

## FAULT DETECTION AND LOCATION IN LOW VOLTAGE GRIDS BASED ON RF-MESH SENSOR NETWORKS

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### ABSTRACT

The paper presents the results of the MONITOR BT project with special focus into faults detection and their location in the low voltage (LV) grid and in public lighting feeders. The fault detection and location algorithms run in the Distribution Transformer Controller (DTC) deployed in secondary substation who receive data from monitoring sensors deployed along the LV grid that communicate via RF-mesh. The pilot demonstration of the system was implemented over a selected LV network in Portugal generating results that are also discussed in the paper.

### INTRODUCTION

Project MONITOR BT (started in June 2013 and concluded in June 2015) was an R&D project granted by the Portuguese Strategic Reference Framework. It aimed at researching innovative technologies to increase the monitoring and control of the LV level in distribution grids. Advanced voltage control mechanisms were developed within the project [1]. In this paper, we focus into the final results of the project concerning detection and location of faults in the LV grid, as well as detection and location of faulty light bulbs in public lighting (PL) feeders.

The monitoring of the LV grid is done by sensors, which communicate via an RF-mesh wireless sensor network. The sensors are deployed in strategic points of the LV grid, like secondary substations (SS) and along their respective feeders. The sensor measurements, e.g., current and voltage, are communicated to the secondary substation controller, also known as DTC, which runs the appropriate algorithms to detect LV grid faults and localize them. This information can be seen locally in the SS via the DTC GUI and also remotely, as the DTC information is transmitted to the SCADA/DMS and Outage Management System of the Distribution System Operator (DSO). Another mechanism based on the same principles is also implemented to detect faulty light bulbs in PL feeders. The complete system was demonstrated life in the LV grid of EDP Distribuição in the region of Batalha, Portugal.

### COMMUNICATION ARCHITECTURE

The MONITOR BT communication architecture supports end-to-end DLMS communication between the DTC and sensor nodes, by means of an Internet of Things (IoT) protocol stack (Figure 1). Sensorization of the LV grid is based on an RF-Mesh Wireless Sensor Network (WSN). The WSN comprises Wireless Mesh Nodes (WMNs),

which receive requests and report their data to the DTC via the Wireless Mesh Gateway (WMG). The latter is connected to the DTC by Ethernet and to the WMNs by an RF-Mesh interface. The RF-Mesh is implemented with XBee-Pro@868 radio adaptor modules [2], which implement the IEEE 802.15.4 standard. The radio modules operate in the Short Range Device 868 MHz frequency band. The maximum transmit power is 315 mW (25dBm) and the receiver sensitivity is -112 dBm. It supports a raw RF data rate of 24 kbit/s. This results into 2.4 kbit/s of usable data rate due to the mandatory duty cycle of 10%.

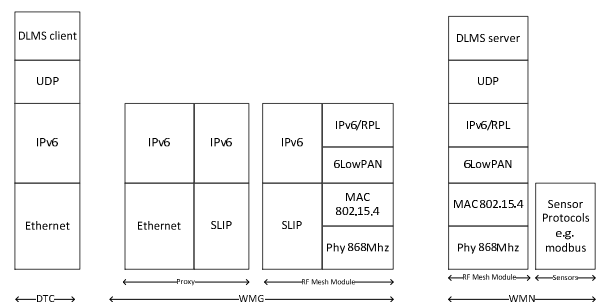


Figure 1: Protocol architecture of Monitor BT.

The IoT protocol stack operates above RF-Mesh. IPv6 implements the network layer, spanning end-to-end, between the WSNs and the DTC. Inside the WSN, IPv6 headers represent too much overhead, given the data rate constraints. The 6LoWPAN adaptation layer compresses the IPv6 headers, taking advantage of fixed filled values and of information available at the MAC layer. The IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) is the mesh routing protocol used inside the WMN. The WMG is divided into two parts: Proxy module and RF Mesh module. The RF-Mesh module is also based on an XBee-Pro@868 radio adaptor, while the Proxy board is based on an Atheros AR9331 System on Chip. The two parts communicate through a serial interface, with Serial Line Internet Protocol (SLIP) encapsulation.

### DTC AND SENSORS

The DTC is a controller for distribution networks that integrates both MV and LV network control and monitoring. The overall system architecture (see Figure 2) matches transversal smart grid requirements as it copes with distributed monitoring and control, by including open communication protocols deployed over proven wireless (RF Mesh) and powerline carrier technologies (PLC Prime) [4]. This architecture supports communications (DLMS protocol over RF Mesh) between master units and their

sensor devices, enabling fault detection and location in the LV grid and in public lighting feeders.

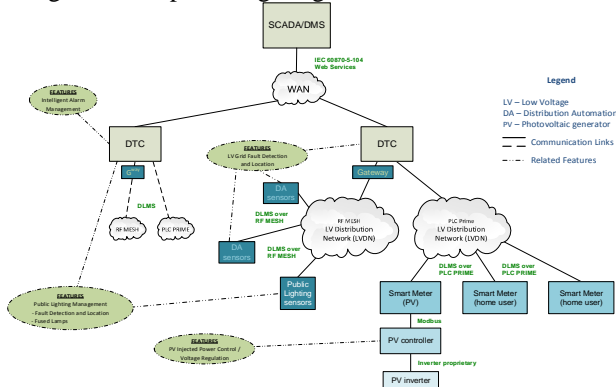


Figure 2: Overall architecture of the Monitor BT [3].

According to the architecture of the WMNs (shown in Figure 3), the main modules of the WSN are:

- LV Sensing which measure the voltage and current of the 3 phases (L1, L2, L3) of the LV feeder;
- PL Sensing which measure the voltage and current of the Public Light feeder;
- Voltage/Current Fault Detector which detects the voltage and current faults of the LV and PL feeder;
- RF Mesh Module, which contains the control processor with very low consumption, the 868 MHz radio module and runs the Contiki operating system.
- AC/DC power module.

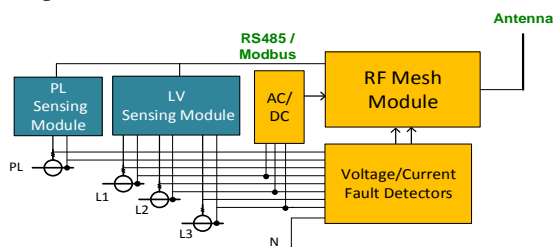


Figure 3: Wireless Mesh Node architecture.

Low power consumption and energy storage are needed in these components as they are required to transmit alarms to the DTC up to 20 seconds after they lose power.

## FAULT DETECTION AND LOCATION ALGORITHMS

Fault detection and location in the LV grid is still very depending on customers' calls. Distributed sensors will enable automatic fault detection and location, sending alarm notifications once a fault is impending or detected. This will greatly optimize the operation of the maintenance crews, significantly reducing recovery times.

An example of a LV Grid is shown in Figures 4 and 5. It consists of the SS, a Feeder and Electric Distribution Cabinets (EDCs). By installing electronic sensors in the EDCs, a Segment is defined as the connection between a feeder and Node (LV Grid Point where a Sensor is

installed), between two Nodes or between a Node and a Grid Dead End.

Note that Node 1 is inside the SS, so it is seen as being the feeder. Each sensor node is able to monitor three phases, measuring the following quantities: voltage, current, power factor and temperature.

The sensor nodes are able to report their measurements remotely to the DTC, which is located at the SS and concentrates the data received from the feeder. Besides the periodic poll of quantity measurements, the sensor nodes are able to asynchronously detect fault currents and outage events, which are also reported to the DTC by means of alarm messages. The algorithm running on the DTC, which has access to the LV Grid data (static topology and real time data from sensors), may produce automatic fault detection and location information, featuring the LV Grid with the ability of proactively inform the upper central systems of one or more faults. In the presented architecture, the DTC is thus the "decision maker" and the Sensors, scattered across the Grid, are the data providers and local alarm validators.

Fault Detection and Fault Location are two different algorithms, with the first being the second's trigger.

### Fault Detection Algorithm

The Fault Detection State Machine is initially in Idle State, waiting for an Event input or the finish of the measurements polling. When one of the inputs is present, the process will then treat the new data, decoding it, in four basic types of data:

- Fault Event – Event reported by a sensor, indicating the detection of a very high current (fault current) in the segment; when this event happens, usually it will be followed by a low voltage alarm, indicating the fusion of the protection fuse;
- Power Loss Event – Event indicating the loss of power in the segment;
- Quality Event – When voltage or current measured by a sensor exceeds the pre-configured threshold limits, the sensor will send an event;
- Electrical Measures Poll – Periodically, the DTC will request by polling the electrical measurements (voltage, current, active power, etc.).

When an event is received (independently of the method used), a confirmation timer is started. If the timer timeouts and the event still exists, then it is considered a "Confirmed Event Detection". The timer must consider the network communication delay, so all sensors have time to report their alarm status.

### Fault Location Algorithm

The Fault Location algorithm is initially waiting for a "Confirmed Fault Detection" event. When this event is triggered, the DTC must start the Fault Location sequence. The following examples show how to perform the location.

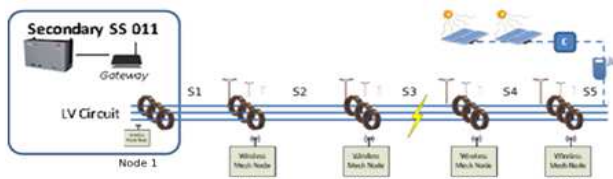


Figure 4: Fault in a typical segment

In this example, a fault occurred in Segment 3 and detected by Sensors 1, 2 and 3. Once the fault is “Confirmed”, the algorithm leaves its idle state and starts its routine. The first step of the algorithm is to jump between sensors, starting from the first until it finds the most distant faulty node (3). Then it must check the following nodes and, if it detects that no fault was signaled by them, the algorithm concludes that the fault is in the segment that connects it with the no fault node(s). In this case, Node 4 has no fault detected and so the faulty segment is S3 (Figure 4).

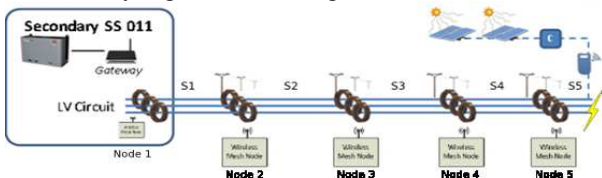


Figure 5: Fault in a Dead End segment

In the example of Figure 5, a fault has happened in Segment 5 and was detected by all wireless sensors. Once the Fault is “Confirmed”, the algorithm leaves its idle state and starts analysing. The algorithm polls the sensors, starting from the first until find the most distant faulty node (5). Then it checks the following nodes and if no fault was detected by them, the algorithm concludes that the fault is in the segment that connects it with the no fault node(s). In this case there are no more sensors after Node 5 (Dead End) and so the algorithm concludes that the faulty segment is 5.

## DETECTION OF FAULTY BULBS IN PUBLIC LIGHTING

Currently, there are no means to detect Public Light (PL) bulbs failure and this detection is made by human observation or customer complaints. Providing the PL circuits with sensing capability, it is possible to enable an automation process and greatly minimize the PL circuit fault detection and also to reduce maintenance costs. The detection of faulty bulbs algorithm has as inputs the PL sensors topology and the real time data from those sensors. The typical PL feeder presents a linear topology, with the several luminaries connected in parallel along the line. To detect if one or more luminary are faulty or fused, a method is used to compare the real time measured current, with a reference current measure acquired with all luminaries working well. If  $I_L$  is the current of an individual luminary, the total current of the segment, assuming that all bulbs have equal power, should be  $I_{pl} = k * I_L$ , where  $k$  is the

number of luminaries connected in the sensor node. This method presents high accuracy since PL circuits are equipped with electronic ballast, keeping bulbs’ current constant and independent of voltage variations.

In order to achieve an accurate fault detection, the Fault Detection and Location algorithm and correspondent sensors are deployed along the public light network (see Figure 6). The segment defined by sensor nodes represents groups of one or more public light bulbs.

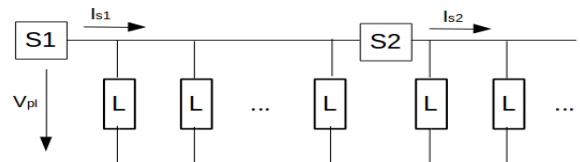


Figure 6: PL circuit with sensors

The segment current calculation is done by the following expression, in which the real time current measured in one sensor ( $i + 1$ ) is subtracted to the previous ( $i$ ).

$$I_{segment\ i} = I_{sensor\ i} - I_{sensor\ i+1},$$

$i$  - Segment and node number

If the following condition is verified,

$$I_k \leq I_{segment}(t_0) - I_{segment}(t)$$

$I_k$  - current consumed by one bulb in the segment (worst case);  $t$  - time;  
 $t_0$  - initial time instant (with all bulbs working well)

then at least one bulb is fused, triggering the alarm condition.

The number of failed bulbs can be obtained by,

$$N = (I_{segment}(t_0) - I_{segment}(t)) / I_k$$

$N$  - Number of failed bulbs

The DTC, following the previously explained methodology, can poll current real time measures from LV sensors and calculate the current each segment is consuming. A variation from the reference current in that segment indicates the existence of one or more bulb faults. For this method to have accurate results, the measures acquisition must be time synchronized.

## PILOT DEMONSTRATOR

The project was demonstrated in a real life scenario in the EDP Distribuição grid. Two SS were selected in the Batalha region and one LV feeder and one PL circuit was selected for each. The major difference between the two feeders is that one has underground cables and the other overhead lines. Within each SS a DTC was deployed and interconnected to the wireless sensors. The sensors are deployed in distribution cabinets (underground lines), or in poles (overhead lines), along the feeder and inside the SS. Figure 7 illustrates the location for one of the feeders. The sensor locations are indicated by the red circles on top of the green line (feeder).



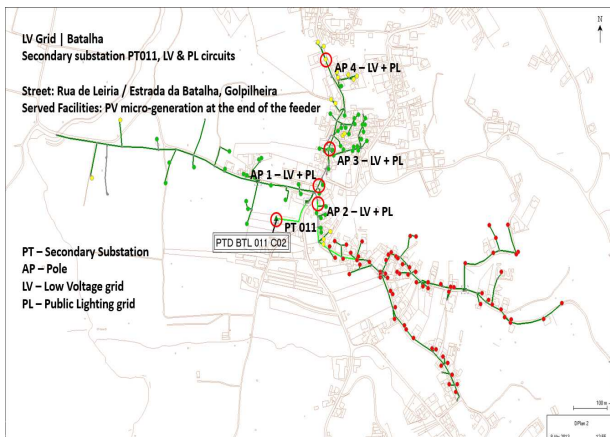


Figure 7: Sensor Deployment in one SS and LV feeder.

A set of functional tests were made to demonstrate the network access, the overall protocol interoperability between all the components of the demonstrator and the sensor data acquisition functionalities, namely:

- Access to individual sensors, polling instantaneous values of voltage and current plus active, reactive and apparent powers;
- Set threshold values to define current and voltage alarms of the phases of the different sensors;
- Mesh routing, namely to show that the RF Mesh is automatically reconfigured in case of node failure or loss of power;
- Fault Alarm tests, to demonstrate the capabilities of the sensors to detect faults (high current, low voltage) and send alarms through the mesh network;
- “Last Gasp” tests to demonstrate the capabilities of the sensors to send the Last Gasp message through the mesh network in case it loses power.

The outcome of the functional tests was successful. The network performance tests that were also done showed good results. The obtained Round Trip Time (RTT) and throughput were respectively 274 ms (with 95% confidence interval of 19 ms) and 2.1 kbit/s (with 95% confidence interval of 0.4 kbit/s). The measured packet loss probability was around 9%, measured at the upper interface of the MAC layer. However, no packet loss was experienced at the DLMS, which is able to perform 3 retries per packet, though the maximum number of reported retries was 1 for each of the 9% lost packets. Regarding wireless communication coverage, the tests revealed that all communications have spanned a single hop, which is explained by the extended range provided by the 868 MHz frequency band. Looking at Figure 7 and based on the wireless communication range tests performed during the integration phase, it is possible to extrapolate that 2 hops are probably needed to cover a typical feeder completely. In this case, for the more distant nodes, the RTT would be expected to rise to approximately a bit more than twice the value measured for one hop, while the throughput would decrease to approximately one half. Packet losses would

also be expected to rise due to hidden terminal problems in the multi-hop scenario. Overall, results showed that the wireless sensor network performs as planned and proved that the technology is ready to support the target applications. In Figure 8 it is possible to observe a scenario where both the public lighting and the LV feeder circuits are being monitored in real-time. Through the algorithms described previously, the DTC is able to autonomously detect and locate eventual electrical faults that may occur. On this example, a public lighting pole with 2 fused light bulbs was detected and its location determined (second pole downstream of the SS).

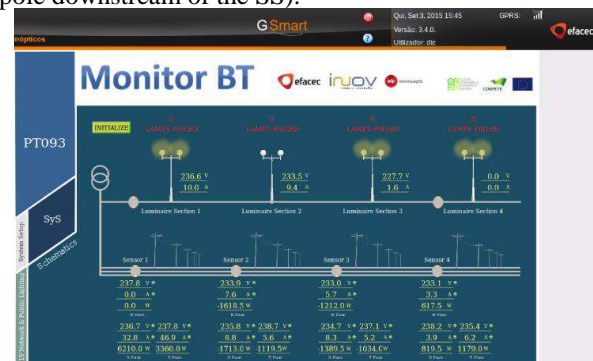


Figure 8: HMI of the DTC for monitoring purposes.

## CONCLUSION

The MONITOR BT project is a step towards the realization of Smart Grids and the functionalities demonstrated are a relevant subset of advanced features that allow DSOs to have a greater observability of LV networks. The fault detection and location in LV and PL feeders allow the DSOs to be proactive and reduce customer communication dependence, as well as allows DSOs to be more precise when sending operational teams to the field. The benefits result in an increase of efficiency in LV network management and in operational management teams.

## ACKNOWLEDGMENTS

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