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Massive data analysis to assess PV/ESS integration in residential unbalanced LV networks to support voltage profiles

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ABSTRACT

The integration of energy storage systems (ESSs), co-located with distributed photovoltaic (PV) units in low voltage (LV) networks, offers new opportunities to support distribution system operator (DSO) in distribution network operations and management. The deepening penetration of renewable resources exacerbates the challenge to maintain demand–supply equilibrium. ESSs can tackle this challenge making PV resources dispatchable. Here, we apply a Monte Carlo analysis by varying residential load profiles, penetration levels, capacities, capabilities and locations of PV/ESSs to assess the impact that two different control strategies have in supporting the DSO in improving the power quality of the distribution network. Time series unbalanced power flow simulations are carried out for winter and summer days in an LV Italian distribution network. The results have pointed out a significant reduction of voltage problems in the network.

1. Introduction

In recent years, photovoltaic (PV) systems are the most widespread form of distributed generation in low voltage (LV) Italian distribution networks. As PV units often can improve the performances of the system, for instance, when loads are locally supplied, the development of new PV-based ancillary services represents a good opportunity for the distribution system operator (DSO) in improving power quality, reducing losses, and defering investments. However, as the number of installation of PV units is continuously increasing, the intermittent and stochastic production poses also technical and economic challenges for DSOs [1]. In particular, if the PV generation exceeds the local demand, the surplus of power may cause reverse power flows in the feeder and, in some cases, voltage rises [2]. On the other hand, if the power demand is high while the PV production is low or absent, voltage drops can be consistent. In both cases, voltage violations occur in the network [3]. Distributed generation units can locally support the grid in addressing these challenges providing an ancillary service.

In the literature, active power curtailments and reactive power controls are proposed to solve voltage violations [4], also considering coordination strategies between independent power producers and DSOs [5]. The specific role of PV units in developing ancillary services in distribution systems by using reactive power is described in Ref. [6]. Solutions based on energy storage systems (ESSs) in LV networks are implemented in Ref. [7], where a scenario-based method to define the minimum capacity of ESSs in LV networks to prevent voltage rises has been proposed. However, the study is tested on a balanced LV three-phase system and without considering the possibility that users can control ESSs. In Ref. [8], in order to improve the voltage quality in an LV network, Authors present an innovative management strategy for distributed battery storages that increases the capability of distribution networks to exploit PV generation. Each battery cycle is optimized to minimize battery losses and costs, and to improve voltage profiles. The work considers only one random allocation of 26 ESSs. Furthermore, a small radial LV network and a daily time simulation are carried out for testing the strategy. Thus, the solution cannot be generalized. Often the approach to deal with PV units in distribution networks is probabilistic and Monte Carlo (MC) simulations are typically used [9–11]: Ruiz-Rodriguez et al. [9] propose a stochastic method to evaluate the voltage unbalance in a radial distribution network with PV units by means of a probabilistic three-phase load flow; in Ref. [10], the Authors assess the impact of PV units on a radial distribution systems by means of stochastic simulations; instead, a MC analysis is carried out in Ref. [11] to tackle the stochasticity of generation and demand in a LV network. In Ref. [12], a coordinated control strategy of PV with co-located ESS is presented and a MC analysis is performed in order to evaluate the possible benefits in supporting the DSO in controlling voltage profiles. In Ref. [13], the coordination of ESSs operations with traditional voltage regulators, as step voltage regulators (SVR) and on-load tap changer (OLTC), is presented, but the analysis is performed only for one day with the objective to relieve the stress due to tap changer operations, shave the utility peak load and decrease the transmission and distribution resistive power losses under high solar power penetration.

Although economic analyses still show several barriers to the deployment of ESSs, the introduction of an economy of scale together with a forecasted capital cost reduction of the assets make this solu-

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tion more and more feasible for the distribution network. In fact, storage systems are becoming of interest to both utilities and energy power producers or prosumers, because of their ability to optimize energy management increasing self-consumption of energy [14–16], to integrate small-scale renewable energy sources into commercial and residential sectors [17–22], and to increase the efficiency of supply maintaining the required PQ in the power system [23].

The literature gives two main suggestions that represent also the most important motivations of the paper: (i) it is necessary to develop an analysis based on different period of the year that allows having a complete view of the combined PV/ESSs potential to support the network; (ii) it is necessary to evaluate new policies and support DSO starting from the PV/ESS installation in the distribution networks. For this reason, here we propose a comprehensive analysis, based on a MC analysis able to assess the effects that a local integration of PV units with ESSs have in providing *voltage support*. In particular, this paper completes the study of Ref. [12], by using its results as a starting point to perform some exhaustive analysis. In fact, in comparison to Ref. [12], we propose the following new features: (i) an analysis that takes into account two different seasons (summer and winter) in which the PV profiles are randomly chosen from a database of real profiles of a PV farm located in the south of Italy; (ii) a focus on the effect due to changing the ESS capability rather than the capacity, based on the results obtained in Ref. [12]; (iii) an enhanced analysis with historical data of the coordinated charging/discharging control (CCD) strategy and a comparison with an uncoordinated charging/discharging control (UCD) strategy.

By using the UCD strategy the charging and discharging phases of the ESS owned by each customer is a function only of the PV production and the customer demand (uncoordinated control strategy); by means of CCD strategy, instead, the DSO is involved in the PV/ESS control by estimating a time interval in which the ESSs of each involved customer should be charged or discharged in order to support the network in controlling the voltage (coordinated control strategy). The last control strategy represents also the main contribution of the paper: to evaluate the possibility to promote ancillary services at LV level for improving voltage profiles by using co-located PV and battery energy storage residential systems without implementing complex local controls.

The proposed analysis allows also assessing the possibility to reduce the power during the charging phase to support the DSO in controlling the voltage for a long period.

In real-life systems, the integration of co-located PV/ESSs can have different effects depending on the specific scenario, control strategy, customer needs, irradiance and local demand. To the end, we take into account the above-mentioned parameters in the Monte Carlo analysis. In detail, our simulations are developed for a summer and a winter day by varying generation and demand profiles, penetration level, location, capacity and capability of the PV/ESS. Thus, the massive data developed analysis allows obtaining a clear vision of the benefits in terms of voltage quality and local self-consumption. The results can give important indications to the DSO in order to incentivize the installation of ESSs where residential PV units are located.

The remainder of this paper is organized as follows. Section 2 contains the model of the system and the description of the stochastic analysis. Section 3 describes, in detail, the case study developed in our work, while Section 4 presents the simulation results obtained by the application of the different control strategies in a real Italian distribution system. Finally, Section 5 contains remarks and conclusion.

2. Model and stochastic analysis

The ability to provide voltage support through ESSs in LV networks must take into account both the stochastic behavior of solar production and load demand under different PV/ESS penetration levels. To the end, an accurate model of the whole system is required.

2.1. Model of the system

The system is made up of one transformer, feeders, loads, PV units, ESSs, and meters. A series impedance and a shunt reactance model are used for each feeder section; the loads and the PV units are modeled as P-Q buses. Load and generator profiles are modeled by means of time-series profiles. The profiles of the residential customers are simulated using a modified version of the high-resolution model developed by the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University [24]. The PV generation profiles are obtained multiplying the rated power of the PV units by real profiles. An ideal current generator, which supplies/stores constant power for each time interval, models ESSs. The State of Charge (SoC) can be evaluated according to the Coulomb-counting formula:

$$SoC(T + \Delta T) = SoC(T) \pm \frac{I(T) \times \Delta T}{3600 \times C_{ESS}} \quad (1)$$

where C_{ESS} [Ah] is the ESS's capacity, $I(T)$ represents the ESS's current, obtained by dividing the charging/discharging power of the ESS at its constant voltage, and ΔT is the time interval of the control. The SoC is limited between a maximum and a minimum value during the analysis in order to consider the limited capability of the storage system. The 4-wire grid is modeled by means of a three-phase plus neutral system and the power flow allows to take into account the unbalanced nature of the LV network. The stochastic behavior of the system is emulated applying a MC analysis.

2.2. Energy storage system control

The PV/ESS under study is composed of a residential lithium-ion battery and a PV generator (for instance a rooftop PV unit). The interconnection with the main grid is 1-phase and is implemented by means of an inverter. Two ESS control strategies are implemented in order to evaluate the impact of the batteries on voltage profiles.

The *uncoordinated charging/discharging* (UCD) control allows maximizing energy self-consumption in the presence of a co-located PV unit. Taking into account the single PV/ESS system and the demand of the house where it is connected the control works as follows:

- the ESS is charged when there is power surplus between the PV production and the demand;
- the ESS is discharged when the demand exceeds the generation;
- otherwise, the ESS is in idle mode.

Each customer controls independently its PV/ESS; the DSO is not involved in the process of ESSs charging and discharging [19].

The *coordinated charging/discharging* (CCD) control charges/discharges the ESS according to some indications coming from the DSO in terms of time intervals. The DSO is able to estimate by means of historical data and forecast analysis the generation and demand peak during the day. During these intervals, the possibility of having voltage rises and voltage drops increases. As such, a control strategy where the DSO requires that the customers limit the time intervals where the ESS can be charged (ΔT_c) and discharged (ΔT_d) has been applied. In particular, ΔT_c is set in correspondence of the daylight hours characterized by peak generation due to PV units while ΔT_d is set in correspondence of the peak demand hours in which no power generation comes from PV units and there is a high load demand to satisfy (evening time). Formalizing, the ESS is charged if the following inequalities are verified:

$$\begin{cases} T_c^{\min} \le T \le T_c^{\max} \\ P_{PV_i}(T) \ge P_{load_i}(T) \\ SoC_{ESS_i}(T) \le SoC_{ESS_i}^{\max} \end{cases} \tag{2}$$

and it is discharged if

$$\begin{cases} T_d^{\min} \le T \le T_d^{\max} \\ P_{PV_i}(T) \le P_{load_i}(T) \\ SoC_{ESS_i}(T) \ge SoC_{ESS_i}^{\min} \end{cases} \tag{3}$$

where $\Delta T_c = \left[T_c^{\min}, T_c^{\max}\right]$ and $\Delta T_d = \left[T_d^{\min}, T_d^{\max}\right]$. $P_{PV_i}(T)$, $P_{load_i}(T)$ and $SoC_{ESS_i}(T)$ are the power generated by the i-th PV unit, the load demand of the i-th customer and the SoC of i-th ESS at the time step T, respectively. Furthermore, $SoC_{ESS_i}^{\min}$ and $SoC_{ESS_i}^{\max}$ are minimum and maximum allowable values of the SoC related to i-th ESS, in this work we suppose lithium-ion batteries. To the end, the storage system is in the idle phase when Eqs. (2) and (3) are not verified.

2.3. Stochastic analysis

Several methods able to estimate voltage profiles in LV networks taking into account the generation and demand uncertainties were developed in the literature. Here, we perform a massive data stochastic analysis by applying a MC simulation that allows taking into account different penetration levels and locations of PV/ESSs on the grid, and different generation and load profiles. The objective is to estimate the impact that the ESS have to support DSO in solving voltage problems as a function of locations, penetration levels, ESS capability, PV unit capacity, load and generation profiles. A classical MC approach estimates the mean and the variance of the output variables by means of the following equations:

$$\langle x \rangle = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{4}$$

$$s^2(x) = \frac{N}{N-1}\left[\left\langle x^2 \right\rangle - \langle x \rangle^2\right] \tag{5}$$

where x_i is the number of occurrences of the event that we want to analyze and N is the number of simulations (cases). Furthermore, it is interesting to analyze the standard error of the mean ($SE_{\langle x \rangle}$) that can be defined as follows

$$SE_{\langle x \rangle} = \frac{s}{\sqrt{N}} \tag{6}$$

In detail, the simulations are carried out for two seasons: winter (Scenario I) and summer (Scenario II). Although EN50160 suggests a weekly analysis, we consider only the two periods of the year that can present critical aspects in terms of voltage profiles. On the basis of other studies (e.g., Ref. [11]) this analysis is sufficient to have accurate information. For each scenario and for each control strategy (UCD and CCD), we explore the space of solutions by applying the MC analysis according to the following step-by-step procedure (depicted also in the flow chart in Fig. 1):

1. set the PV penetration level, defined as the percentage of PV units in the network compared to the total number of residential customers (from a minimum value of 0% to a maximum value of 100% with steps of 10%);
2. perform a random allocation of PV units on the residential buses of the LV network;
3. associate to each bus a load profile chosen randomly from a database created by means of a high-resolution software;
4. associate to each PV unit a generation profile chosen randomly from a database of real PV profiles;
5. perform a random choice of PV units capacity;
6. perform a random choice of ESSs capability from a list of different models;
7. perform three different daily unbalanced power flows: the first considering only the PV units (Step 2), the second taking into account also the co-located ESSs controlled by using the UCD strategy, and the third one by applying the CCD control to the previous case;
8. repeat the Steps from 2 to 7 up to the maximum number of cases (k_{MAX});
9. come back to the Step 1 and increase the PV penetration level up to 100% (with steps of 10%)

The MC simulations allow keeping track of the occurring voltage violations and analyzing the self-consumption of solar production of the residential customers. For each PV penetration level, we calculate the mean (Eq. (4)), the variance (Eq. (5)) and the standard error of the mean (Eq. (6)) of voltage problems occurrences in case of (i) only PV

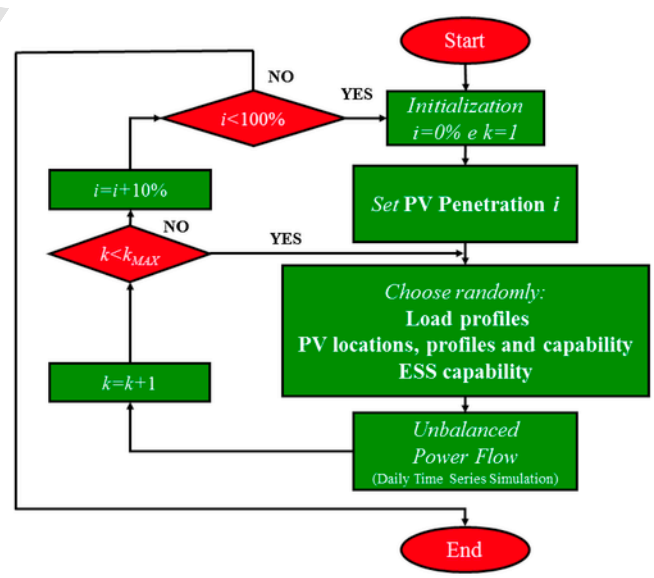


Fig. 1. Monte Carlo analysis flowchart.

units connected to the buses, (ii) PV and co-located ESSs controlled with UCD control and (iii) CCD control.

3. Case study

The system under study is shown in Fig. 2, it is a typical LV Italian distribution network [25] with 3 LV feeders (A, B, C) connected to the MV network through a 10/0.4 kV Δ/Yg transformer with rated power equal to $S_T = 250$ kVA, and $V_{cc} = 4\%$. The transformer tap is fixed to 1.00 p.u.

The network consists of 68 buses with 136 mono-phase residential loads, and 9 three-phase between industrial and commercial loads. Taking into account the rated power of each customer it is possible to divide the demand as in Ref. [25]: 43% in the feeder A, 44% in the feeder B, and 13% in the feeder C.

Mono-phase residential profiles are simulated by using a modified version (customized for the Italian case) of the software elaborated by the CREST [24], which allows creating a database of high resolution domestic profiles (in this case, the resolution is 5 min) for specific periods of the year, load compositions and number of family members [26]. We have created a database of 250 different daily residential load profiles. To the end, the three-phase loads are characterized by typical commercial and industrial profiles [5].

Mono-phase PV systems are randomly allocated at each MC iteration. PV penetration level changes from 0% to 100% of the demand, with steps of 10%. The rated power of residential PV systems changes randomly at each iteration from 2 to 6 kW, the power factor is set to 1, because in this study we are interested in understanding how to mitigate voltage problems without reactive power support. Furthermore, there are 3 three-phase PV units with a rated power of 15 kW and a unitary power factor; their position is indicated in Fig. 2 and it does not change during the MC analysis. PV profiles are randomly chosen from a database of 10 real Italian PV generation profiles of a winter day (Scenario I) and 10 real Italian PV generation profiles of a summer day (Scenario II) [27]. ESSs, co-located with PV systems, have a capacity of 3 kW and a capability chosen randomly during the Monte Carlo analysis among one of the three possible solutions illustrated in Table 1.

By applying the UCD control the ESSs can be charged or discharged during the day depending only on the customers' behavior. In order to enhance the peak shaving capacity of ESSs, instead, the charging and discharging periods can be constrained in two time intervals, during higher generation and demand periods, by means of CCD control.

Here, the choice of ΔT_c and ΔT_d is not the result of an optimization process but it is based on historical data and a day-ahead forecast of the demand and generation profiles. DSO communicates the set-points to the customers through an information layer. Considering the historical and the irradiation data of the PV site located in the south of Italy [27] both with the demand profiles we have estimated ΔT_c and ΔT_d, respectively, for the two scenarios. We consider $\Delta T_c = [12{:}00,18{:}00]$ and $\Delta T_d = [18{:}00,24{:}00]$ for the summer scenario and $\Delta T_c = [10{:}00,16{:}00]$ and $\Delta T_d = [16{:}00,24{:}00]$ for the winter scenario. The time intervals are wide enough to take into account possible forecast error due to the typical high variability and uncertainty of residential demand and PV units. The aim of fixing two time intervals for charge and discharge the ESSs is to support the network during the period of generation and demand peak. It is possible to show that providing this service to the DSO will not limit the purpose of residential ESSs (increasing local self-consumption of energy). Furthermore, by limiting the charging and discharging period of the ESS it is possible to increase the cycling life of the batteries (the battery cycle is limited to 1 per day).

Unbalanced power flow problems are solved monitoring each phase of the network by using OpenDSS [28]. The position of 8 m, able to measure the voltage in the network, are shown in Fig. 2. $N = 1000$ cases are simulated for each PV penetration level. Whereas

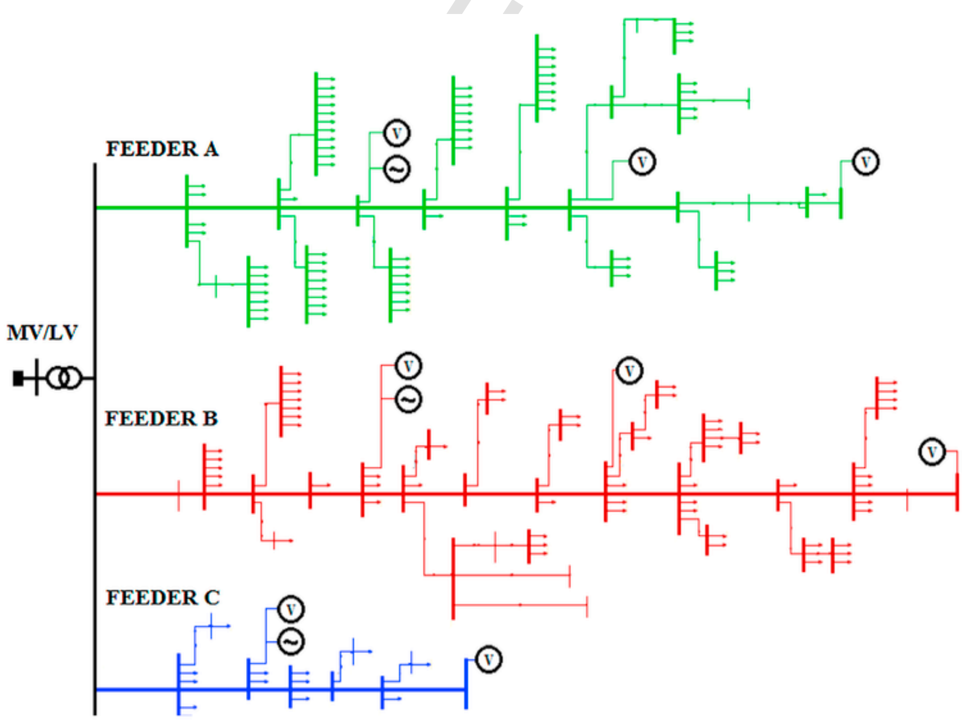


Fig. 2. LV network under test.

Table 1
ESSs characteristics.

Capacity (kW)	Capability (kWh)	SoC limits (%)
3	5.25	20–90
3	7	20–90
3	8.75	20–90

we analyze two scenarios with 11 PV penetration levels, a total number of 22,000 cases are simulated. In order to achieve and analyze the MC solutions, for each case we run three power flows (without ESS, ESS controlled with UCD, ESS controlled with CCD) every 5 min for 24 h so that we perform 19.008×10^6 unbalanced power flows. For each load flow the thermal limits of each single line is checked in order to verify the technical feasibility of the solution.

4. Results and discussion

CEI EN50160 is considered as the reference standard to determine voltage violations in the feeders [29].

The analysis is carried out considering two different scenarios: in Scenario I, we consider a typical Italian winter day with one of the PV generation profile randomly chosen by the database of 10 depicted in Fig. 3a, and with a peak demand forecasted in the early evening. In Scenario II, instead, a typical Italian summer day is represented characterized by a great generation of PV energy during the afternoon, as shown in Fig. 3b, with a peak demand slightly shifted toward late evening. In Scenario II, the network is highly affected by voltage rises, so that we consider the possibility to limit the maximum ESS charging power to 1.5 kW for each ESS residential system (when the CCD control is applied). The generation profiles are normalized respect to the rated power of each PV unit as shown in Fig. 3.

The results of the MC analysis show, for both scenarios, that feeders A and B are subjected to voltage infringements. Feeder C, instead, does not have any voltage problem because it is a short feeder with a low percentage of installed loads.

4.1. Scenario I: winter

Fig. 4 compares the voltage drops occurrences obtained by the MC analysis in feeders A (Fig. 4a) and B (Fig. 4b) as a function of PV penetration levels. In blue we depict the results without ESSs; instead, in red and in green we show the daily mean of the occurred voltage drops with the integration of ESSs considering UCD and CCD control, respectively. The ESSs are able to reduce the occurrences of voltage drops at each penetration level. It is clear that the benefits grow with the increase of the PV/ESS penetration. This behavior depends on the increasing capacity that the PV/ESS have to supply locally the residential energy demand. Moreover, the CCD control achieves in most cases better results compared to the UCD control.

The analysis of the results in terms of voltage drops shows that UCD or CCD, in comparison with the case without ESSs, give similar benefits. As voltage rises are negligible for Scenario I, due to a reduction of PV production in winter, the simulation results are not reported. Fig. 5 shows that the CCD does not reduce drastically self-consumed energy compared to the UCD; both controls, instead, allow increasing local energy consumption compared to the case where ESSs are not installed. In Table 2, the statistical results for the feeder

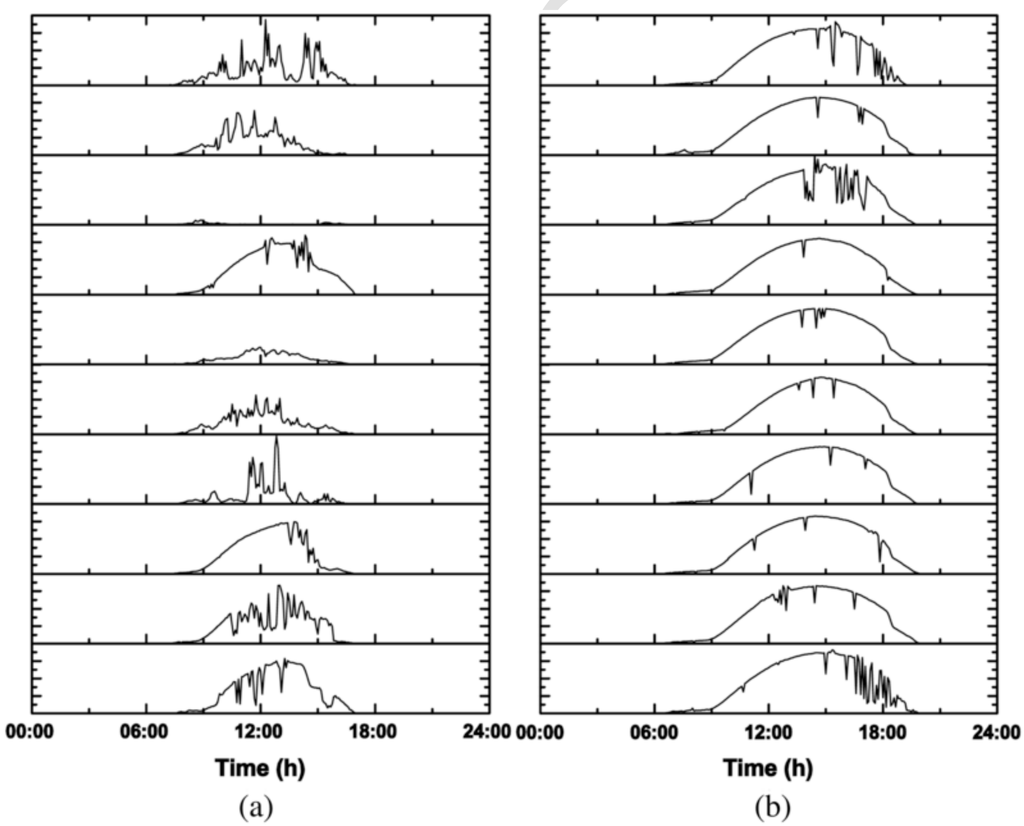


Fig. 3. Real Italian normalized PV generation profiles for winter (a) and summer (b).

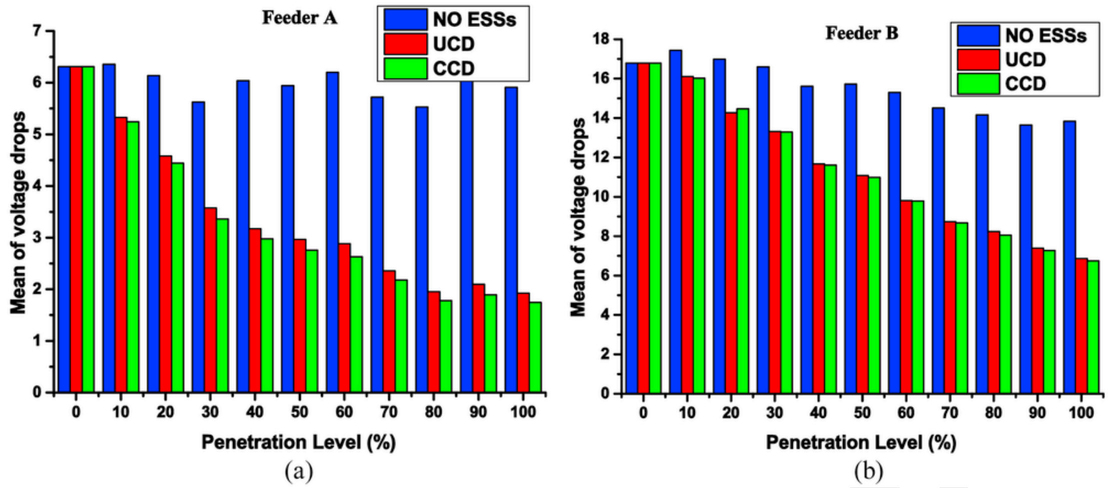


Fig. 4. Mean of voltage drop infringements in winter in feeder A (a) and feeder B (b). (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

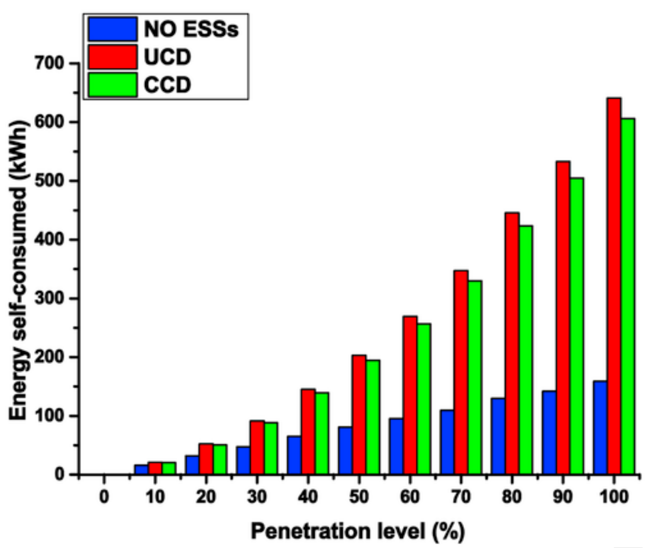


Fig. 5. Daily mean of aggregated self-consumed energy in winter.

Table 2
Statistical results of Scenario I: voltage drops in feeder A.

Penetration	UCD			CCD		
	$\langle x \rangle$	$s^2(x)$	*SE*	$\langle x \rangle$	$s^2(x)$	*SE*
0%	6.31	6.52	0.21	6.31	6.52	0.21
10%	5.32	5.80	0.18	5.24	5.78	0.18
20%	4.58	5.93	0.19	4.44	5.85	0.19
30%	3.57	5.01	0.16	3.36	4.81	0.15
40%	3.17	4.94	0.16	2.98	4.74	0.15
50%	2.96	4.55	0.14	2.76	4.32	0.14
60%	2.88	4.89	0.15	2.63	4.64	0.15
70%	2.35	4.39	0.14	2.18	4.20	0.13
80%	1.95	3.88	0.12	1.78	3.66	0.12
90%	2.09	4.16	0.13	1.89	3.90	0.12
100%	1.92	3.90	0.12	1.75	3.69	0.12

A are reported. The standard error (*SE*) confirms that the solution is stable because the variability of the mean is low (*SE* is less than 0.21 for each penetration level).

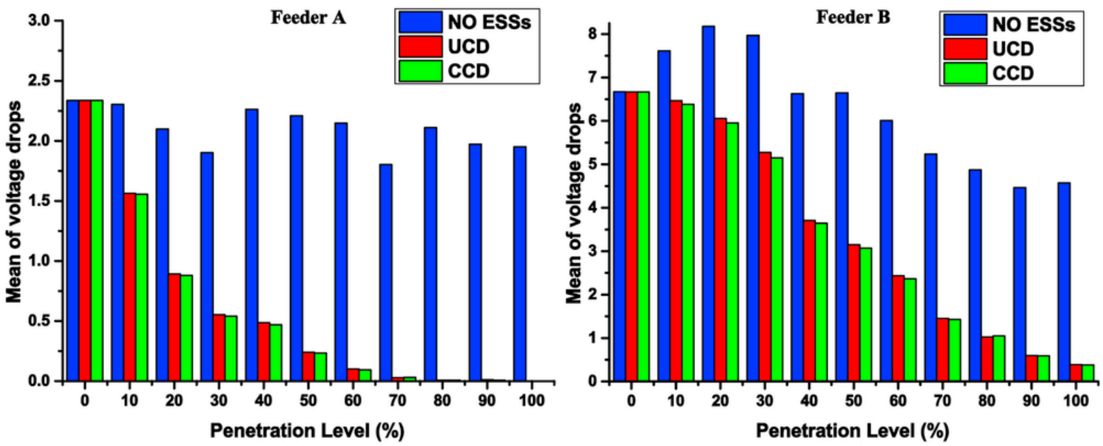
4.2. Scenario II: summer

The increase of PV power production in summer allows exploiting the ability of the battery systems to provide voltage support by shifting energy consumption. Voltage drops are conspicuously reduced with the introduction of ESSs, as in Scenario I. Voltage drops are almost independent from the PV penetration level when no ESSs are installed into the grid because usually they occur during the demand peak where the PV generation is very low or zero. Also, in this case, there is not a substantial difference between UCD and CCD controls, as shown in Fig. 6. In particular, UCD control achieves better, also if comparable, results compared to CCD control for some PV/ESS penetration levels in feeder B (Fig. 6b). Indeed, voltage drops can occur outside the time windows that limit the discharging period when the CCD control is applied.

If the results obtained by using CCD control are promising by analyzing voltage drop problems, they are noteworthy in the case of voltage rises. Fig. 7 shows the reduction of voltage rise problems in the network achieved by applying the CCD control for different PV/ESS penetration level. This result may be explained considering that the integration of an ESS with a PV system can solve, in most of the cases, voltage rise violations by flattening the net demand in the network.

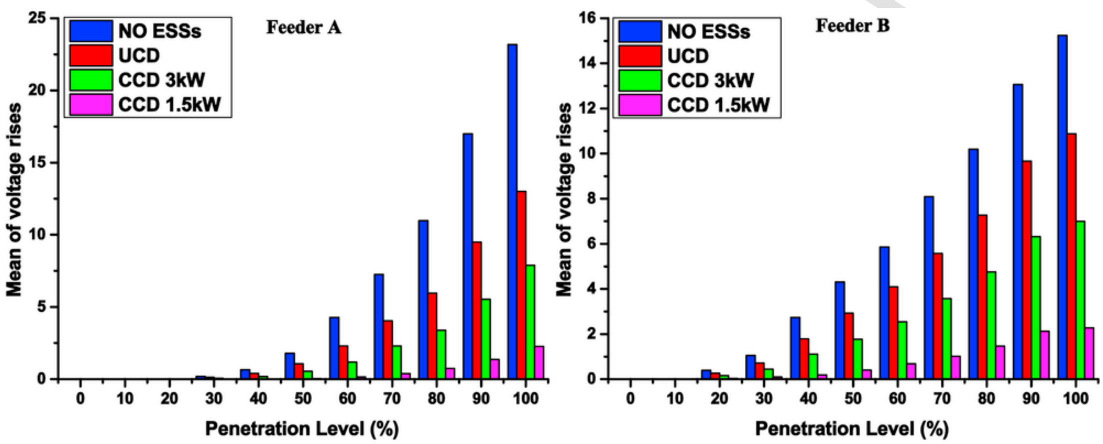
The UCD control limits the possibility to support the network during demand and generation peak because the ESS is allowed to charge and discharge during the whole day. Furthermore, the UCD control increases the number of charging and discharging phases in a day reducing the life of the battery system.

It has also been exploited the possibility of implementing the CCD control by reducing the maximum charging power of the ESS to 1.5 kW. This allows spreading the ability to store energy for a longer time period. This choice does not reduce energy self-consumption compared to the CCD control without a capacity limit. Moreover, in summer, the high PV production during the day allows fully charging the battery systems even if the maximum capacity is reduced. The reduction of the maximum charging power has also a positive effect on the battery life because of the reduction of the C-rate. It is worth noting that the latter CCD control configuration allows reducing considerably voltage rise occurrences in both feeders in the days of maximum PV energy production, increasing the hosting capacity. Considering that the voltage rise occurrences admissible for a day should be



(a) (b)

Fig. 6. Mean of voltage drop infringements in summer in feeder A (a) and feeder B (b).



(a) (b)

Fig. 7. Mean of voltage rise infringements in summer in feeder A (a) and feeder B (b).

lower than 1 for day, the CCD control with maximum 1.5 kW during the charging phase increase the hosting capacity compared to the UCD control from 40% to around 80% in the feeder A and from 30% to around 60% in the feeder B.

The reduction of voltage rise infringements allows avoiding PV systems disconnections or curtailments. Fig. 8 depicts the daily self-consumption of solar energy considering all the customers. The CCD does not reduce significantly energy self-consumption compared to UCD control. Moreover, the CCD control compared with UCD control allows reducing the daily charging/discharging cycles of the ESS increasing its lifetime.

In Tables 3 and 4, the statistical results of the MC analysis are summarized. It is worth noting that up to 60% of penetration level the average of voltage problems is lower than 1 for day in Feeder A by using the 3 kW-CCD control. Similar conditions are reached in feeder B up to 30%. As just discussed before, the 1.5 kW-CCD control further reduces voltage rise occurrences at each penetration level. In Fig. 9, we highlight the robustness of the solution after 1000 cases: we represent the variation of the mean of voltage drops as a function of increasing cases of feeder B without and with the ESSs. The MC analysis comes to stable values at around 250 iterations. Finally, a snapshot of the three-phase daily voltage profiles at 100% of PV pen-

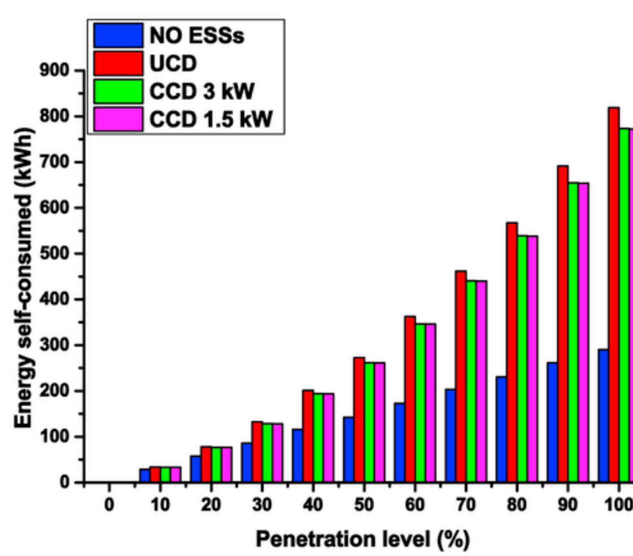


Fig. 8. Daily mean of aggregated self-consumed energy.

Table 3
Statistical results of Scenario II: voltage rises in feeder A.

Penetration	UCD			CCD (3 kW)			CCD (1.5 kW)		
	$\langle x \rangle$	$s^2(x)$	SE	$\langle x \rangle$	$s^2(x)$	SE	$\langle x \rangle$	$s^2(x)$	SE
0%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20%	0.01	0.16	0.01	0.01	0.13	0.00	0.00	0.00	0.00
30%	0.13	1.00	0.03	0.06	0.48	0.02	0.00	0.00	0.00
40%	0.39	1.88	0.06	0.17	0.99	0.03	0.01	0.11	0.00
50%	1.06	3.45	0.11	0.55	2.09	0.07	0.04	0.38	0.01
60%	2.31	5.04	0.16	1.18	3.06	0.10	0.15	1.03	0.03
70%	4.04	6.68	0.21	2.31	4.40	0.14	0.39	1.76	0.06
80%	5.95	7.59	0.24	3.38	5.12	0.16	0.75	2.83	0.09
90%	9.49	8.49	0.27	5.53	6.12	0.19	1.37	3.93	0.12
100%	12.99	7.94	0.25	7.89	6.42	0.20	2.26	4.42	0.14

Table 4
Statistical results of Scenario II: voltage rises in feeder B.

Penetration	UCD			CCD (3 kW)			CCD (1.5 kW)		
	$\langle x \rangle$	$s^2(x)$	SE	$\langle x \rangle$	$s^2(x)$	SE	$\langle x \rangle$	$s^2(x)$	SE
0%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10%	0.01	0.14	0.00	0.00	0.07	0.00	0.00	0.00	0.00
20%	0.26	1.86	0.06	0.16	1.27	0.04	0.03	0.47	0.01
30%	0.71	2.99	0.09	0.45	2.10	0.07	0.10	0.90	0.03
40%	1.78	4.52	0.14	1.11	3.04	0.10	0.19	1.10	0.03
50%	2.93	5.93	0.19	1.76	3.98	0.13	0.40	2.18	0.07
60%	4.09	7.08	0.22	2.54	4.90	0.15	0.69	2.65	0.08
70%	5.57	7.78	0.25	3.57	5.57	0.18	1.01	3.04	0.10
80%	7.27	8.40	0.27	4.75	6.12	0.19	1.47	4.28	0.14
90%	9.66	9.10	0.29	6.31	6.69	0.21	2.12	4.97	0.16
100%	10.87	8.71	0.28	6.99	6.51	0.21	2.27	5.32	0.17

etration in feeder A is depicted in Fig. 10 in order to show how the integration of storage systems with PV units allows keeping the voltage within the mandatory limits of 0.9 p.u. and 1.1 p.u.

5. Conclusions

A massive data analysis has been carried out in order to show the benefits that the integration of ESSs with PV units has in a real LV network in terms of voltage quality improvements. Thus, the ESS control has allowed not only promoting self-consumption but also reducing the risk of possible PV disconnections due to voltage infringements.

The results show that an indirect voltage support can be reached by ESS installations to support both local consumption of energy and the DSO (with a global balance of demand and generation in the network). The co-located systems have been locally monitored by the residential customers without adding other meters in the grid. The possibility to provide ancillary services by means of residential ESSs can help the deployment of battery systems in order to become more attractive and economically sustainable. The set-points for ESS charge/discharge introduced by the CCD control allow also increasing the life of battery systems without a significant impact on self-consumptions.

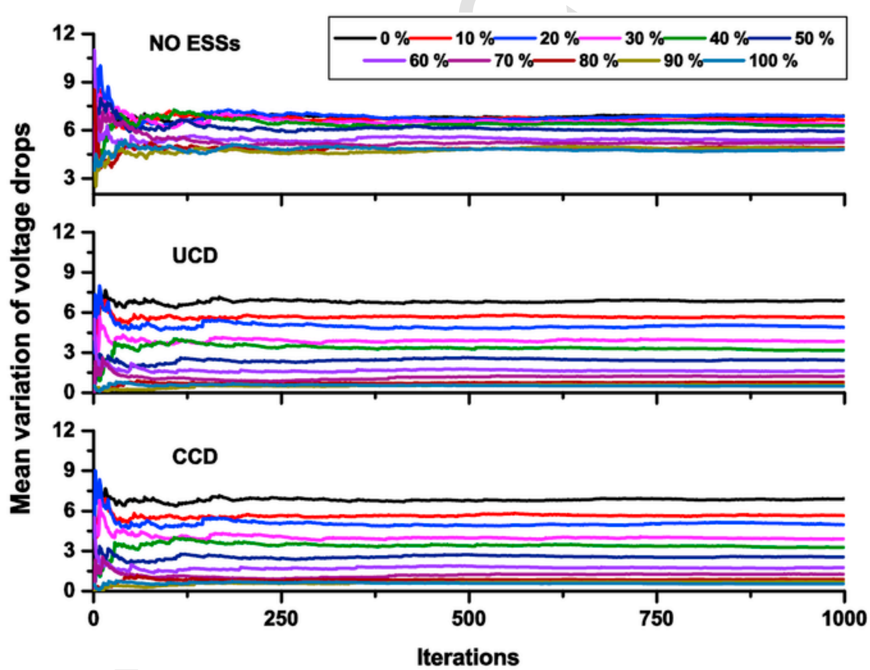


Fig. 9. Mobile average of voltage drops on feeder B.

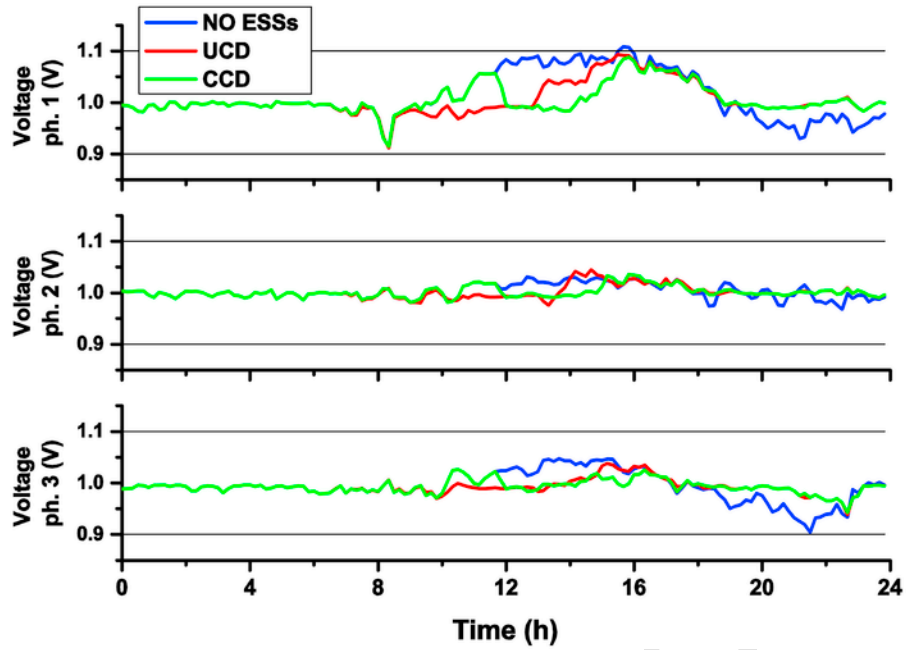


Fig. 10. 3-phase voltage profiles.

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