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Advanced voltage control for smart microgrids using distributed energy resources

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ABSTRACT

Large scale integration of distributed generation (DG), particularly based on variable renewable energy sources (RES), in low voltage (LV) distribution networks brings significant challenges to operation. This paper presents a new methodology for mitigating voltage problems in LV networks, in a future scenario with high integration of distributed energy resources (DER), taking advantage of these resources based on a smart grid type architecture. These resources include dispersed energy storage systems, controllable loads of residential clients under demand side management (DSM) actions and microgeneration units. The algorithm developed was tested in a real Portuguese LV network and showed good performance in controlling voltage profiles while being able to integrate all energy from renewable sources and minimizing the energy not supplied.

1. Introduction

Large-scale integration of DER, especially DG but also energy storage systems or controllable loads, at the level of the LV distribution grid presents a set of challenges in order to ensure efficient and secure network operation while guaranteeing quality and continuity of service to end-users [1]. Voltage profiles in particular can be severely affected by the integration of decentralized units, namely based on variable RES [2].

Therefore, it is essential to develop tools for grid operation in order to manage the available DER that may help in solving the technical problems caused by a high integration of RES generation, particularly at the LV level [3]. In this context, the microgrid and smart grid concepts appears as an alternative paradigm for distribution networks that will allow integrating distributed resources with increased flexibility for grid operation, taking advantage of advanced control infrastructures and enabling the provision of ancillary services to the system [4,5].

Several studies addressing the issue of renewable integration in LV networks have been recently conducted and published with interesting results. For instance, the authors in Ref. [6] consider the use of a meta-heuristic to minimize the microgeneration shedding and active power losses in order to avoid voltage violations. In fact, this methodology has proved successful at ensuring that voltage was kept within admissible limits but at the expense of some microgeneration curtailment in LV networks.

Other works such as Ref. [7] attempted to overcome this limitation by utilizing storage systems present in the network in order to store excess energy from microgeneration, thus avoiding renewable curtailment that would be required to control voltage values. The results obtained were encouraging as a good geographical distribution of these storage systems across the network provides a good solution to control voltage levels for the Distribution System Operator (DSO). This enables preventing overvoltages caused by high levels of RES-based microgeneration and simultaneously avoids under-voltage problems by discharging the stored energy during periods of high consumption where the voltage profiles are typically low. Alternative measures include the control of the consumption of domestic customers in LV grids. Accordingly, from the scientific literature, some studies in this field have been performed where different researchers have different methods and technologies with the objective of controlling customers' consumption, for instance Refs. [8,9].

From the foregoing, it is understood that there are different alternatives to integrate the increasing penetration of renewable microgeneration, but few alternatives actually include the combination of all these different DER in order to solve that problem. Consequently, a monitoring and control system that considers the coordinated operation of storage systems, loads under active DSM and microgeneration units can constitute an advance towards

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advanced voltage control in LV distribution networks in the future. The proposed approach consists of an algorithm for day-ahead operational planning control that is run at every hour taking advantage of the available DER for voltage control purposes.

2. Control architecture and management architecture

A microgrid can be regarded as an LV network with microgeneration units, controllable loads and storage devices that can be managed as an active cell of the distribution system in an autonomous way, supported by a control and communication infrastructure [10]. This methodology involves a voltage control tool applied to distribution systems to be installed at the level of the MicroGrid Central Controller (MGCC), *i.e.* at the MV/LV secondary substation. This algorithm should be implemented as a software module dedicated to the operation of the microgrid running every hour in order to define the control actions required to maintain voltage profiles within an admissible range.

There is a wide variety of technologies with great potential for voltage control, associated to different DER. In this work, regarding the voltage control scheme, the following systems at the LV level were considered:

- Storage devices (batteries);
- Controllable loads at the domestic level under DSM actions;
- Microgeneration units (photovoltaic – PV – panels).

This requires that a suitable communication infrastructure be available in order to enable the interaction between the different DER and the control centre. This infrastructure could be based on a smart metering infrastructure, for instance, exploiting communication solutions that can be either wired (such as PLC prime) or wireless (such as GPRS).

For the proposed algorithm, there is also the need to rely on short-term load and renewable generation forecasting in order to define the control actions for the following hour. It is also assumed that the system is completely observable. However, in real life context it may not be necessary to have full observability if adequate state estimation algorithms are used, where the availability of a set of measures with sufficient redundancy may allow obtaining the current state of the system. In the scientific literature, new methodologies for state estimation, Refs. [11,12], which can be applied here, are available and reveal show good results in determining unobservable magnitudes in real-time.

2.1. Storage devices

Storage systems are regarded as a distributed resource to be used by the voltage control algorithm and their characteristics are essential for a proper modelling of these devices. The main features that influence the possibility of storage systems supporting voltage control are the storage capacity, the available power and the efficiency [13].

Usually, the battery connection to the network is ensured by power electronic interfaces such as voltage source inverters. With these devices, it is possible emulate the behaviour of a synchronous machine to use the energy stored in batteries and enable voltage or even frequency control in microgrids [10].

2.2. Controllable loads

Loads at the domestic level may also be regarded as an additional resource for the DSO so that an effective control of the customer's consumption can be exploited in order to solve problems in LV distribution networks, particularly in terms of voltage. A good management of this resource may contribute to optimize the use of electricity, reducing customer costs as well DSO costs. According to Ref. [14], it is possible to define a number of categories for the control of various domestic applications classified as follows:

- Uncontrollable load—loads that may present technical difficulties to control, where a drastic change in consumer habits will potentially cause discomfort;
- Load shedding—electrical equipment which can be switched off for short periods of time without compromising the quality of service and consumer habits;
- Shiftable load—loads that can be shifted in time, namely transferring consumption from peak hours to periods with high microgeneration levels that have no relevant impact on the consumer.

These actions should be implemented respecting some restrictions in order to avoid a drastic change in consumption habits, ensuring that there is no significant discomfort for the customers. For example, equipment such as refrigerators can be interrupted only for short periods of time, without compromising their primary function.

2.3. Microgeneration

Renewable-based microgeneration are non-controllable sources and a source of variable power since they depend on the primary source, which is usually wind (in the case of micro wind generators) or sun (in the case of PV panels).

Therefore, in order to control the voltage profiles, it may be necessary to reduce the active power injected by renewable-based microgeneration units. It is assumed that the control system presented in Fig. 1 is used to send pre-defined values of active power from the MGCC to the MC that controls the inverter and the active power that the microgeneration unit injects into the network. Thus, microgeneration curtailment is presented as a last resource to be used by the advanced voltage control algorithm.

2.4. Control actions

The control actions envisaged are defined through set-points that are sent by the DSO through the MGCC to each load controller (LC) to control or change the electric consumption and to each microsource controller (MC) to control the microgeneration (curtailment of renewable energy) and storage systems (charge or discharge a certain amount of energy). Communication and information exchange between these controllers is assumed to be bidirectional such that the smart meters are able to obtain data at the level of the LV domestic customer such as the electricity consumption and send this information to the MGCC, as illustrated in Fig. 1.

It is expected that the use of smart meters will ease the implementation of programs for managing large-scale consumption in the residential sector. From the point of view of the DSO, an intelligent control of consumption prevailing in this sector will reduce peak demand in distribution networks. With the implementation of smart meters it will be possible to analyse in detail customers' consumption and contribute to a better balance between supply and demand. This will also enable increasing security of supply by integrating microgeneration in a more effective way and easier to control.

3. Mathematical formulation

The proposed procedure involves solving an optimization problem. The main objective consists in minimizing the voltage control

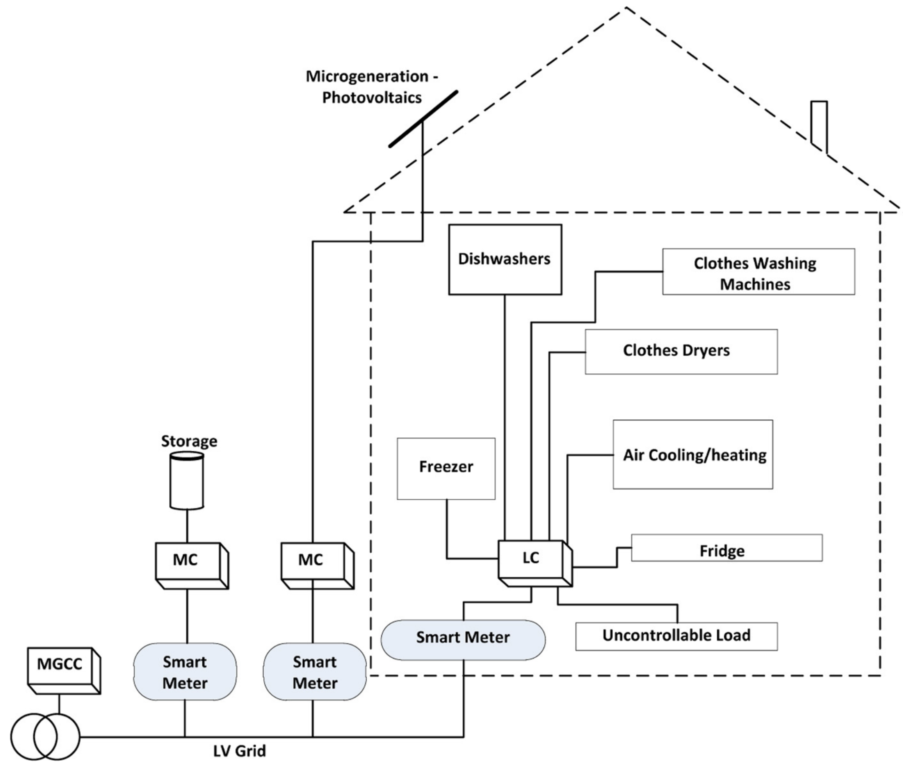

Fig. 1. Proposed control LV architecture for residential customers.

actions in order to use the least possible power of these resources to ensure that voltage profiles are within the technical limits subject to a set of technical constraints and operational associated to the problem. The control actions identified are the following:

- Charging/discharging storage devices;
- Shifting controllable loads;
- Shedding non-priority loads;
- Curtailing microgeneration (last resort action);
- Curtailing of essential loads (last resort action).

3.1. Objective function

The objective function *f* used is presented in Eq. (1).

$$\min f = \sum_{i=1}^{n} \left[P^h_{chrg_i} + P^h_{dchrg_i} \left(P^h_{shift_i} \cdot \mu_{shift_i} \right) \cdot \rho_1 + \left(P^h_{shed_i} \cdot \mu_{shed_i} \right) \cdot \rho_2 + \left(P^h_{micro_i} + P^h_{ns_i} \right) \cdot \rho_3 \right] \quad (1)$$

$\forall h \in \mathbb{Z}; \quad 1 < h < 24; \quad \forall i \in nr$

where

$P^h_{chrg_i}$	Power charge of battery *i* at hour *h* (kW)
$P^h_{dchrg_i}$	Power discharge of battery *i* at hour *h* (kW)
$P^h_{shift_i}$	Shifted load in bus *i* at hour *h* (kW)
μ_{shift_i}	Binary variable {1, load shifted | 0, no load shifted}
$P^h_{shed_i}$	Non-priority load shedding in bus *i* at hour *h* (kW)
μ_{shed_i}	Binary variable {1, load shedding | 0, no load shedding}
$P^h_{micro_i}$	Renewable microgeneration power curtailment in bus *i* at hour *h* (kW)
$P^h_{ns_i}$	Power not supplied to customer in bus *i* at hour *h* (kW)
ρ_j	Weight *j*
n	Number of buses

The weights used in the objective function aim at prioritizing the actions of the control actions and were set as follows: $\rho_3 \gg \rho_2 \gg \rho_1$. However, these weights may be changed according to the preferences of the decision maker (*i.e.* the DSO).

3.2. Constraints

3.2.1. Storage constraints

In the management of storage systems, it is necessary to limit the maximum storage capacity of each unit as presented in Eq. (2).

$$E^h_{sto_i} \le E_{max_{sto_i}} \quad (2)$$

The limits for charging and discharging are considered, as shown in Eqs. (3) and (4).

$$P^h_{chrg_i} \cdot \mu^h_{chrg_i} \le P_{max_{chrg_i}} \quad (3)$$

$$P^h_{dchrg_i} \cdot \mu^h_{dchrg_i} \le P_{max_{dchrg_i}} \quad (4)$$

Eqs. (5) and (6) ensure that storage systems do not operate with a load rate that exceeds their maximum storage capacity and do not operate with a discharge rate that exceeds the energy that stored in the batteries, respectively.

$$P^h_{chrg_i} \cdot \mu^h_{chrg_i} \cdot \Delta h + E^{h-1}_{sto_i} \le E_{max_{sto_i}} \quad (5)$$

$$-P^h_{dchrg_i} \cdot \mu^h_{dchrg_i} \cdot \Delta h + E^{h-1}_{sto_i} \ge 0 \quad (6)$$

Eq. (7) inhibits simultaneous charging and discharging.

$$\mu^h_{chrg_i} + \mu^h_{dchrg_i} \le 1 \quad (7)$$

Eq. (8) updates the state of the storage system.

$$E^h_{sto_i} = E^{h-1}_{sto_i} + P^h_{chrg_i} \cdot \mu^h_{chrg_i} - P^h_{dchrg_i} \cdot \mu^h_{dchrg_i} \quad (8)$$

where

$E_{sto_i}^h$	Energy stored in battery i at hour h (kWh)
$E_{max_{sto_i}}$	Maximum energy storage of battery i (kWh)
$\mu_{chrg_i}^h$	Binary variable {1, storage system is charging at h period | 0, storage system is not charging at h period}
$P_{max_{chrg_i}}$	Maximum power charging of battery i (kW)
$\mu_{dchrg_i}^h$	Binary variable {1, storage system is discharging at h period | 0, storage system is not discharging at h period}
$P_{max_{dchrg_i}}$	Maximum power discharging of battery i (kW)
Δh	Time step Δh = (h) − (h − 1)

3.2.2. Load constraints

The DSO may control the consumption in two ways: by shedding loads classified as non-priority by the client or by shifting loads from certain periods of time to others. Load shifting can be achieved by delaying/anticipating the use of certain domestic appliances, for instance dish washers and clothes washers/dryers. The way of controlling these devices is modelled by a discrete set of variables α_1, α_2, α_3 which represent the load that can be shifted, as presented shown in Eq. (9).

$$P_{shift_i}^h = P_{shift_{i_\alpha}}^h \cdot \mu_{shift_{i_\alpha}}^h \quad (9)$$

$\forall \alpha \in A = \{\alpha_1; \alpha_2; \alpha_3\}$

An additional constraint is implemented to ensure that if a device α was used at hour h it will not be used in a subsequent hour $h + \Delta h$, as shown in Eq. (10).

$$-P_{shift_{i_\alpha}}^h + P_{shift_{i_\alpha}}^{h+\Delta h} = 0 \quad (10)$$

Also, for a period of 24 h, this action can be performed only once for each load α, as shown in Eq. (11).

$$\sum_{h=1}^{24} \mu_{shift_{i_\alpha}}^h = 1 \quad (11)$$

where

$P_{shift_{i_\alpha}}^h$	Average shifted power of appliance α in bus i at hour h (kW)
$\mu_{shift_{i_\alpha}}^h$	Binary variable {1, appliance α is shifted at hour h | 0, appliance α is not shifted at hour h}
A	Set of discrete variables that represent the average power of domestic appliances that can be shifted (A = {α_1; α_2; α_3})
α_1	Clothes washer average power (kW)
α_2	Clothes dryer average power (kW)
α_3	Dish washer average power (kW)

Another possible way to control the voltage levels, including under-voltage levels during high consumption periods, is through shedding of non-priority loads. This action involves cutting load for short periods of time and it is modelled by a set of discrete variables β_1, β_2, β_3 which represent the power that can be curtailed for each customer i. Eq. (12) represents the power that can be cut at a certain hour h as a combination of the average active power of a set of equipment (B) from the customer at bus i, namely the fridge, the freezer and the air cooling system.

$$P_{shed_i}^h = \mu_{shed_i}^h \cdot C_B \quad (12)$$

With $B = \{\beta_1; \beta_2; \beta_3\}$ and $C_B = \{\beta_1\}, \{\beta_2\}, \{\beta_3\}, \{\beta_1, \beta_2\}, \{\beta_1, \beta_3\}, \{\beta_2, \beta_3\}, \{\beta_1, \beta_2, \beta_3\}$

Again, during a 24 h period, this action can only be performed once for each load β as shown in Eq. (13).

$$\sum_{h=1}^{24} \mu_{shed_{i_\beta}}^h = 1 \quad (13)$$

where

C_B	Choice of k elements of a set of B elements
B	Set of discrete variables representing the average power of all domestic appliances that can be switched off (kW)
β_1	Fridge average power (kW)
β_2	Freezer average power (kW)
β_3	Air cooling system average power (kW)
$\mu_{shed_{i_\beta}}^h$	Binary variable {1, load β is shed | 0, load β is not shed}

3.2.3. LV network constraints

For each hour, the three-phase power flow equations, presented in Eqs. (14) and (15), must also be satisfied.

$$P_i^p = |V_i^p| \cdot \sum_{k=1}^{n} \sum_{m=a}^{c} |V_k^m| \cdot \left[G_{ik}^{pm} \cdot \cos\left(\theta_{ik}^{pm}\right) + B_{ik}^{pm} \cdot \sin\left(\theta_{ik}^{pm}\right)\right] \quad (14)$$

$$Q_i^p = |V_i^p| \cdot \sum_{k=1}^{n} \sum_{m=a}^{c} |V_k^m| \cdot \left[G_{ik}^{pm} \cdot \sin\left(\theta_{ik}^{pm}\right) - B_{ik}^{pm} \cdot \cos\left(\theta_{ik}^{pm}\right)\right] \quad (15)$$

The inequality constraints presented in Eqs. (16) and (17) correspond to admissible range for voltage magnitude at each bus and the maximum power flow in the branches.

$$V_i^{p^{\min}} \le V_i^p \le V_i^{p^{\max}} \quad (16)$$

$$S_{ik}{}^p \le S_{ik}^{p^{\max}} \quad (17)$$

where

P_i^p	Injected active power in bus i, phase p (W)
V_i^p	Voltage magnitude at bus i, phase p (V)
G_{ik}^{pm}	Conductance $3n \times 3n$ matrix (S)
θ_{ik}^{pm}	Voltage angle difference between bus i and k, phase p (°)
B_{ik}	Susceptance $3n \times 3n$ matrix (S)
Q_i^p	Injected reactive power in bus i, phase p (var)
$V_i^{p^{\min}}$	Minimum voltage magnitude allowed at bus i, phase p (V)
$V_i^{p^{\max}}$	Maximum voltage magnitude allowed at bus i, phase p (V)
$S_{ik}{}^p$	Apparent power flow between bus i and k, phase p (VA)
$S_{ik}^{p^{\max}}$	Maximum apparent power flow between bus i and k, phase p (VA)

3.3. Voltage control algorithm

The work included an algorithm for advanced voltage control developed in MATLAB that exploits in a coordinated way microgeneration units, controllable loads and storage devices. The resulting voltage control tool includes a set of algorithms, namely:

- A three-phase power flow routine;
- An optimization method based on a meta-heuristic, Evolutionary Particle Swarm Optimization (EPSO);
- A sequential voltage control algorithm.

The algorithm used is illustrated in Fig. 2. The purpose of this algorithm was to obtain a baseline scenario by conducting an hourly simulation for a period of 24 h with a typical load and production profile (ideally these data should come from load and renewable generation forecast tools) in order to assess if the voltage mag-

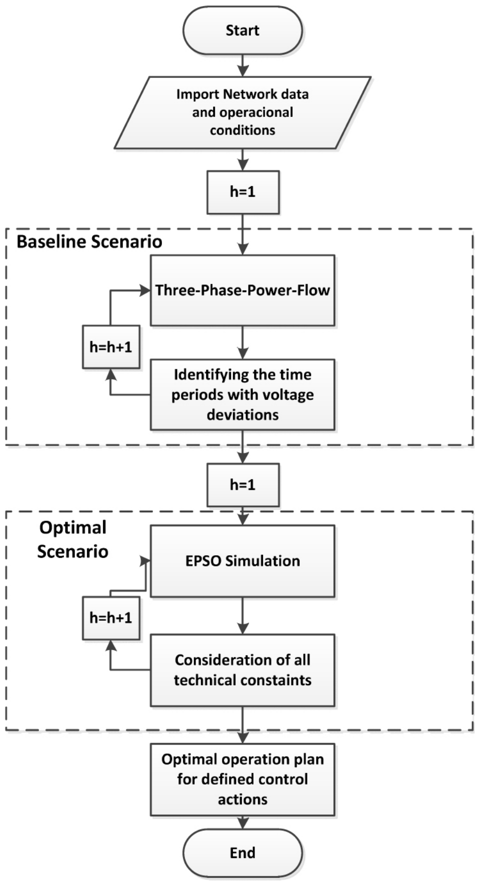

Fig. 2. Voltage control algorithm.

nitude at all buses of the network complies with the regulatory technical limits. This scenario is built using the three-phase power flow algorithm presented in Ref. [15]. In the iterative process of the optimization problem using EPSO [16], for each solution (particle), the three-phase power flow algorithm evaluates the voltage magnitudes for different values of the control variables (storage systems, controllable loads and microgeneration).

4. Main results

The voltage control algorithm developed was tested using the real Portuguese distribution network presented in Fig. 3. This network is a typical LV grid with a radial structure, a distribution transformer of 100 kV A, 33 buses and 32 branches. It is a three-phase unbalanced network with a nominal voltage of 400 V. For this network, a future scenario considering PV microgeneration distributed in all three phases was created.

Table 1 shows the installed power of microgeneration, the contracted power of the clients and the available power for the storage devices as well as their location in the LV network. As can be seen, due to the high number of single-phase loads, there is a small imbalance in different phases.

It should be noted that the amount of storage power considered was specified in order to showcase the performance of the algorithm to a full extent. In order to determine the ideal amount of storage capacity to be installed in the grid, the DSO should conduct a detailed analysis of the most relevant scenarios of operation.

Fig. 4 shows the domestic consumption and PV microgeneration profiles that were used. Since real forecasting information is hard to obtain, the data for the scenario used in simulation was obtained for the day of May, 31st 2013, according to the forecast released by the Portuguese Energy Regulator (ERSE). The choice of this particular day was purposeful, because it was a day with high solar generation and moderate consumption, thus allowing creating situations that include severe overvoltages. These profiles have been normalized taking into account the total PV microgeneration for the PV profile used as well as the peak load for that specific network for the load profile.

In order to define the load for each LV node at each hour, the value of the load profile in that hour is multiplied by the load contracted power in that node. For instance, the load in Bus 2, phase 1 at hour 13 is $0.175 \times 3.45 \approx 0.6$ kW. The same process is used for the microgeneration units. In this case, the generation level for each LV node at each hour is obtained by multiplying the value of the PV profile (it is assumed that all microgeneration present in the grid is based on PV units) in that hour by the PV installed power in that node.

Then, two distinct scenarios have been analysed:

- Baseline scenario—simulation in steady-state using the three-phase power flow algorithm developed without the consideration of control actions (*i.e.* batteries' charging/discharging, load shifting, load shedding or microgeneration curtailment);
- Optimal scenario—simulation of the voltage control algorithm developed including all control actions.

4.1. Baseline scenario

In order to identify if there are voltage deviations for this scenario, a three-phase power flow was run for the 24 h of the day. The results obtained are summarized in Table 2 for the cases where voltage violations have occurred.

Considering a limit of ±5% in voltage magnitudes, the results obtained for the worst case (*i.e.* bus with highest voltage deviations—Bus 32 for phase 1 and phase 2 and Bus 26 for phase 3) are illustrated in Fig. 5.

One can conclude that overvoltage problems in the LV distribution network buses occurred during the periods with high PV generation *i.e.* periods of high solar radiance, between hour 11 and hour 17, particularly in the buses furthest from the MV/LV distribution transformer since the high resistivity of the LV lines greatly contributes to the aggravation of the overvoltages. At hour 22, there is high consumption (peak hour) and there is no microgeneration, which causes several under voltages in some buses.

4.2. Optimal scenario

The main objective of the voltage control algorithm developed is to define an optimal operation plan for the available DER. The algorithm finds the amount of power required for each control action in order to ensure that there are no voltage violations. This will enable minimizing the renewable energy spilled that would occur if the voltage limits were violated and there were no other control actions available. The algorithm was run for a sequential period of 24 h in order to mitigate the voltage deviations identified after running the baseline scenario.

It can be observed in Fig. 5 that in the baseline scenario (without control actions), several voltage values were out of the admissible range considered. Using the voltage control algorithm developed it was possible to adjust these values to ensure that no violations occur based on an optimal management of the DER, without requiring microgeneration curtailment or essential load shedding. Fig. 6 shows the highest voltage deviations that occurred in one of the most problematic buses of the network (Bus 32).

In Table 3 it is possible to observe that all voltage values are now within the admissible range after running the voltage control algo-

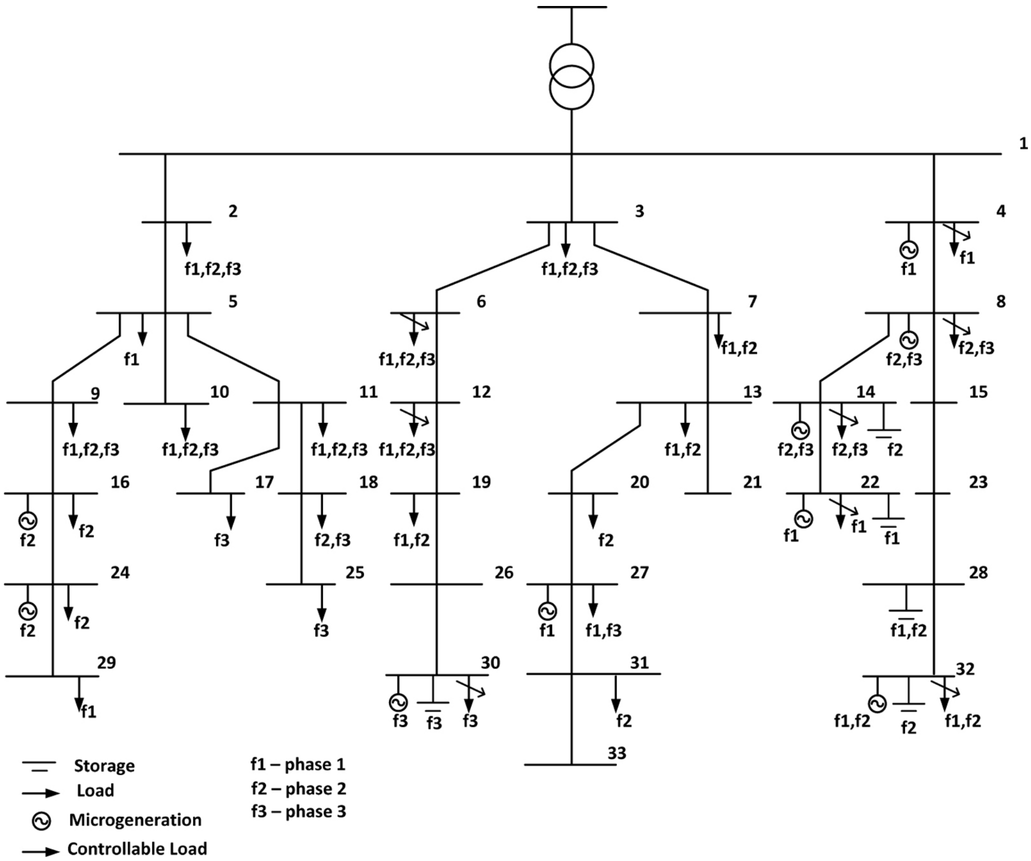

Fig. 3. LV test network.

Table 1
Total power of the distributed energy resources.

Bus	Load contracted power (kVA)			PV installed power (kVA)			Storage available power (kW)		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
1	0	0	0	0	0	0	0	0	0
2	3,45	3,45	20,7	0	0	0	0	0	0
3	13,8	13,8	10,35	0	0	0	0	0	0
4	6,9	0	0	3,45	0	0	0	0	0
5	20,7	0	0	0	0	0	0	0	0
6	1,15	3,45	3,45	0	0	0	0	0	0
7	10,35	3,45	0	0	0	0	0	0	0
8	0	3,45	3,45	0	1,725	1,725	0	0	0
9	6,9	3,45	3,45	0	0	0	0	0	0
10	3,45	13,8	13,8	0	0	0	0	0	0
11	3,45	3,45	3,45	0	0	0	0	0	0
12	3,45	3,45	6,9	0	0	0	0	0	0
13	6,9	3,45	0	0	0	0	0	0	0
14	0	3,45	3,45	0	1,725	1,725	0	4	0
15	0	0	0	0	0	0	0	0	0
16	0	6,9	0	0	3,45	0	0	0	0
17	0	0	3,45	0	0	0	0	0	0
18	0	3,45	3,45	0	0	0	0	0	0
19	3,45	3,45	0	0	0	0	0	0	0
20	0	3,45	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0
22	10,35	0	0	5,175	0	0	6	0	0
23	0	0	0	0	0	0	0	0	0
24	0	17,25	0	0	5,75	0	0	0	0
25	0	0	3,45	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0
27	6,9	0	10,35	3,45	0	5,175	0	0	0
28	0	0	0	0	0	0	6	4	0
29	3,45	0	0	0	0	0	0	0	0
30	0	0	13,8	0	0	5,75	0	0	4
31	0	6,9	0	0	0	0	0	0	0
32	10,35	10,35	0	5,175	5,175	0	0	4	0
33	0	0	0	0	0	0	0	0	0

Table 2
Voltage values for baseline scenario.

Hour	Phase 1 voltage (p.u.)			Phase 2 voltage (p.u.)		Phase 3 voltage (p.u.)		
	Bus 22	Bus 28	Bus 32	Bus 28	Bus 32	Bus 19	Bus 26	Bus 30
12	1,066	1,062	1,075	1,062	1,075	–	–	–
13	1,074	1,070	1,084	1,070	1,084	–	–	–
14	1,083	1,078	1,094	1,078	1,094	–	–	–
15	1,082	1,077	1,093	1,077	1,093	–	–	–
16	1,076	1,071	1,086	1,071	1,086	–	–	–
17	1,058	1,054	1,066	1,054	1,066	–	–	–
20	0,921	0,924	0,908	0,927	0,912	–	–	–
21	0,897	0,900	0,880	0,905	0,884	0,947	0,945	0,940
22	0,888	0,892	0,870	0,897	0,875	0,943	0,941	0936
23	0,911	0,914	0,896	0,918	0,900	–	–	0,948
24	0,941	0,943	0,932	0,946	0,934	–	–	–

Table 3
Voltage values for optimal scenario.

Hour	Phase 1 voltage (p.u.)			Phase 2 voltage (p.u.)		Phase 3 voltage (p.u.)		
	Bus 22	Bus 28	Bus 32	Bus 28	Bus 32	Bus 19	Bus 26	Bus 30
12	1,050	1,037	1,050	1,041	1,050	–	–	–
13	1,050	1,035	1,050	1,036	1,050	–	–	–
14	1,050	1,033	1,050	1,415	1,050	–	–	–
15	1,050	1,033	1,050	1,415	1,050	–	–	–
16	1,015	1,040	1,049	1,035	1,050	–	–	–
17	1,033	1,031	1,037	1,039	1,050	–	–	–
20	0,950	0,965	0,950	0,965	0,950	–	–	–
21	0,950	0,969	0,950	0,964	0,950	0,958	0,957	0,954
22	0,952	0,996	0,982	0,958	0,950	0.956	0,954	0,950
23	0,980	0,962	0,952	0,959	0,950	–	–	0,997
24	0,972	0,987	0,976	0,963	0,953	–	–	–

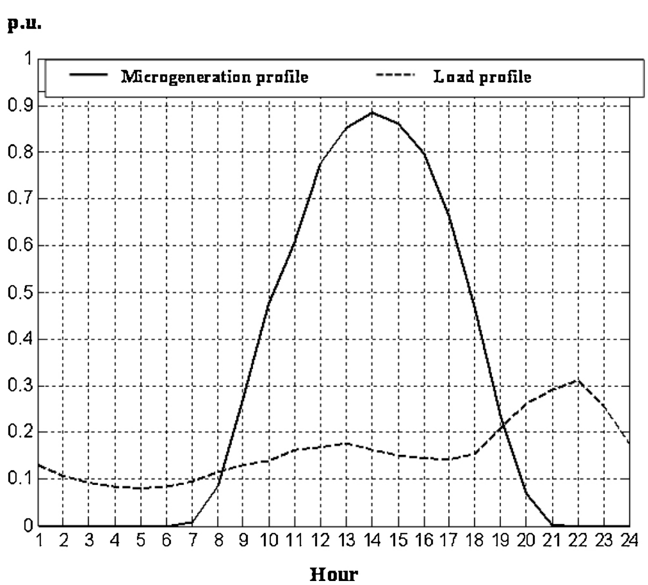

Fig. 4. Microgeneration and load profiles.

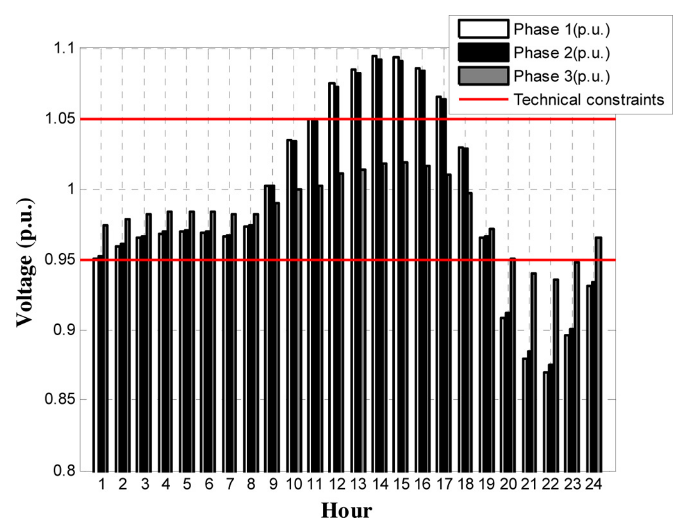

Fig. 5. Highest voltage values in each phase for baseline scenario.

rithm, compared to the values without control actions presented in Table 2 for the baseline scenario.

4.3. Example of control actions in phase 1

Fig. 7 illustrates the control actions implemented on phase 1 for the period of 24 h considered. It can be observed that, from hours 12 to 16, the algorithm recommends the use of the storage systems to absorb power. In the period from hours 16 to the 17, the algorithm suggests using the controllable loads as an option to control the voltage levels, including increased consumption by shifting loads from peak hours to this period since the batteries reached their maximum storage capacity.

By the analysing Fig. 7, in order to control under voltages from hours 20 to 24 (peak hours), the batteries discharge the energy stored during the day. Simultaneously, consumption decreases in hours 22–24 since part of the load had been previously shifted to the period from hours 15 and 16. Finally, since the actions mentioned above were still insufficient to control the voltage levels, the algorithm defines the need for non-priority load shedding, thus reducing consumption during these periods and, consequently increasing the voltage levels above the minimum limit of 0,95 p.u. With the control actions suggested above it was possible to control voltage levels without requiring microgeneration curtailment or shedding of essential loads.

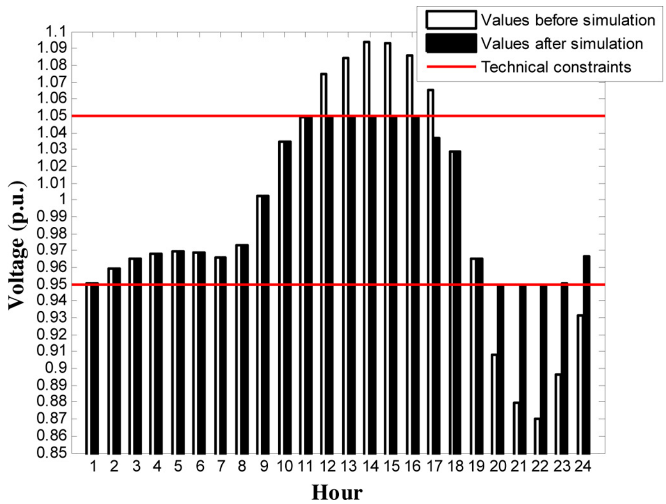

Fig. 6. Highest voltage values at phase 1 of Bus 32 before and after optimization.

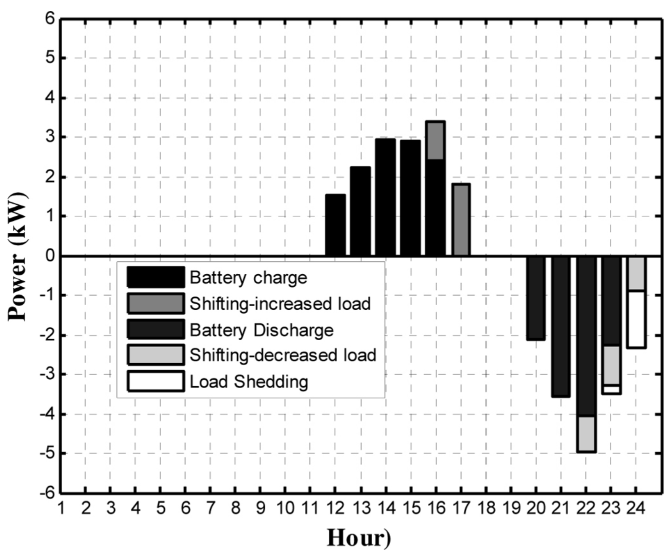

Fig. 7. Control actions performed in phase 1.

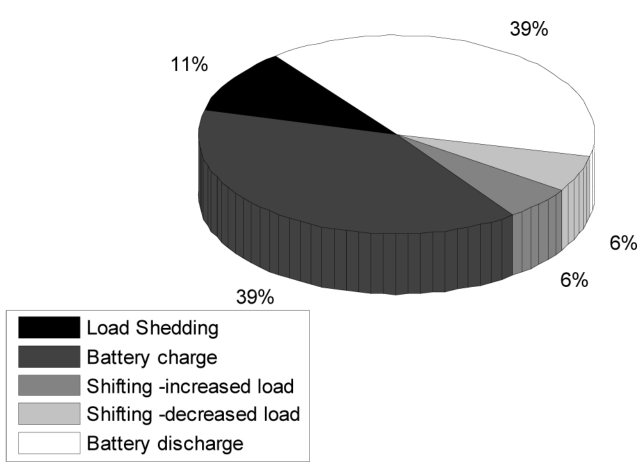

Fig. 8. Total energy from each control action performed.

Fig. 8 presents the energy balance of the DER management, selected as actions for voltage control on all three phases of the test network used. One can conclude that the energy stored (39%) and discharged (39%) was an important action, since the algorithm developed prioritizes the use of storage systems. Only when the energy provided by these systems is insufficient due to maximum charge and discharge rates or maximum storage capacity, the algorithm defines DSM actions that consist in domestic load management (load shifting and a non-priority load shedding).

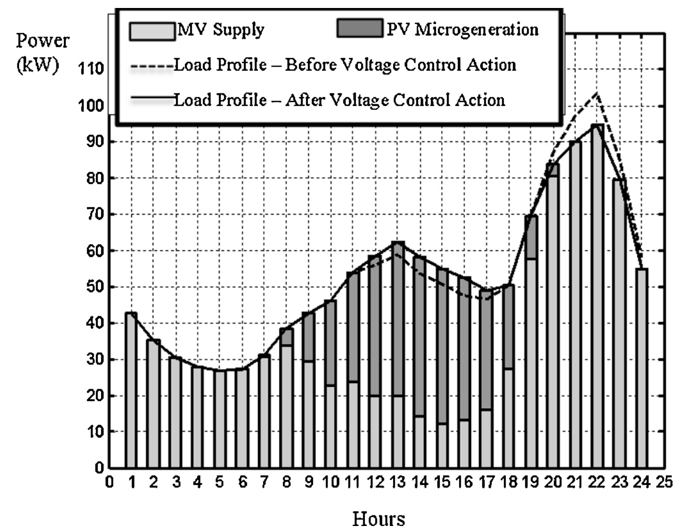

Fig. 9. Balance of power before/after voltage control action.

The overall power balance for the three phases can be seen in Fig. 9. With the control actions it was possible to control voltage levels and integrate all the power of the microgeneration with a load increase due to the action of the storage systems and the load shifting from peak periods (high consumption) to off-peak periods (low consumption). The injection by the storage systems as well as the load shifting in hours 20–24 is also able to mitigate the under voltages during peak load. Moreover, the shedding of non-priority loads was an important resource in situations where load shifting and the discharge of storage systems were not enough to control voltage deviations.

It should be emphasized that, in this scenario, it was possible to mitigate voltage deviations in the buses of the LV network without requiring microgeneration shedding and at the same time avoiding the need for indiscriminate load shedding that could affect priority loads, which highlights the benefits from the proposed approach.

5. Conclusions

The approach developed in this paper for voltage control included an advanced scheme for managing DER in LV networks that may constitute an important tool for the DSO, since it uses various distributed resources that may be available in order to ensure that voltage profiles are kept within admissible limits. The consideration of forecasts for load and renewable generation for the short/medium term will allow establishing an optimal plan for operation in order to address the voltage control problem at the LV level one hour ahead as proposed.

The main contribution of this work is a methodology that can help the DSO in controlling the voltage profiles in LV networks while maximizing the integration of renewable microgeneration. The proposed approach provides an optimum solution for the voltage control problem while ensuring a coordination between the several DER. Nevertheless, it assumes the deployment of a suitable communication infrastructure and, apart from the availability of forecasting data, requires the use of advanced state estimation techniques in order to turn the network observable. From the results obtained in the real LV network used, it was seen that it was possible to mitigate voltage violations without requiring the curtailment of microgeneration in overvoltage situations (thus integrating more energy from renewable sources) and also avoiding shedding of essential loads in peak hours where under voltages occur (thus minimizing the energy not supplied).

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