MONITOR BT PILOT PROJECT: COMBINED VOLTAGE REGULATION APPROACH FOR LV GRIDS WITH PV PENETRATION

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ABSTRACT

Monitor BT project aims at improving LV grid resilience by combining LV grid sensors and smart meter information to enable grid awareness, providing an innovative method for voltage regulation under PV generation presence. Monitor BT communications open architecture comprises IEEE 802.15.4 RF Mesh for the LV grid sensors and PLC PRIME / GPRS / RF Mesh for smart meters.

For the validation of the communication architecture, the fault detection and location, and the grid voltage control methodology, a field project demonstration is under deployment involving LV clients from two MV/LV substations and a set of feeders, including public lighting.

INTRODUCTION

The Smart Grid concept is innovative concerning the use of Information and Communication Technologies (ICT) in the management and control of the electric power grid, including all its grid segments: generation, transmission, distribution and consumption. According to this concept, the Smart Grid will provide features, such as integration of micro-producers (also playing the role of prosumers), automatic fault detection and service restoration, and the reconfiguration of the grid according to the energy offer/demand at each moment.

Aiming at being possible to achieve these features, the electric power grid primarily has to be monitored (i.e. integrate sensors for relevant measuring of the electric power grid state, and then send them to the systems responsible for its processing). Furthermore, the grid has to incorporate electro-mechanic actuators which are used for grid reconfiguration. Due to the dimension of the grid infrastructure already installed, it is expected a gradual evolution from the traditional grid to the Smart Grid.

The extent of deploying grid resilience features over MV or LV grids is different. LV grids show a predominance of resistance over reactance, therefore, PV penetration impacts on voltage profiles. Due to grid code compliance, PV unit individual protection will trip for overvoltage, affecting the micro-producer outcome and resulting in a sudden change in the load perceived by the transformer at the secondary substation. Furthermore, the tripping occurrence may cause a cascading series of PV units to be disconnected due to the neighboring effect, leading to further voltage drops.

Traditionally, LV grids have no active voltage regulation control options, nor on-load tap changing, capacitor banks or topology changes. Advanced solutions such as Demand Response, community storage or electric vehicle smart charging are not currently deployed in Portugal. . Dynamic control of active power injected by PV is, thus, an adequate solution for voltage regulation, dealing with voltage magnitude severity, as a time function of generation and load. A combined approach for tackling these real-time contingencies is deployed with advantages for grid stability and resilience as well as for prosumers who can maximize their energy selling profit.

STATE OF THE ART

The High Voltage (HV) and Medium Voltage (MV) grid monitoring and remote control infrastructure is already significantly developed.

Yet, the level of LV, grid monitoring and remote control is reduced or almost inexistent, except in some specific grid areas. Therefore, it is essential to increase LV network visibility and controllability, as well as to increase grid reliability.

Monitoring of LV Grids

The LV network has currently a passive character due to the lack of suitable equipment to allow gathering of information on the infrastructure’s operational status, as well as to allow any kind of remote actuation.

LV Grid Fault Detection and Location

Fault detection and location in the LV grid is still inefficient due to the lack of LV grid monitoring. LV fault detection relies on customer calls informing the DSO about outages and the fault is located based on inspections made by maintenance crews.

LV grid monitoring will enable deploying fault detection and location features, by sending alarm notifications once a fault is impending or detected through the correlation of real-time data from the wireless sensors deployed along the LV feeder.

Public Lightning Infrastructure Segment Fault Detection and Location

A public lighting segment suffers from the same fault vulnerability of conventional LV grid segments, either overhead or underground. Public lighting segment fault detection also relies on complaints from clients or on visual inspections made by maintenance crews.

Public lighting segment monitoring will also enable deploying fault detection and location features. Besides, blown out bulbs detection in extensive public lighting segments is a key feature for improving the related service quality perceived by the customers, while providing improved maintenance. The detection of blown out bulbs on a circuit is done by comparing historical values of current or on changes on the current profile, taking voltage values into account (given the specific characteristics of this type of loads).

Dynamic Control of Power injected by Micro-producers

Distributed micro-generation presents many challenges to the DSO due to the increased complexity and variability of power flows.

The stochastic nature of both the renewable sources expressed by an intermittent behavior of the PV micro-generation assets, and the demand profiles arising from typical end-user, also present a challenge for any attempt to automatically anticipate voltage limit violations and to cope with that by mitigating their impact on the grid.

The main aim of this paper is to describe the role of LV grids monitoring while providing solutions to mitigate the described impact of PV micro-generation, by means of deploying a new combined approach for voltage regulation suitable for LV grids with PV penetration.

PROBLEM DEFINITION

The modelling of the combined behavior of PV dispersed generation and load in LV grid feeders is complex, due to their stochastic nature. This represents a challenge for the DSO at both operation and maintenance levels.

On one hand, LV dispersed PV micro-generation assets provide neighborhood power sources thus allowing the DSO to defer grid investment in order to deal with increased demand trends; on the other hand, these assets do not follow the peak demand, since their production peak behavior is far shifted from the peak demand period.

What used to be a top-down unidirectional power flow, presently and due to these new active LV distribution grids, became a bottom-up or transversal power flow. The result is that now, in many LV distribution grid feeders, unpredictable bidirectional power flows emerged, following the variable nature of the solar power source feeding the PV micro-generation assets, as well as the stochastic nature of loads, namely domestic. When combined, these two DSO, especially in rural grid segments. Besides, LV distribution grids are unbalanced due to single-phase domestic loads and PV micro-generation units. To add further complexity, it is worth mentioning that some three-phase loads may coexist in parallel to those single phased.

In [1], different LV distribution grid scenarios were simulated: peak load with no PV micro-generation presence – the night period – and off peak with the presence of PV micro-generation – the daylight period.

The mentioned simulation took into account the stochastic nature of both demand and PV micro-generation; therefore, a Monte-Carlo simulation with 10.000 runs was performed. As a result, voltage rise/drop events outside the acceptable voltage limits (EN 50160) have occurred. The simulation considered that the voltage at the secondary substation (transformer LV winding) has been set to 1.05 pu which is a standard practice to deal with voltage drops under peak load conditions.

The simulation outcome showed that there was a small probability (3%) of the voltage being less than 0.9 pu under peak load conditions. Nevertheless, the feeder nodes where the most severe voltage drops occurred also have faced a huge power unbalance and a voltage rise on the neutral conductor. Load shedding was considered as a feasible solution for solving the problem, provided that a demand response mechanism could be implemented.

Still according to the simulations performed in [1], during off peak conditions but in presence of PV micro-generation assets, the probability of the voltage being greater than 1.1 pu is high (30%), strongly arising from the fact that the tap changer of the secondary substation transformer was set to 1.05 pu.

Several methods have been presented to deal with the previous voltage rise effect:

MV/LV Transformer Tap Changing

Resetting the voltage tap changer at the secondary substation transformer to 1.0 pu will reduce significantly the probability of voltage rise occurrences (12%); yet the distribution feeder would then be prone to severe voltage drops at the remotest loads within the LV feeder. A transformer provided with a dynamic OLTC fully automated, placed at the secondary substation would be a possible contribution for solving a complex issue [3].

In [4], interactions between controllable transformers connected to the same LV grid were analyzed, yet without any combined control. A simulation with two independently controlled transformers was carried out; an autonomous control in one transformer influences the other, after some slight and stable oscillations, both transformers would cope with the injection node voltages being under 1.1 pu. The described method excludes the use of any communications infrastructure. No further simulations were taken to comprise more than two transformers.

PV Micro-generation power factor control

Although the power electronic features by PV micro-generation inverters provide reactive power flow control,

the measure is, in itself, unproductive, due to the low inductive component of the LV distribution cables and lines [1] [2].
In [2], it is proposed a method by a controller placed at the secondary substation, suitable for controlling voltage profiles at injection nodes by PV micro-generation. This controller calculates P (and also Q) set-points which would be coordinated centrally by mechanisms running at the SCADA/DMS level. These set-points would then be sent to the PV micro-generation inverter, through the corresponding Smart Meter, an important piece of this voltage control puzzle.

PV Micro-generation shedding

According to the study attained in [1], during daylight off-peak conditions, PV micro-generation shedding would be the most convenient method for mitigating the impact of voltage rises. Specifically, the PV generator located at the grid node with the larger overvoltage would be firstly disconnected and this procedure would be repeated until all node voltages were under 1.1 pu.
The same study showed that only in 5% of the times there would be no need for PV shedding; moreover, by removing two PV generators, it would be normally enough to keep the voltage under 1.1 pu along the entire feeder, corresponding to a probability of 40 %.

JOINT APPROACH FOR LV REGULATION

Monitoring and distribution automation have moved downwards the secondary substation, meaning that LV monitoring is now possible. Furthermore, PV inverters may offer a local droop control function for voltage regulation. When all these features are combined, in other words, when those features are managed by the secondary substation controller, fast and accurate local (neighborhood wide) algorithms will improve LV grid resilience, comprising the mitigation of voltage rise effects by dispersed PV micro-generation.
The aim of the Monitor BT project – developed by a team comprised by Efacec, INOV and EDP Distribuição – was the deployment of RF Mesh enabled sensors along LV feeders in both aerial and underground segments. New controllers (DTC – Distribution Transformer Controller) manage the overall LV power consumption and micro-generation power injection, through monitoring feeder measurements and topology status data. These measurements and status data are collected by the mentioned LV sensors. This monitoring and automation step further into the LV grid is aligned with the smart grids paradigm, matching the overall goals of the project partners within EDP's InovGrid major national project.
The monitoring and fault detection process over the LV grid equipment and lines aims at being efficient and proactive, as it will be performed automatically and remotely, through the deployment of sensors and suitable communication modules in LV Electric Protection Cabinets (EPC) and Electric Distribution Cabinets (EDC). These sensors will perform measuring of voltage, current, power factor, temperature and humidity.
Concerning the mitigation of voltage rise effects by dispersed PV micro-generation, a new approach is being proposed. At the secondary substation, the DTC offers enough computational capacity for power flow calculation, so that active power injection set-points can be calculated and sent to each PV unit. Sensors deployed along the LV feeder provide detailed operational data to the DTC together with smart meter data from PV nodes. Besides sending active power set-point values to PV units, the DTC also decides when to send them. This is the role of DTC's global control loop.
Consumption and PV generation profiles at every node present a stochastic behavior, despite their predictable daily patterns. Instantaneous voltage magnitude after set-point control execution over a PV unit may be affected by a sudden change in consumption or in the solar source. Communication delays also affect DTC's LV grid awareness, burdening its stochastic scope.
To overcome that, an additional local controller was developed for the prosumer node. This local controller will be used at each PV unit set (comprising the smart meter), performing local control loop at each PV node, quickly and automatically tuning the node voltage by refining the active power being injected by the PV inverter, limited to the active power set-point sent by the DTC – the main controller at the secondary substation.
Figure 1 highlights the overall approach, representing the global control loop – or outer loop – managed by the DTC; a PV node local control loop – or inner loop – is also highlighted at each PV micro-generation node.
Presently, such combined approach for LV regulation cannot be demonstrated in a real scenario. On one hand, the present regulation in Portugal does not allow controlling the active power being injected by PV micro-generation inverters. On the other hand, no specific prosumers affected by voltage rise violations with loss of income - that could take advantage from any of the proposed features - were selected. To face these constraints, three steps were envisioned:
1) Simulation of a LV grid with two prosumers and four customers.
2) The mentioned LV grid – in simulation mode – was replicated in a laboratory demonstrator, the DemoLab. This DemoLab comprises two real PV inverters, two PV controllers, as well as four end user load resistances (R1, R2, R3, R4), cable resistances, a secondary substation controller, six Smart Meters (two for the prosumers and four for the end users), a grid 230 Vac reference and a DC voltage input to simulate the solar panels. In order to deal with low value power measurements, the grid scope was downsized, i.e. resistances' values were tuned to match such criteria.
3) As a later step and after Monitor BT project conclusion, two real prosumers will be selected, so that the DemoLab approach will be deployed, as part of the "e-balance" project (financed by FP7 grants) demo goals.

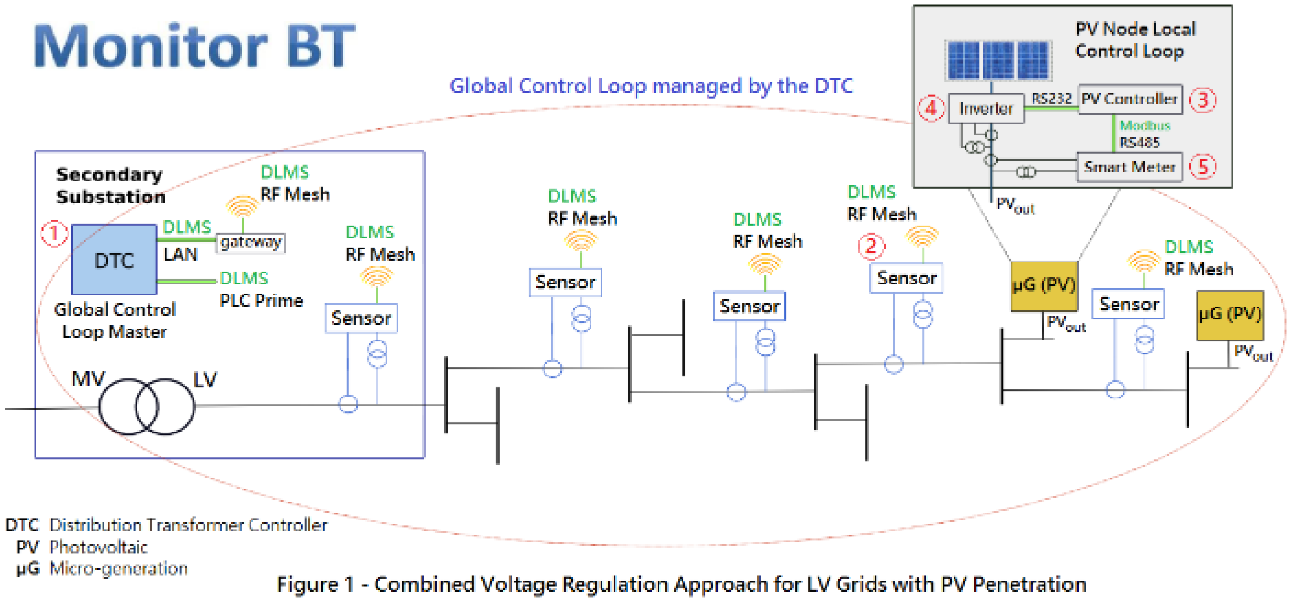

Figure 1 - Combined Voltage Regulation Approach for LV Grids with PV Penetration

Voltage Control under the Combined Approach

Figure 2 depicts the voltage control sequence, as a result of the combined voltage regulation approach, comprising a global (outer) control loop managed by the DTC and local (inner) control loops managed by each PV controller.

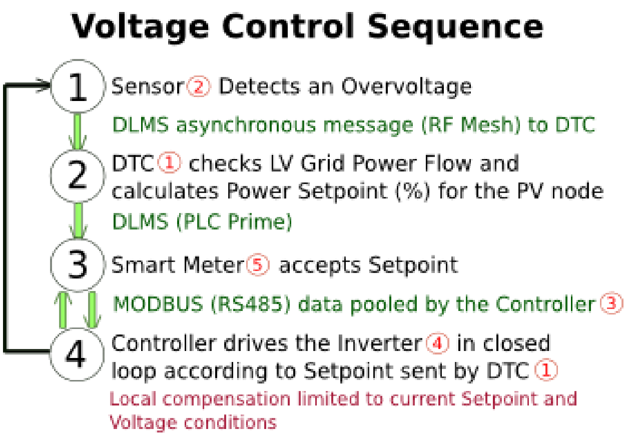

Figure 2 – Monitor BT's voltage control sequence

INNER LOOP SIMULATION

A software tool to simulate the local control (inner) loop was developed in order to optimize the power being injected into the grid by PV units. The grid components list was presented in SPICE format.

Different algorithms were specified and tested with different topologies, as well as different generation profiles and load characteristics.

The software tool allows defining the initial power generated in each PV micro-generation unit followed by the initial voltage at the Secondary Substation Transformer (SST).

The initial values of the loads at the different nodes of the feeder are also shown by the tool. Their values were downsized for the simulation purpose. During simulation, the user may change all the referred variables, namely the voltage of the SST, the value of the loads and the power produced by each PV unit. The user may define set-points to the PV inverters in order to limit the power injected by each PV unit, according to the values derived from the algorithms under test.

Variation of the current injected by PV inverter

The power injected by the different PV units connected in the simulated feeder will have an impact on the voltage along the feeder that depends significantly on the loads and on the SST voltage. For that reason, there is the need to simulate different combinations of these variables. For the inverter we use the injected current as the primary variable, which will be varied from 0 to 5 A, in steps of 0.5 A.

SST Voltage Variation

The voltage of the SST is varied from the minimum to the maximum value (as a percentage range of the nominal value) in 5 Volt intervals, and the tool calculates the optimal PV inverter active power set-points to correct any voltage rises on the feeder. This test is made with a maximum current, i.e., with minimum value of R1, R2, R3 and R4 equal to 230Ω.

Load Variation

Each load (R1, R2, R3 and R4) could take different values (230 Ω, 540 Ω, 1 kΩ) and the tool calculates the optimal active power set-points of the inverters for mitigating voltage rises along the feeder nodes.

Simulation Results

Among the several simulation results, values on node 4 of the simulated LV grid are worthy to be presented (normal node voltages are shown in green).

Table 1 – Results for both PV units injecting 5A, and the voltage at the SST being 230V

Loads (Ω)	Node 4 (V)	Max current (A)	Set-point (W) for Node 4 PV unit
1 k	257.5	3.87	979
540	255.4	4.4	1113
230	247.0	n.a.	n.a.

Table 2 – Results for both PV units injecting 5A, and the voltage at the SST being 235V

Loads (Ω)	Node 4 (V)	Max current (A)	Set-point (W) for Node 4 PV unit
1 k	262.4	2.64	668
540	260.3	3.15	797
230	254.1	4.7	1189

Table 3 – Results for both PV units injecting 4.5A, and the voltage at the SST being 235V

Loads (Ω)	Node 4 (V)	Max current (A)	Set-point (W) for Node 4 PV unit
1 k	259.5	2.8	708
540	257.3	3.4	860
230	251.2	n.a.	n.a.

Table 4 – Results for both PV units injecting 3.5A, and the voltage at the SST being 235V

Loads (Ω)	Node 4 (V)	Max current (A)	Set-point (W) for Node 4 PV unit
1 k	253.5	3.37	853
540	251.4	n.a.	n.a.

THE DEMOLAB

The combined voltage regulation approach is also being demonstrated using a demo platform called DemoLab, so that the simulation results can be validated. DemoLab is actually a real implementation of a LV grid segment with two prosumers and four customers (Figure 3). It comprises one DTC, six smart meters, two PV controllers, two PV inverters, as well as load and line resistances.

After Monitor BT’s conclusion, this solution will be improved and implemented in a real scenario during the deployment and demonstration stage of the “e-balance” project led by IHP (Germany), with whom Efacec, INOV and EDP Distribuição also participate, among other partners.

Figure 3 – the DemoLab, for control of active power being injected by PV units, aiming at mitigating voltage rise events

THE DEMONSTRATOR AT BATALHA

As of January 2015, the LV sensors equipped with RF Mesh communications are being installed in EDP’s EPC and EDC of the LV distribution grid in the region of Batalha, Portugal. During the remaining period of the project, the complete set of sensors and distribution transformer controllers (DTC) will be installed, communicating via DLMS over RF Mesh. At that stage, LV grid resilience mechanisms will be deployed.

CONCLUSIONS

The general conclusion is that the higher the voltage value at the SST, the lower is the power each PV unit can inject into the grid to avoid voltage rise violations.

Other important conclusion is that the inverters located in different nodes along the LV feeder will be able to inject different power values in the grid, especially in periods of low local demand, without being shed. In that situation simulations have shown that the PV units located far from the secondary substation will be able to inject less power in the grid than the PV units located near it. The ongoing tests of DemoLab showed that PV units may participate actively in a secondary substation centric voltage regulation approach, comprising remote PV controllers.

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