TRANSFER TRIP OF LOSS OF MAINS PROTECTIONS AND LOGIC SELECTIVITY BY IEC 61850 PROTOCOL: AN ANALYSIS BASED ON EXPERIMENTAL DATA

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ABSTRACT

The paper details the Smart Grid experiment developed by A.S.SE.M. SpA (a DSO of Central Italy), incentivized by the Italian Energy Authority in the framework of Resolution ARG/elt 39/10. The work focuses on the analysis of the experimental data collected about two innovative features: the increase in the reliability of Loss of Mains protections by transfer trip messages and the logic selectivity between MV protections. Both functions are achieved exploiting the capabilities of the IEC 61850 communication protocol.

INTRODUCTION

The increasing penetration of Dispersed Generation (DG) currently involving power systems requires a conceptual revolution of the approach to manage distribution networks. These grids have been designed as passive systems, with unidirectional electricity flows from the HV network to MV/LV grids. However, DG injections can cause power flows to reverse. In this situation, the distribution grid is an active system and its operation is no longer consistent with the original design criteria.

The term "Smart Grid" (SG) identifies the solutions to overcome these problems: they make extensive use of innovative products and services, combined with intelligent monitoring, control, communication and self-healing technologies. The development and experimentation of SG solutions covers a pivotal role in all the strategies recently proposed at EU level to promote the evolution toward a new, efficient and sustainable, energy paradigm. With a similar approach, in Italy, the Energy Authority (Autorità per l'Energia Elettrica il Gas ed il Sistema Idrico, AEEGSI) recognized a central role to the DSOs in the evolution of electrical networks toward the SG concept. In 2010, AEEGSI launched a selection process for SG demonstration projects, providing an innovative incentive scheme for SG experiments set up on active MV networks (Resolution ARG/elt 39/10 [1]). The projects worthy of incentive are granted an extra-WACC (Weighted Average Cost of Capital) of +2% (on top of the "ordinary" WACC, equal to 7%, for distribution network investments) for a period of 12 years. By this initiative, AEEGSI aims to collect detailed data from the experimental projects, useful to define a novel regulation for SG investments, based on the actual effects of interventions on the operational performance of the grid.

To gain access to the selection procedure, the project proposals have to satisfy a set of minimum requirements: the experiment has to involve a real MV network with Passive and Active Users; the MV network has to be an active network (reverse power flow at the HV/MV interface for at least 1% of the year); non-proprietary communication protocols have to be used to communicate with Active Users. In addition, demonstration projects can adopt further "smart" functionalities [2]: demand response strategies with final customers, infrastructures for electric vehicles, storage systems, DG dispatching, and so on.

In the just mentioned framework, A.S.SE.M. SpA (Azienda San SEverino Marche SpA, a small DSO of Central Italy) submitted an experiment proposal aimed at introducing a set of innovative automation and control features within its distribution network. The proposal has been approved by AEEGSI, together with 7 other projects, through Res. ARG/elt 12/11 [3].

In the following, the paper will focus on the main features, architectural characteristics and beneficial effects of the A.S.SE.M. SG experiment, with particular reference to two innovative features: the increase in the reliability of Loss of Mains protections by transfer trip messages, and the logic selectivity between MV protections. More details on the other innovative features developed in the Project can be found in [4].

THE PROJECT ARCHITECTURE

The Smart Grid pilot project is developed on the 20 kV electricity distribution network of San Severino Marche (a town of about 13,000 inhabitants in the Macerata province), involving the A.S.SE.M. control center, a HV/MV substation, an MV/MV Satellite Substation (SaS), ten MV Active Users (AUs in Figure 1) and one LV Active User. The devices widespread over the distribution network are connected with a suitable communication system, created by mobile network, Wi-Fi and Fiber Optic (FO) technologies.

The Project provides the following main features:

1. increase in the reliability of Loss of Mains protection of AUs by transfer trip messages with "fail-safe" logic, in order to prevent the unintentional island operation of DG plants (or their unwanted disconnection with possible domino effects);
2. novel fault management based on the selective interlocking between the protection relays in the HV/MV substation and SaS, and on the remote control of switches along lines, with the purpose to improve Users' continuity of service;
3. centralized voltage regulation performed by modulating reactive power injections of each DG

unit, aimed at increasing the network Hosting Capacity for RESs, improving the voltage quality and the distribution service efficiency;

4. limitation/modulation in emergency of the active power injected by each DG unit;
5. monitoring and control of DG injections, to provide data suitably categorized (DG; load) to the TSO and to allow the management of DG power injections according to the needs of both the transmission and the distribution network.

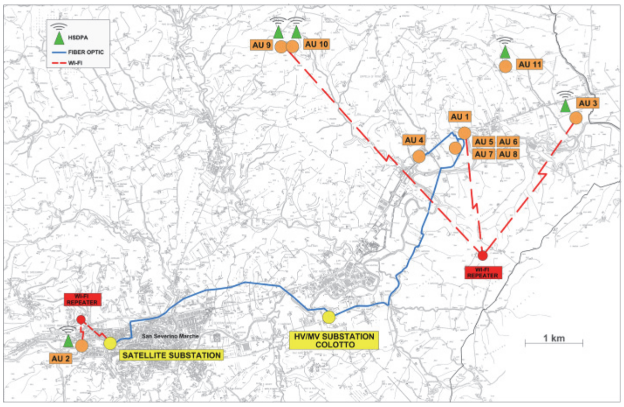

Figure 1. Communication system developed in the Project.

The control center and the HV/MV substation

The SCADA/DMS unit sited in the A.S.SE.M. control center (located close to the HV/MV substation) is the heart of the SG architecture. It provides the usual capabilities of conventional SCADA and DMS units, plus the novel SG features conceived in the Project. In detail, the SCADA/DMS allows the DSO to have a real-time overview of the MV network and to control the peripheral units and generators on the grid. In addition, it performs fault selection and isolation procedures by coordinating the maneuvers of switch disconnectors in MV/LV substations and the reclosing procedures of circuit breakers in HV/MV substation and SaS. As better explained in the following, the core unit also supervises the exchange of transfer trip and keep-alive messages with the Interface Protection Relay (IPR) of DG power plants and manages the communication with the TSO, to provide data about the DG/load subtended to the distribution grid and to enable the reception of limitation commands for DG power injections. Moreover, the SCADA/DMS is equipped with a voltage regulation algorithm, which optimizes the voltage profiles on the MV network through the control of DG reactive power injections, and supervises the Automatic Voltage Regulator (AVR) of HV/MV transformers.

In addition to the SCADA/DMS, the Primary Substation (PS) is equipped with novel protection and automation devices, which replace the conventional devices installed in HV/MV substations. Atop of each MV feeder a circuit breaker piloted by a Feeder Protection Relay (FPR) designed to send transfer trip messages to the downstream DG units is installed. Similar devices are also placed on the HV and MV side of transformers. In addition, the PS is equipped with an acquisition system for the voltage/current measurements and a communication interface with the A.S.SE.M. control center (Fiber Optic).

The Satellite Substation

The Satellite Substation (SaS) is a MV substation with 5 outgoing MV feeders. The SaS is equipped with a subset of the equipment of the HV/MV substation: atop of each outgoing MV feeder, a circuit breaker piloted by a protection relay equivalent to the relays installed in HV/MV substation atop of each MV feeder is installed; moreover, a data monitoring system and a FO communication link with the PS are present.

The Active User

Each MV AU involved in the Project is equipped with an innovative Interface Protection Relay (IPR) of the DG power plant, designed to receive transfer trip and keep-alive messages from the upstream FPR. In addition, further control and monitoring devices are installed to perform all the features provided by the experiment. A processing unit manages the switch disconnectors and fault detectors on the MV line (Fault Passage Indicators) and allows the acquisition of voltage measurements at the MV busbars of the MV/LV substation, the metering data acquisition (through the existing meters, if they support a ModBus communication, or dedicated meters) and the control of DG active and reactive injections. A DG Controller actuates the set-point of reactive power on the generator and, when needed, the active power limitation command received from the core unit in the PS.

The communication system

The communication system is a combination of three different transmission vectors: mobile network (GSM/3G), Wi-Fi and FO (Figure 1). Non-proprietary communication protocols are used to communicate with Users and devices over the network (IEC 61850 [5]).

Two communication channels in FO depart from the PS: a FO line links the SaS to the central system, while the second one reaches the industrial area of San Severino Marche, where most of AUs are located. The FO link between the PS and the SaS is installed partially on overhead lines and partially on underground cables, while the link toward the eastern area of the city is created with underground FO.

In order to connect AUs in sites difficult to reach by FO, Wi-Fi links have been used. The experimental configuration includes three Wi-Fi links toward four different AUs, based on the IEEE 802.11n technology and supporting Layer 2 communication with a transmission rate up to 300 Mb/s.

Communication with the UAs connected by the Wi-Fi channels is backed-up by the mobile network (AUs 2, 3, 9 and 10), so as to increase the reliability of the system and to allow a comparative performance assessment of the two carriers. The LV User (AU 11) has only access to the mobile network, to provide a cheaper solution (easily deployable in the future).

TRANSFER TRIP OF ACTIVE USERS' LOSS OF MAINS PROTECTIONS

The A.S.SE.M. project provides an evolution in the management of IPR of AUs, devoted to improve their operational performance w.r.t. the scenario in which only local measures are exploited. Moreover, the communication system is used to perform logic selectivity among MV protections, increasing the Quality of Service of Users.

Today, as a result of the tripping of an FPR detecting a fault, the entire line is disconnected and an automatic reclosing procedure is carried out to try to restore the service. To accomplish the fault current extinction, it is essential that, when the circuit breaker atop of the line opens, the IPR of the subtended DG detects the loss of mains and disconnects the relevant power plant (within the first reclosing maneuver: 400/600 ms on Italian MV distribution networks). This action is performed according to network voltage and frequency (passive islanding detection methods): when deviations beyond the given thresholds are detected, the IPR trips. However, problems could occur in scenarios with great DG penetration: if the generation equals the load, LoM protections do not detect significant deviations on network voltage/frequency and power plants on the MV feeder could remain in operation after the FPR tripping. If narrower frequency/voltage thresholds are adopted on the IPR to avoid this phenomenon, there is greater possibility of nuisance tripping of the IPRs owing to faults on adjacent MV feeders. Furthermore, a massive DG disconnection could take place in the case of severe frequency transients on the interconnected European system.

In the project, proper information is exchanged between the FPR in PS/SaS and the IPR located at the DG premises to increase LoM protections reliability. In addition, the IPR is equipped with a suitable logic enabling the DSO/TSO, during emergency conditions, to control the disconnection of DG power plants on the distribution network (scheduled DG shedding), according to the recent requirements of the Terna Annex 72 [6].

To overcome the poor performance of actual IPRs, which operate only with local information (voltage magnitude and frequency), two types of messages are exchanged with IPRs: "keep-alive" and "transfer trip" messages. Keep-alive messages monitor cyclically (e.g., every second) the proper operation of the communication channel between the central system and the AU. If the communication system works properly, the LoM protection relay keeps wider settings (wide frequency thresholds: 47.5-51.5 Hz); on the other hand, if the communication fails (a keep-alive message is not received), the IPR comes back to operate based on local information (narrow frequency thresholds, 49.8-50.2 Hz, or activation of the voltage unlock logic). By adopting this protective strategy, nuisance tripping owing to faults on MV adjacent feeders is avoided. Moreover, the risk related to the massive disconnection of DG, which could considerably impact on the overall power system stability, is greatly reduced (during normal operation the wider, less sensitive, frequency thresholds are adopted). The transfer trip message is sent by the FPR to the subtended IPRs in order to ensure the DG disconnection when the feeder protection trips (Figure 2).

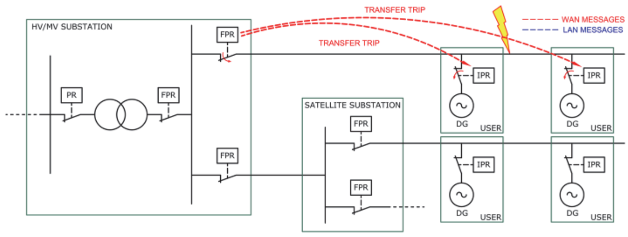

Figure 2. Transfer trip message sent to the DG units underlying a distribution feeder.

The transfer trip message (based on a GOOSE message defined by protocol IEC 61850) is sent directly by FPRs to IPRs to minimize the time required for the data processing and transmission. However, the process requires the supervision of the core system: the correspondence FPR-IPRs must be kept properly up to date to allow the FPR upstream of the faulted line to disconnect all (and only) the underlying DG units. Changes in the network configuration can entail the transfer of some AUs from one feeder to another. To this purpose, the core unit configures the communication interface of AUs (routers) in real-time, to associate the FPR with the underlying IPRs. This way a selectivity of MAC addresses is obtained: each router properly filters the GOOSE messages sent on the Wide Area Network in order to receive only the information addressed to the relevant IPR.

The logic implemented on the IPR of the AUs to manage the frequency thresholds according to the availability of the communication system is shown in Figure 3.

a. The reception of the GOOSE keep-alive message (signal #1 in Figure 3) switches the logic signal #2 to the "high" condition.
b. The logic signal #2 stills in the "high" condition for a time equal to 1.5 T_{KA}, where T_{KA} is the time between two consecutive keep-alive messages (e.g., 1 s).
c. The logic signal #3 is the #2 negated: it switches to "high" if the communication system is not available (in the worst case, at least for a time equal to 1.5 T_{KA}).
d. For hydro generators (to minimize the risk of an out-of-sync automatic reclosing), the dotted link #4 is enabled, commanding, in the absence of the communication system, the narrowing of frequency

thresholds (through “high” logic signals #4 and #5).

e. For PV generators (which tolerate possible out-of-sync reclosings), link #4 is disabled, so the absence of the keep-alive messages orders the activation of the signal #5, which enables the voltage unlock logic (inhibited in the presence of the communication system by the logic AND condition, not verified by the state “low” of signal #5). This way an improvement of the continuity of service w.r.t. the standard condition is achieved.

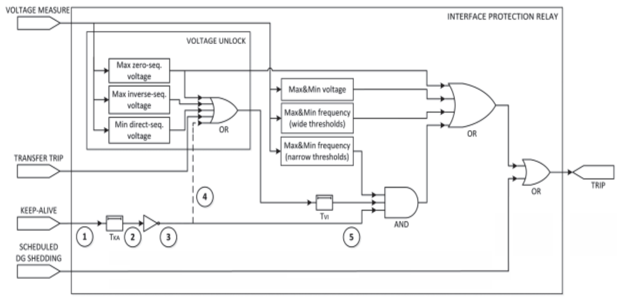

Figure 3. The logic implemented on Active Users' IPRs.

LOGIC SELECTIVITY BETWEEN MV FEEDER PROTECTIONS

In the A.S.SE.M. Smart Grid experiment, MV feeder protections are coordinated by the exchange of suitable IEC 61850 messages. By means of these messages, logic selectivity among protections is set up, improving the performance in the selection of the faulty section of the MV feeders. The logic selectivity during a short-circuit operates as follows (Figure 4): the FPR upstream the fault detects an overcurrent (protection functions 50, 51, 67N) and sends a block message to the FPRs in the HV/MV substation. The FPR that does not receive the block message within a given time commands the tripping of the relevant circuit breaker. If messages do not reach a protection relay due to problems on the always-on communication, the system operates with time selectivity.

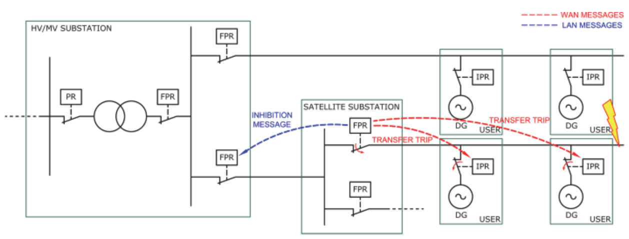

Figure 4. Automatic reclosing with logic selectivity.

According to this strategy, the isolation of the fault is carried out with a single maneuver, by disconnecting only the faulted section. Therefore, this innovation has clear effects on the number and duration of interruptions affecting Users. Moreover, the reclosing procedure is carried out directly by the FPR in SaS, avoiding perturbations on the upstream feeder and disconnecting only the DG underlying the tripped protection (Figure 4).

EXPERIMENTAL RESULTS

The main factor affecting the performance of the SG architecture in improving the reliability of IPRs and the continuity of service of Users is the time required to exchange messages among the apparatuses along the network's feeders (IPRs or FPRs in the Satellite Substation) and the central system (FRPs, atop of MV feeder, in the HV/MV substation).
To ensure the disconnection of an AU when the relevant FPR trips, avoiding the islanded operation of the DG and possible damages to the generator, the IPR must receive the transfer trip message sent by the FPR before its first reclosing maneuver (as already mentioned, usually performed 400/600 ms after the tripping):

$$t_T + t_{IPR} + \varepsilon_{DR} < t_{DR} \tag{1}$$

In eq. (1):

- t_T is the time needed for the transmission of the transfer trip message on the communication system;
- t_{IPR} is the time required by the IPR to detect the reception of the transfer trip message and to open the interface circuit breaker of the relevant DG unit (e.g., 100 ms);
- ε_{DR} is a security margin against time errors (e.g., 10% of t_{DR});
- t_{DR} is the time delay set on the FPR for the first reclosing maneuver (e.g., 400 ms).

The time required by the FPR to detect the fault and begin the transmission of the transfer trip message does not appear in eq. (1) because the time delay of the first reclosing maneuver is calculated from the instant of transmission of the opening command by the FPR to the relevant circuit breaker, which is simultaneous to the instant of transmission of the transfer trip message by the FPR to the IPR.
As for the logic selectivity among the protections in the SaS and the protection atop of the relevant MV feeder, the upstream FPR must receive the inhibition message sufficiently in advance with respect to the scheduled tripping:

$$t_{DW} + t_{UP} + t_T + \varepsilon_{DT} < t_{DT} \tag{2}$$

In eq. (2):

- t_{DW} is the time required by the downstream FPR to detect the fault and to order the transmission of the inhibition message (e.g., 20 ms for the phase overcurrent function);
- t_{UP} is the time required by the upstream FPR to detect the reception of the inhibition message and to activate the logic inhibition (e.g., 10 ms);
- t_T is the time needed for the transmission of the inhibition message on the communication system;
- ε_{DT} is a security margin against time errors (e.g., 10%

of t_{DT});

- t_{DT} is the time delay set on the upstream FPR (e.g., 100 ms), which includes the base time of the upstream relay.

Figure 5 and Figure 6 report the estimated time for the accomplishment of the just mentioned novel SG features. In detail, Figure 5 shows an estimation of the time needed for the tripping of the IPR (the time is measured starting from the instant of transmission of the opening command by the FPR to the relevant circuit breaker). Figure 6 shows the estimated time needed to accomplish the inhibition of the upstream FPR and perform the logic selectivity (time measured starting from the fault instant).

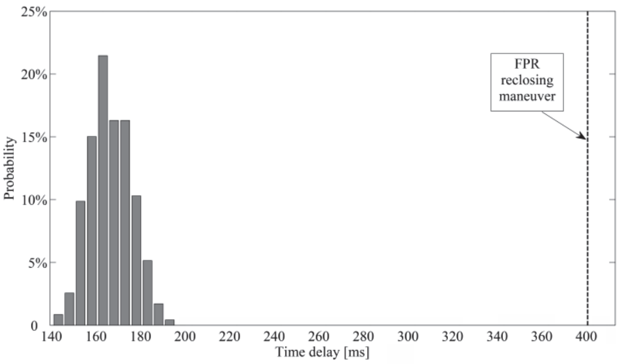

Figure 5. Estimated time for the IPR tripping.

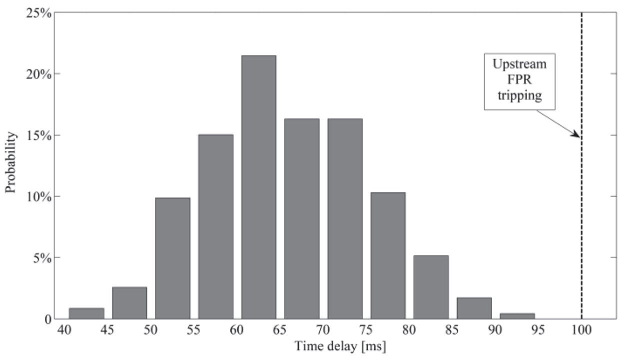

Figure 6. Estimated time for the FPR inhibition.

The two plots are obtained applying eq. (1) and eq. (2) to the time delay for the transmission of GOOSE messages (t_T) measured on the experimental SG project during May 2014 (about 240 messages). Both the just mentioned SG features exploit IEC 61850 GOOSE messages to satisfy the binding time requirements of the data exchange between the relays. Therefore, from the communication system point of view, transfer trip and inhibition messages are managed exactly in the same way. For the parameters t_{IPR}, ε_{DR}, t_{DR}, t_{DW}, t_{UP}, ε_{DT} and t_{DT} the typical values previously mentioned are assumed. To collect a suitable amount of experimental data, the performance of the transmission system was tested continuously, by exchanging test GOOSE messages among all the protections. These signals are identical to standard messages, with the exception that they do not activate any logic function on the receiving protection.

One can observe that, in both cases, the time delay measured experimentally is compliant with the time requirements of the SG features envisaged: all GOOSE messages are received within the time limits of the relevant function. However, it is worth noting that the tests performed do not consider the possible decay in performances due to temporary events (e.g. severe weather conditions could drive to contingencies in electric equipment, but also to outages in TLC apparatuses, decreasing communication performances). Only the future evolution of SG technologies will allow to deal with these situations, typical of real life applications.

CONCLUSION

The Smart Grid pilot project developed by A.S.SE.M. SpA, incentivized by Italian Res. ARG/elt 39/10, allows the testing of the main functionalities required to address the increasing RES spreading on power systems in a real scenario. The assessment of the performance and practical applicability of SG solutions in real contexts is essential in the perspective of a full-scale deployment of SGs. Among the experimented features, the control of the IPR of AUs by transfer trip and keep-alive messages will ensure the reliable and effective management of DG units underlying distribution grids, even during faults and perturbations on the HV system. Moreover, the logic selectivity among FPRs will allow the DSO to limit the impact of faults on Users' continuity of service.

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