Predictive Voltage Control for LV Distribution Grids exploiting Flexibility from Domestic Customers

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Abstract

In order to avoid voltage problems derived from the connection of large amounts of renewable-based energy generation to distribution networks, new advanced tools need to be developed that are able to exploit the presence of Distributed Energy Resources (DER). This paper describes the approach proposed for a predictive voltage control algorithm to be used in LV distribution networks in order to make use of available flexibilities from domestic consumers via their Home Energy Management System (HEMS) and more traditional Distribution System Operator's (DSO's) resources, such as transformers with On-Load Tap Changer (OLTC) and storage devices. The proposed algorithm for the Low Voltage Control (LVC) is detailed in this paper. The algorithm was then tested through simulation using a representative Portuguese Low Voltage (LV) network in order to assess its performance in several future scenarios with different operating conditions. The future prospects for field-trial validation in a Portuguese smart grids pilot are also discussed.

1 Introduction

Voltage control in distribution networks is often a concern for DSOs, particularly in situations where high levels of Renewable Energy Sources (RES) – such as solar photovoltaics (PV) – are connected directly at the end-user's premises [1]. This phenomenon is especially registered in weak low voltage (LV) networks, that have long lines usually with low reactance / resistance (X/R) ratios, and where the injection of large amounts of renewable energy may lead to voltage rises that fall out of the range defined by the EN-50160 standard [2].

Therefore, new approaches to this problem need to be developed. Many of the solutions available in the scientific literature involve some type of optimization algorithms that aim at optimizing the use of the available resources in the LV grid. For instance, in [3], the authors present an algorithm developed for the optimization of LV grids that takes advantage of DER such as storage devices and flexible loads based on a multi-temporal Optimal Power Flow (OPF) algorithm that feeds from forecasting tools for load and renewable generation. Other similar approaches to the coordination of different DER in smart microgrids can be found in [4-5].

This makes the tools computationally complex, which in turn requires having more complex, dedicated systems in order to be able to run it (such as an Advanced Distribution Management System – ADMS – developed specifically for supporting the operation of the LV distribution system). Consequently, simpler alternative approaches are sought in order to enable efficient monitoring and control of LV distribution grids with large integration of DER, namely based on RES.

In the H2020 InteGrid project [6], a new tool for voltage control designed specifically for LV networks is currently being developed – the LVC module. In the context of InteGrid, it is assumed that the presence of DER can be explored by the DSO for grid control and management purposes. These DER can be owned by the DSO, such as grid storage units, or owned by consumers willing to participate in grid operation under a contractual agreement. The proposed tool is intended to be a decision support tool, to assist the DSO in the management of the LV grid in an active way. Its aim is to identify a set of preventive control actions that can be implemented by the DSO in order to avoid foreseeable technical problems in the LV grid, such as voltage violations or branch/transformer overloads.

The proposed tool is in fact an evolution of a previous algorithm developed within the FP7 SuSTAINABLE project [7]. This tool was embedded in the Distribution Transformer Controller developed by EFACEC (project partner) and demonstrated in a real LV network in the smart grids pilot (InovGrid) of Évora, Portugal. The algorithm was extensively tested and was successful in sending set-points to controllable resources (PV panels, storage devices and electric vehicle) in order to correct under and overvoltage problems. Results from the pilot trial demonstration are included in [8]. It should be emphasized that the previous version of the algorithm operated on a purely corrective base (i.e. the algorithm would react to any violation detected in the LV network only in the time step subsequent to that event). Another distinctive aspect of this new version of the algorithm is its intelligence to predict when a problem may occur (in preventive mode) and to act in advance in such a way that the event is circumvented.

2. Low Voltage Control Algorithm

2.1 Proposed Framework

The proposed approach addresses the operation control of the available flexible resources based on a predictive analysis and real-time monitoring of voltage profiles. This will ensure that the DSO will be able to comply with the requirements of the EN 50160 standard concerning admissible supply voltage variations, even under scenarios where high RES penetration levels are expected, as observed from the simulations that were conducted. Controllable resources are here defined as network assets with which the DSO can interact. These resources can be property of the DSO, or privately owned by consumers willing to provide flexibility to the grid operation through a bilateral contract. The controllable resources considered here are the transformer with OLTC, energy storage devices, flexible loads and microgenerators, and the HEMS of LV domestic clients, that are able to provide flexibility to the grid operation by changing their energy consumption or production levels. The following objectives are pursued by the LVC tool:

- Define a preventive operation plan, based on the available flexibilities, demand load and RES generation forecasts, in order to prevent potential network problems, namely in terms of voltage deviations and branch/transformer overloads.

- Monitor and manage the network operation in real time using the available flexibilities.

The predictive analysis defines an operation plan for the available flexibilities in order to avoid potential operation problems, considering a time horizon of *n*-hours ahead. This analysis uses a three-phase power flow routine, fed with PV microgeneration and demand load forecasts for each of the network's nodes, to identify potential operational problems during the considered horizon. The available flexibilities for each period of the considered time horizon are also taken into consideration, in order to define the best-suited control action plan in accordance with the DSO's preferences.

In real time operation, the algorithm analyses the network measurements that are directly obtained through the metering infrastructure. If any node measurements are missing, a state estimation function is used to obtain the state of all of the network's nodes. The current state of operation is compared to the one produced by the predictive analysis and, if a significant difference between states is observed, the control action plan is updated in accordance to the real state of the network. In this way, the real time approach intends to manage all unforeseen network constraints and correct/update the control action plan previously determined by the predictive control module.

The control actions produced by the preventive control module are communicated to the DSO, for validation purposes. In real-time operation, if the previously computed control action requires a correction, the DSO is also informed of the new control action plan. Furthermore, it is important to mention that the definition of the control action plan follows a merit order of actuation of the mentioned flexible resources. It is reasonable to assume that the DSO controllable assets will always be considered first, as these are considered to have a lower operational cost, and only then the customers' flexibilities will be considered.

The proposed framework for the LVC is shown in Fig. 1.

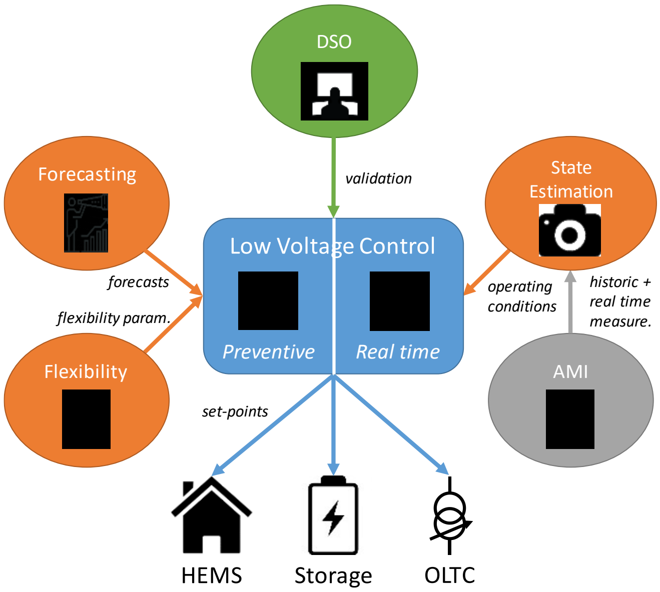

Fig. 1 Proposed framework for the LVC

2.2 Voltage Fluctuations in Weak Networks

The voltage drop across a line, ΔV, can be approximated by the following equation:

$$\Delta V \approx R \times P + X \times Q \quad (1)$$

where P and Q are the active and reactive power, R is the line resistance and X is the line reactance. Traditionally, the operators of the distribution networks require microgeneration to operate at unity power factor. This fact, in addition to the weak character of LV lines (i.e. that R » X), results in the following simplification of (1):

$$\Delta V \approx R \times P \quad (2)$$

From the previous equation it is possible to derive that fluctuations in active power result in proportional fluctuations in the terminal equipment's node voltage. Situations where the active power injection largely exceeds consumption – such as peak solar production coinciding with low demand – can lead to overvoltages that violate admissible voltage limits. Therefore, the proposed approach is based on active power consumption / injection of the controllable DER. The set-points computation to apply is performed according to:

$$\Delta V \approx R \times \Delta P \Leftrightarrow \Delta P \approx \Delta V / R \quad (3)$$

where ΔP is the variation in active power (set-point) to apply to the DER and ΔV is the magnitude of the voltage deviation, relative to the admissible limits.

2.3 Control Actions Management Module

The core of the LVC tool is the Control Actions Management Module (CAMM). The CAMM is responsible for analysing the network data and the computation of the actual set-points to apply in the network's resources. On the other hand, if no voltage violations are registered or foreseen in the network, the CAMM is also responsible for constraint management, i.e. lifting set-points that may have been imposed in the LV network controllable resources that are no longer required for the normal operation of the network.

When a voltage violation is registered, the CAMM starts by evaluating the available LV controllable resources, with the objective of determining the best-suited resources to address the constraint. The ranking of the resources is performed according to criteria established by the DSO, with the overall objective of minimizing the grid operation costs. The rank of each network resource is established according to the following criteria, by priority:

- Resource type: the resource type is the highest priority criterion. It was assumed that each resource has an associated cost and therefore resources with lower costs should be actuated first. In this sense, priority is given to DSO-owned resources (OLTC transformers and energy storage devices) and then consumer-owned resources (flexibility from domestic clients via their HEMS, microgenerators or flexible loads).

- Electrical distance to the voltage violation node: the next criterion in the rank computation of the resource is the electrical distance to the node where the voltage violation is registered. Priority is given to resources located in the same phase that are closer to the voltage violation node.

- State of Charge (SoC): for energy storage devices and HEMS. In case of overvoltage, devices with a lower SoC are prioritized; in case of undervoltage, priority is given to devices with higher SoC.

- Contract characteristics and curtailment time: other criteria taken into account are the nature of the contract with private consumers for the use of flexibility, and curtailment time.

Once the best-suited resources are selected and ranked according to the aforementioned criteria, the first resource is selected and a set-point is computed, based on the electrical distance between the controllable resource's node and the node where the voltage violations occurs. The impact of the set-point on the network nodes' voltages is then evaluated recurring to a three-phase power flow routine according to the formulation presented in [9]. If the established set-point is unable to solve the constraint, the next resource in the controllable resources' list is selected and a new set-point is computed. The control action plan is closed when the computed set-points are able to solve the violation or when the resources list is exhausted.

In constraint management restrictions mode, the ranking of the controllable resources is performed in "reverse" manner. Only resources with established set-points are included in the list, and priority is given to resources which operation is more expensive – in this case, private consumers' flexibility, followed by DSO-owned resources. In this mode, the node closest to a voltage violation is considered to be the reference node. In this sense, the ranking methodology prioritizes resources that are farther from the reference node, since they will have the least impact in the reference node voltage. The control action plan (managing all constraints, i.e. lifting set-points) is generated when the resource list is exhausted.

3 Simulation Results

3.1 Test-case Scenario Definition

The LVC algorithm was tested for a network with the electrical characteristics of a representative LV network in Portugal. The network is composed by 33 buses and 32 lines, a transformer with OLTC and it is considered the existence of a 10kW / 22 kWh energy storage device at the secondary side of the MV/LV transformer. The single-line diagram of the test-case network can be seen in Fig. 2. The data related to this LV network is presented in [10]. The characteristics of the network's microgenerators, flexible loads and HEMS are listed in Table 1, Table 2 and Table 3, respectively.

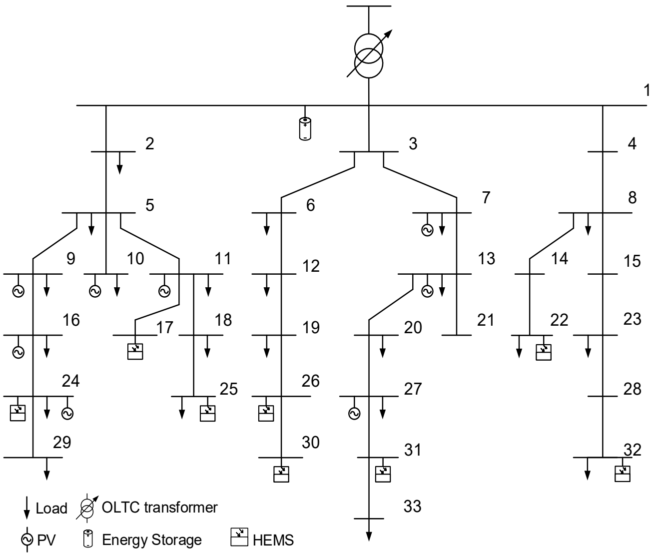

Fig. 2 Test-case LV network single-line diagram

The LVC algorithm was run in preventive control mode, for a planning horizon of 24 hours, at each 15 minutes, i.e. with a frequency of 4 plans per hour. This sampling rate is considered to be sufficient to manage slow dynamics as the inclusion of local control will ensure the response to fast events. All of the resources were considered to be controllable by the LVC module. For simplicity reasons, the demand was considered to be identical for all loads, as well as the production for all of the microgenerators, which were assumed to be all based on PV panels. For the demand and PV production, typical diagrams were used, as shown in Fig. 3 [10]. The voltage limits considered are ±5% of the distribution transformer nominal voltage. Although these are not the limits set in the EN 50160 standard, it was assumed that the DSO would require voltage to be kept within stricter limits.

Table 1 Test Case Network Characterization (Microgenerators)

Bus no.	Generat. Installed Capacity [kVA]			Generat. no.
	Phase R	Phase S	Phase T	
7	5.175	-	-	1
9	3.45	-	-	2
10	-	5.75	-	3
11	-	-	3.45	4
13	3.45	-	-	5
16	-	3.45	-	6
24	-	5.75	5.75	7 / 8
27	5.75	-	-	9

Table 2 Test Case Network Characterization (Flexible Loads)

Bus no.	Load Installed Capacity [kVA]			Load No.
	Phase R	Phase S	Phase T	
2	3.45	3.45	-	1 / 2
5	-	-	3.45	3
6	1.15	-	-	4
7	10.35	-	-	5
8	3.45	3.45	3.45	6 / 7 / 8
9	6.9	3.45	3.45	9 / 10 / 11
10	3.45	13.8	-	12 / 13
11	3.45	-	-	14
12	3.45	3.45	-	15 / 16
13	6.9	3.45	3.45	17 / 18 / 19
16	-	6.9	-	20
18	-	3.45	3.45	21 / 22
19	3.45	3.45		23 / 24
20	-	3.45	3.45	25 / 26
22	-	3.45	3.45	27 / 28
23	-	-	3.45	29
24	-	17.25	20.7	30 / 31
25	0	3.45	-	32
27	6.9	3.45	3.45	33 / 34 / 35
29	3.45	3.45	-	36 / 37
32	-	3.45	-	38
33	-	-	3.45	39

Table 3 Test Case Network Characterization (HEMS)

Bus no.	HEMS Installed Capacity [kVA]			HEMS no.
	Phase R	Phase S	Phase T	
17	5.75	-	-	1
22	3.45	-	-	2
24	5.75	-	-	3
25	-	-	5.75	4
26	-	5.75	-	5
29	-	-	5.175	6
30	-	-	13.8	7
31	-	3.45	-	8
32	-	-	3.45	9

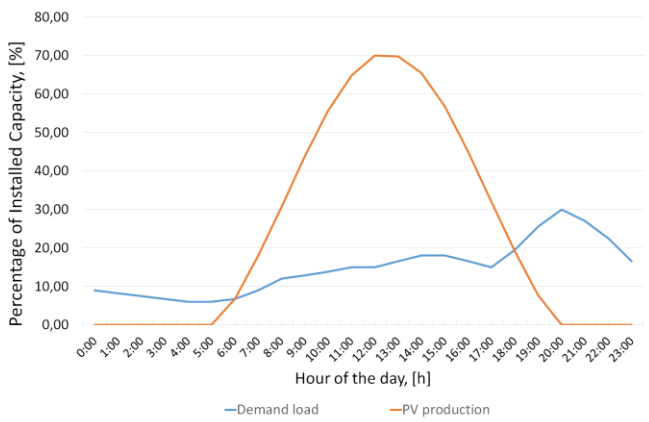

Fig. 3 Daily demand and PV production profiles (typical values)

Fig. 4 shows the maximum and minimum voltage values registered at the equipments' terminals, for each period of the planning horizon, before the application of the LVC tool. In Fig. 5 is possible to see that voltage profiles at the equiments' terminals where voltage violations occur throughout the day, also before the application of LVC. As can be observed, the test case LV network is highly prone to voltage problems. The highest voltage values registered are around 1.14 p.u., from 12:45 to 13:00 at the terminals of the HEMS 4 equipment (node 25 in Fig. 2, phase T). At around the same time, from 12:15 until 13:15, are also registered the lowest voltage values, around 0.9 p.u., in Load 39 (node 33 in Fig. 2, phase T). The registered values, without the application of the LVC tool, are not only outside the admissible range considered but also represent a violation of the EN 50160 standard.

Fig. 4 is also useful to understand the overall tendency of the nodes' voltage values, and where voltage violations are most likely to occur. From the analysis of the voltage profiles, regarding overvoltage problems, it can be seen that the most problematic nodes are the node 25 (HEMS 4) and node 22 (HEMS 2), both above the 1.1 p.u. threshold. Nodes 18 (Load 22), 29 (HEMS 6), 11 (Generator 4) and 27 (Generator 9) also show proneness to overvoltages, with maximum values registered between 1.05 and 1.1 p.u. Regarding undervoltages, the most problematic nodes are the node 33 (Load 39) and node 32 (HEMS 9), both between 0.95 p.u. and 0.9 p.u.

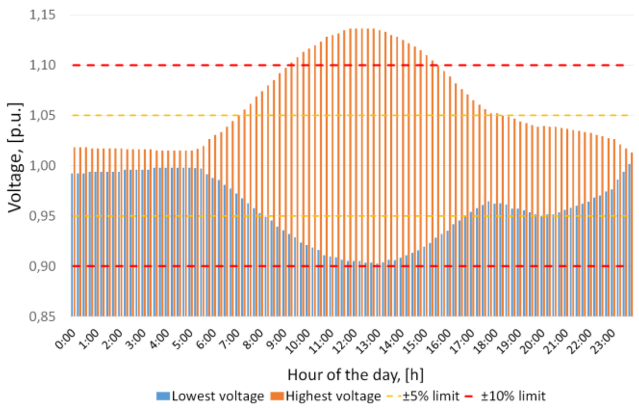

Fig. 4 Highest and lowest voltages registered at the equiments' terminals – without LVC

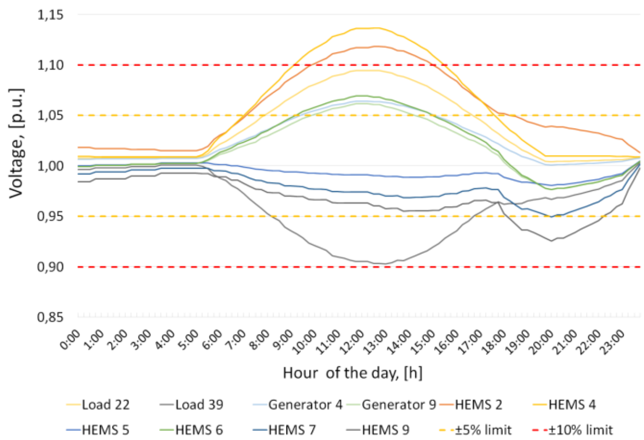

Fig. 5 Voltage profiles the problematic equiments' terminals – without LVC

Fig. 6 shows the maximum and minimum voltage values registered at the equipments' terminals, after the application of the LVC tool. Fig. 7 shows the voltage profiles at the equipments' terminals where voltage violations occur throughout the day, after the application of the LVC tool. From both figures it is possible to see that the algorithm was able to regulate the voltage values registered in the network, even for the severe conditions registered and strict voltage limits imposed. The maximum voltage value registered is 1.06 p.u., in node 30 (HEMS 7). The minimum voltage value registered is 0.94 p.u., in node 26 (HEMS 5). This behaviour can be explained by the high unbalance of load and generation distribution. The algorithm converges to a state that represents the best compromise between over and undervoltage, given the controllable resources it has access to solve the constraints.

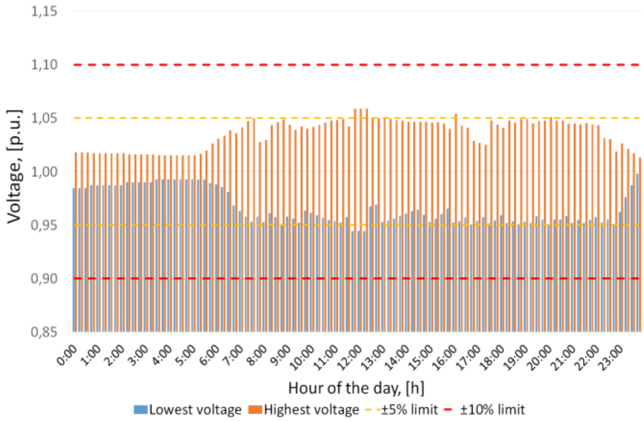

Fig. 6 Highest nd lowest voltages registered at the equiments' terminals – with LVC

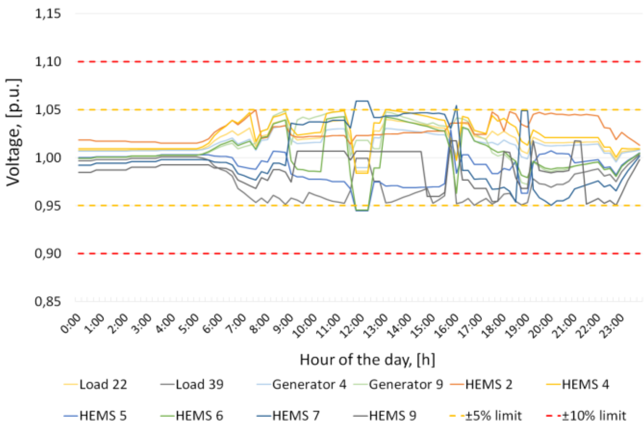

Fig. 7 Voltages registered at the problematic equiments' terminals – with LVC

In Fig. 8 and Fig. 9 is possible to see in greater detail the voltage profiles registered in nodes 25 and 33 – HEMS 4 and Load 39 equipments, respectively – the most severe cases of over and undervoltage deviations registered. As it is possible to see from Fig. 8, the algorithm was able to regulate the voltage at the HEMS 4 equipment, decreasing the maximum voltage value of 1.14 p.u. at the peak solar production period, to values around 1.05 p.u., the upper control limit imposed. In a similar manner, it was also able to regulate the voltage at Load 39 (Fig. 9), increasing the minimum value of 0.9 p.u. to values around 0.95 p.u, the lower admissible limit imposed.

As can be observed from Fig. 8 and Fig. 9 the algorithm was able to address severe simultaneously occurring overvoltage and undervoltage constraints in an effective manner, regulating the voltage deviations at the equipment's terminals to the pre-defined limits.

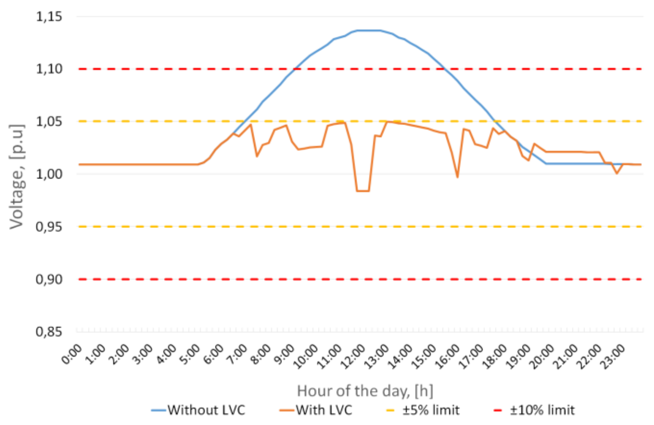

Fig. 8 Detail of node 25 voltage profiles (before and after LVC application)

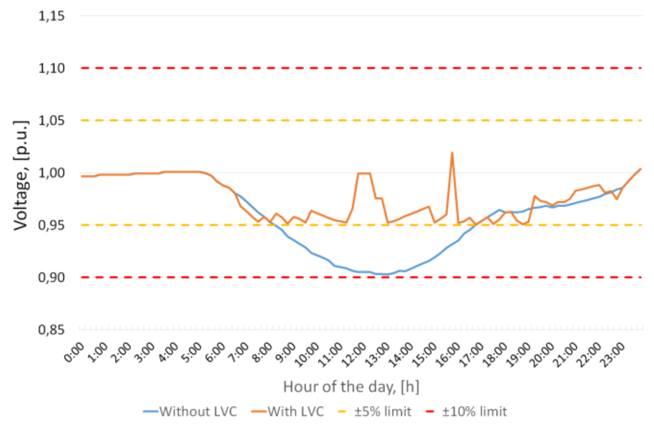

Fig. 9 Detail of node 33 voltage profiles (before and after LVC application)

4 Conclusion

In this paper, a new algorithm for voltage control in LV grids that takes advantage of the available DER and flexibility from domestic consumers is presented. The proposed approach operates in two different time frames: a preventive plan for n-hours ahead and a scheme to implement corrective measures in real time. The main advantages of the proposed approach are its simplicity, for instance when comparing to the formulation of an optimization problem, and the fact that it is a centralized approach that does not require sophisticated ICT solutions. However, there are some drawbacks such as the fact that the prioritization approach lacks global optimization capabilities (for instance when smooth activation near the disturbance is implemented, re-iteration may be needed) and it may often stress resources which are close to disturbance.

The algorithm was tested for a simulated severe scenario, in a highly unbalanced network where over and undervoltage constraints occur simultaneously in the peak solar production period of the day. The algorithm showed a good performance, even for the severe conditions modelled and strict voltage limits imposed, being able to address simultaneously occurring overvoltages and undervoltages to the imposed limits of ±5%, thus validating the proposed approach taken for the LVC algorithm in the scope of the InteGrid project.

Within the framework of this project, the algorithm will also be tested in a laboratorial environment at the Smart Grids and Electric Vehicles Laboratory of INESC TEC and then validated in a live test environment in a smart grids pilot operated by EDP Distribuição (Portuguese DSO) in Portugal, considering actual storage devices and real HEMS installed at the customer's premises.

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