LEVERAGING FAULT DETECTION AND VOLTAGE CONTROL IN LOW VOLTAGE GRIDS BASED ON DISTRIBUTED MONITORING

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ABSTRACT

Monitor BT project's main goal is to develop and deploy advanced functionalities for fault management and voltage control on Low Voltage (LV) grids, potentiated by the information of distributed sensors. These operational parameters collected along the feeders by wireless meshed sensors enable fault detection and localization, fuse-blow detection in cabinets and secondary substations, leading to a reduction on the interruption time, improving Quality of Service (QoS). Furthermore, last-gasp alarms from sensors allow maintenance teams to react faster, supported by geo-referenced outage data provided by the Outage Management System (OMS).

Monitoring LV feeders by deploying distributed sensors assures that the increasing micro-generation penetration is monitored, leveraging dynamic voltage control through the active management of Photovoltaic (PV) production by controlling their inverters with set-points calculated locally at the secondary substation.

The developed equipment and functionalities will be integrated in a pilot grid area of EDP Distribuição (EDP Group), Portugal (Portuguese DSO), whose infrastructure will provide a realistic scenario for validation of the solution.

INTRODUCTION

This paper presents the initial results of the Monitor BT project (started in June 2013) that aims at researching innovative technologies to increase the monitoring and control of the LV level in distribution grids. Currently, in distribution grids, the LV level is still passive due to the lack of observability and control capabilities. Smart Grids envisage the deployment of more intelligent equipment and communication interfaces up to costumer's level. Based on this trend, the project develops a set of advanced functionalities for the LV grid, including: i) LV fault detection and location, ii) detection of faults and faulty light bulbs in public lighting feeders and iii) dynamic control of the injected power by Photovoltaic (PV) micro-generators for voltage regulation.

MONITOR BT OVERVIEW

The Monitor BT is an R&D project supported by EU funds granted by QREN, the National (Portuguese) Strategic Reference Framework.

Efacec Engenharia e Sistemas (Efacec) and Inesc Inovação (INOV) are the project co-promoters. The Portuguese Distribution System Operator (DSO) – EDP Distribuição (EDP) – plays the role of project associated partner, as EDP holds the field demonstrator to be deployed in the region of Batalha, in the centre of Portugal. One of the main goals is to demonstrate fault detection and location in LV grid segments, both at feeder and at public lighting level. Furthermore, it will also allow detecting and locating faulty bulbs in the LV public lighting segments.

Besides this field demonstrator, there is another laboratory demonstrator for controlling the injected power by micro-generators. The reason for this lab proof of concept results from the practical impossibility of controlling micro-generators when installed in the LV grid, for two reasons. In one hand, one cannot interfere in existing installations; in another hand, the present Portuguese regulation does not allow controlling the injected power by micro-generators' inverters, as those assets are supposed to inject as much active power as possible, provided that there is no voltage upper threshold violation.

As a consequence, this trial will be carried out in a live lab, under a physical simulator of the LV grid, using real operational scenarios. These scenarios will reproduce real conditions of the LV segments in Batalha, as close as possible. The system to be developed and installed in the LV grid will be able to collect faulty data, concerning the monitored node voltages and line currents, as well as other measurements (power and power factor). These values will be then used at the live lab, so that real scenarios could be used for simulation and testing purposes.

Figure 1 depicts the system architecture supporting both mentioned demonstrators.

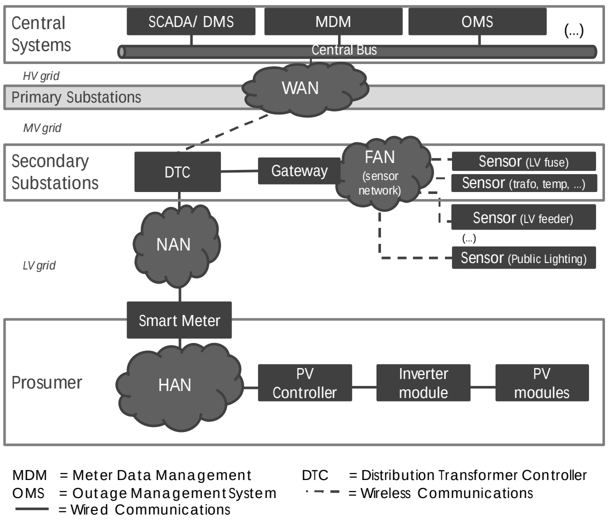

Figure 1: Monitor BT's reference system architecture

The rationale behind the architecture is the distributed approach combining all hierarchy levels of a distribution company.

Central Systems play an important role in any operation paradigm by an electric power utility, which also occurs within the Monitor BT project. Its goal, at this level, is performed by a SCADA/DMS system, managing all status alarm indications arising from the LV grid, in all its components, e.g. fault detection and location at LV feeders and LV public lighting, as well as faulty lamp detection within the latter, and finally any voltage violations arising from dispersed PV micro-generation.

As there will be plenty of technical data from the LV grid, at Central System level it will also be possible to trace the grid stress at LV level, namely at the nodes where sensors will be deployed, covering the secondary substation transformer fuse and the electric cabinets along the feeder.

A wider awareness of the assets and of the way the grid affects them is a key point of the Monitor BT project.

Furthermore, from an operational perspective, fault detection, faulty light bulbs detection and their location, is a key feature which serves the role of the Outage Management System (OMS).

Besides the SCADA/DMS and OMS, both representing the operational perspective of the utility, there is also the meter perspective because, at the lowest level, there are consumers and micro-producers, or even prosumers.

A Meter Data Management (MDM) system collects and deals with metering data arising from all downstream smart meters, for any due purposes such as those by an energy supplier or an aggregator. A central bus network brings all those systems together, as well as any other deemed to perform jointly and in a distributed way.

A WAN bridges the Central Systems with the systems deployed at lower level, namely at the Primary Substations – assuring the automation and protection of the electric power distribution backbone - and at the secondary substations. The Monitor BT project envisions the integration of Distribution Transformer Controllers (DTC), which correspond to the Intelligent Electronic Device (IED) placed at secondary substation level.

The DTC is also able to monitor the MV side of the grid, namely the MV grid switching state, besides providing MV fault detection suitable for self-healing algorithms while responding to the Central Systems. Furthermore, it also comprises LV grid monitoring, acting as the master station of the downstream feeder sensors. The Field Area Network (FAN) supports the connectivity between the DTC and field sensor devices.

DTC acts in the frontier between the MV and LV voltage levels. At LV level, DTC gathers all alarm status indications arising from – but not limited to – LV fuse sensor, secondary winding measurements, feeder distribution cabinet measurements (underground and overhead), as well as public lighting pole installed devices.

Besides, DTC also communicates with downstream Smart Meters, both at customer, producer or prosumer level, the latter depicted in the architecture. Therefore, DTC plays the role of metering concentrator, as it gathers metering data from any downstream Smart Meter via a PLC/Prime Neighbourhood Area Network (NAN). This specific data is transmitted via Web Services to the Central System, namely to the MDM via a metering head-end.

This system wide approach follows the InovGrid [1] paradigm deployed by EDP.

Sensors are deployed both at LV feeder and public lighting level. Furthermore, sensors are also deployed at secondary substation level, able to monitor temperatures (transformer, substation housing), current at the LV fuse and feeder node voltage. These sensors communicate with the DTC, the secondary substation master unit, via a gateway. The communication between the gateway and the sensors is provided via FAN characterized for being an RF meshed network.

The Smart Meter will communicate with the micro-generator's inverter via a Home Area Network (HAN).

One of the major Monitor BT's goals is the control of the injected power by PV micro-generators, a role played by the DTC, the Smart Meter, the PV controller and the inverter module.

Once DTC receives and processes LV node voltages, it is able to assess the grid status and determine which set-point controls should be sent to the PV inverters through the HAN and directly to the PV controller which, in turn, is responsible for setting the appropriate Power level to be injected by the PV inverter, and subsequently, harmonizing the voltage profile and the faulty node.

LV Fault Detection and Location

The first level of LV Fault Detection and Location (FDL) is performed by the sensors deployed along the LV feeders. These sensors are able to detect fault currents and to report them to the upper level master station, the DTC.

As previously mentioned, these sensors dialogue via RF Mesh with a gateway placed in the secondary substation, which in turn dialogues with the DTC.

Upon a power outage, e.g. as a result of the blowing of a LV feeder fuse, sensors are still able to dialogue with any other sensor acting as a communication relay, so that the fault report could be sent to the DTC. This feature is called “last gasp”, corresponding to the last effort of the sensor, under an outage, to assure a proper fault data reporting.

Once aware of all faulty data, the DTC assesses all gathered information – fault indications and respective measurements, other current measurements and node voltage measurements – and as a result, it will be able to identify the pair of adjacent sensors where the fault has occurred. This information is important, as it can be disclosed at Central System level, namely to the OMS, enabling a quick response from maintenance crews.

Figure 2 presents the monitoring sensors expected to be deployed in a LV 3-phase feeder of the pilot demonstrator to be installed by EDP in Batalha. The feeder has five overhead segments, where PV micro-generation is also present.

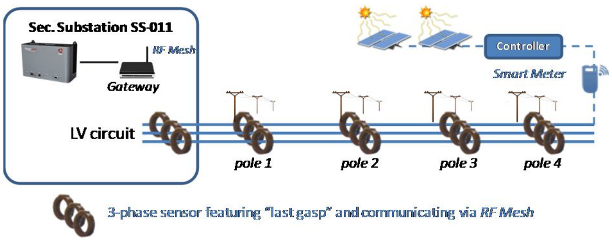

Figure 2: Monitor BT’s pilot demonstrator in Secondary Substation “SS 011”

Figure 3 presents the monitoring sensors expected to be deployed in another LV 3-phase feeder of the same pilot demonstrator. The feeder has four segments, the first three being underground (dashed lines) and the last being overhead. This figure also comprises two single phase Public Lighting feeders.

Public Lighting Fault and Faulty Light Bulb Detection and Location

Public Lighting (PL) fault detection and location does not differ from the description presented in the previous section.

The single difference relies on the fact that for the pilot demonstration, two single phase PL feeders will be used, leading to the deployment of single phase sensors.

Even though, DTC plays an identical role, dealing with faulty data for each PL segment and therefore acting is the same way as described before.

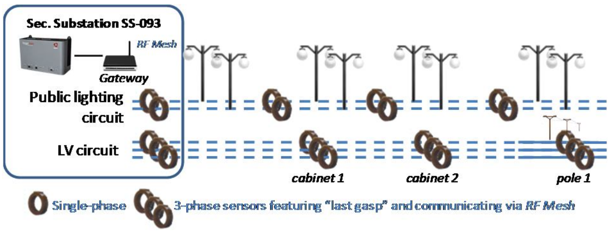

Figure 3: Monitor BT’s pilot demonstrator in Secondary Substation “SS 093”

The pilot includes a 3-phase feeder and two single phase PL underground feeders, each with four segments.

Similarly to the description of the previous section, DTC will be able to identify the pair of adjacent sensors stating any fault location.

Concerning the faulty light bulbs detection and location, any occurrence affects the current level at upstream sensors. This kind of information is gathered and performed by the DTC. DTC algorithm will take into consideration the transient regime of PL switch on and of any intermittent behaviour of specific lamps, which will affect the current on the segment it resides in. This flickering happens commonly when the voltage level is below a certain limit which may occur at the end of the PL feeder.

The DTC will be able to identify the pair of adjacent sensors stating the location where the faulty light bulb is.

Dynamic Control of Micro-generation

The distribution system is becoming more volatile than ever. Several different actors are introducing more variability on network operational parameters. Various customer types with high diversity factor establish the base load of the system. However, the installation of new micro-generation units is being incentivized and several consumers are also becoming producers at LV level. To be able to control all these participants and optimise network operation, smart grids introduce the distributed intelligence and communication capabilities to enable smart control schemes.

Monitor BT also aims at dynamically controlling the power being injected by PV micro-generation.

Due to statutory issues, it is not possible to deploy a pilot demonstration in Batalha or in any other EDP’s real grid infrastructure. As a result, the proof of concept will be tested and demonstrated in a live laboratory.

The live lab will have a simulator representing, the LV grid section presented in Figure 2.

Real inverters and DC power sources will be used, as well as a real LV grid interconnection. A DTC, inverter controllers and smart meters will play their role as well.

The Monitor BT architecture and functionalities enable the Distribution System Operator (DSO) with the possibility to interface with field equipment such as inverters through their communication port in order to control their power output.

Moreover, voltage profile volatility is one of the main problems of weak radial networks which is a common characteristic of LV networks, especially in the presence of high levels of micro-generation units. Voltage magnitude must be kept within the statutory limits at all times. European electricity supply regulations (EN50160) stipulate that steady-state voltage magnitude for low voltage systems should be 230/400V ±10%.

LV networks are mainly radial with high R/X ratio making them prone to voltage drop/rise problems. These can be aggravated if Distributed Generation (DG) is not carefully integrated on the grid. Also, since LV loads are predominantly single-phase, micro-generation units with low installed capacity (up to 3.68kVA in Portugal) can also be connected to the same phase. This can create potential problems of high unbalance factor on the network [2], for certain periods of time. When the voltage profile reaches the statutory upper limit, individual protection of DG units will trip due to overvoltage. When this happens, it is likely that other DG units on the same area will sense the same problem causing their protections to also trip. If a cascading series of DG units are disconnected from the network at the same time, a sudden voltage drop can be felt. This can potentially propagate through the network causing other units to trip aggravating even more this problem and further reducing system voltage.

Most of the current micro-generation power electronic converters play a passive role, as they inject as much power as they produce, with no particular real time tuning of their generation as network conditions could dictate. But power electronics technology can drive the real time converters response, provided that the desired active and reactive power references are received. These set-points can be calculated locally at the MV/LV secondary substation by the DTC and coordinated centrally by mechanisms running at SCADA/DMS level [3].

At each micro-generator node of a specific LV feeder, P and Q reference settings can be received after being dynamically calculated by the DTC and sent via the smart meter and the controller. The DTC would then have to consider the real time operational conditions, given by sensors, in particular the voltage level at each node and the power flowing across the feeder segments. These set-points are calculated depending on the real-time data sent by the LV feeder sensors described earlier and sent to the inverters via the smart meter and controller associated with the generating unit. The set-points depend on the locally measured real-time voltage profile and on the assessment of the position on the feeder where the micro-generator is installed. In case this unit is near the secondary substation, its impact on voltage profile is different from a unit located at the end of the feeder. Therefore, the set-point with a new power reference to be sent can be different for each inverter depending on a local assessment carried by the DTC.

The implementation of this kind of control architectures allows performing voltage regulation at the MV/LV substation, improving the overall stiffness, meeting network regulatory requirements.

COMMUNICATIONS NETWORK

The Monitor BT services and applications require the monitoring of the LV infrastructure, gathering data from both smart meters and field sensor nodes. This section describes the selection of communications technologies, as well as the protocol stack.

Selection of Communication Technologies

The FAN and NAN parts of the communication network represent a significant infrastructure investment due to the high number of nodes to be monitored and controlled, since those networks are located close to the edge of the Smart Grid system. The cost of deployment of cabled network infrastructure is usually prohibitive, calling for the use of communication technologies that feature a smaller footprint. The technologies that were found to be more suitable to support the FAN and the NAN were the following [4]:

- Power Line Communications (PLC);
- Infrastructure-based Wireless Networks;
- Radiofrequency Mesh (RF-Mesh) networks.

These will only require the DSO to perform an investment on the sensor/actuator nodes, as well as a contract with a network provider in the case of Infrastructure-based Wireless Networks.

PLC appears as an obvious solution, since it reuses the power lines as a communications medium. Given the communications ranges required by the FAN and NAN, Narrowband PLC (N-PLC) technologies such as PoweRline Intelligent Metering Evolution (PRIME) and G3 are currently employed in some European countries.

PLC connectivity is usually interrupted by faults in the grid infrastructure, such as broken power lines. RF-Mesh is a robust alternative, which separates communications from energy distribution infrastructure. RF-Mesh is a distributed technology in which communication endpoints also perform the role of routers on behalf of the other endpoints, with no need for base stations or cables. Among the standard RF-Mesh solutions are IEEE 802.15.4 (narrowband) and IEEE 802.11 (broadband), but there are also proprietary solutions. Single hop ranges supported by RF-Mesh may not be enough to support all the links, mainly in rural areas where longer communication ranges are expected. In this case, Infrastructure-based Wireless Networks provide an easy and reliable solution, since mobile cellular operators usually have an overall coverage of the national territory. Data rates can range from narrowband (e.g., GPRS) to broadband (e.g., LTE). Given the scope and size of the Monitor BT demonstrator, a narrowband IEEE 802.15.4 RF-Mesh solution was selected. This solution is based on the XbeePro chip, operating on the 869.4-869.65 MHz band [5], allowing 500 mW transmission power, achieving medium range.

Protocol Stack

Figure 4 depicts the Monitor BT's FAN protocol stack.
At the application layer, DLMS [6] is already supported by the DTC [7]. However, the bandwidth restrictions of narrowband RF-Mesh advise the use of a simpler and more efficient protocol for communication with the FAN sensor nodes. MODBUS was selected. The FAN Gateway performs the translation between MODBUS and DLMS protocols. The selected technology is narrowband RF-Mesh based on IEEE 802.15.4 at 868 MHz. This frequency band was chosen in order to maximize the range of the network and still provide an acceptable data rate. Due to current spectrum limitations in Europe, a single channel between 869.400 and 869.650 can be currently used at a maximum Effective Radiated Power (ERP) of 500 mW. In order to increase the range of the FAN, FAN Relay Nodes may be deployed in selected locations.
On top of the RF-Mesh, an Internet of Things (IoT) protocol stack implements the network (IPv6+RPL over 6LowPAN), transport (UDP) and application support layers (COAP). The latter can provide support to a Web Services based implementation of MODBUS. COAP security is provided by Datagram TLS (DTLS). The secondary substation hosts the FAN Gateway, the Substation Controller and the MV/LV transformer. Communication between those two components is performed through Ethernet or other cabled technology, using a standard TCP/IP protocol stack on top.

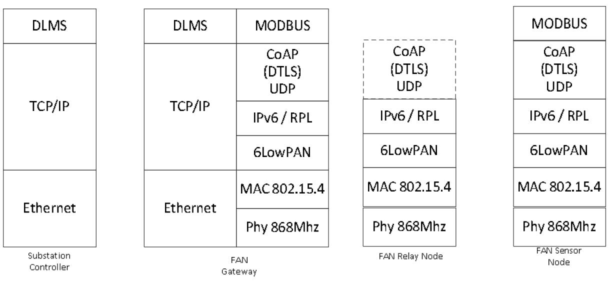

Figure 4: FAN protocol stack.

CONCLUSIONS AND FUTURE WORK

Monitor BT aims at demonstrating the feasibility of LV grids monitoring and automation, another step towards the democratization of automation and ICT solutions, deeper into the distribution grid. These solutions cope with the Smart Grid concept, improving QoS and renewables integration, while promoting grid resilience and awareness, the latter of extreme importance for grid operation and asset management. The proposed architecture, technologies and control strategies show adequacy to the proposed objectives to optimise the LV grid operation and fault detection through critical deployment of sensor nodes. Monitor BT's architecture and requirements have already been defined, as well as the pilot grid. The project team is implementing the prototypes aiming at concluding the lab integration tests by the end of 2014. By mid-2015 the project will be concluded with a real pilot grid demonstrator for LV and PL grids, comprising monitoring and fault detection and location, as well as PL faulty lamps detection and location. Furthermore, a lab demonstrator will comprise the control - performed by DTC at secondary substation level - of power being injected in the LV grid by PV inverters, under real use case scenarios depicting voltage violation occurrences.

ACKNOWLEDGEMENTS

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