in Branch 3.2. SC maximum current relay installed on Branch 3.1 will sense a fault current of 1.577kA and trip instantaneously. After 120ms, Line G-3 protection will trip, being affected by a fault current of 0.796kA. The fault will thus be cleared but all the customers connected to feeder 3 will be left unsupplied.

Finally, it should be pointed out that, in order to assess precisely the possible behaviour of the IPs, more extended simulations should be performed under several transient conditions. However, the developed analysis has shown that assuming for the IPs tripping times slightly longer than the ones of GPs will lead to the aforesaid results.

CONCLUSIONS
The short analysis presented in this paper aims at highlighting some of the main issues regarding the operation of the traditional protections when a portion of the MV distribution network (micro-grid) inherits them after its transition to the autonomous operation. It is apparent that the considered protection schemes have to be updated or even redesigned in order to provide a higher service continuity level to the micro-grid “critical” customers, which are supposed to require it.

The results shown in the paper are part of a preliminary study which is intended to provide useful information needed to design innovative protection schemes that account for the presence of generators based on different technologies as well as for the specific characteristics of the considered micro-grid. It is worth to be remarked that the general micro-grid concept has several possible aspects and an effective protection scheme is not expected neither to be the only possible nor to have general validity for any micro-grid typology.

However, considering the low levels of interruptions frequency and duration that are to be achieved, the protection solutions have to be based on an adequate use of automation and information/communication technologies. To a great extent, such technologies allow to implement innovative and effective protection schemes even if protection designers prefer to make use of traditional fault sensing techniques.
REFERENCES


