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Active power management in low voltage networks with high photovoltaics penetration based on prosumers' self-consumption

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HIGHLIGHTS

- By having a high self-consumption rate (SCR) prosumers enable higher PV penetration.
- Marginal SCR of a network is the minimum shared SCR by prosumers to avoid overvoltages.
- A novel method to create an active power management schedule based on prosumers SCR.
- The method is tested on a benchmark European LV feeder under several test cases.
- Self-consumed renewable energy is increased compared to existing methods.

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ABSTRACT

Increase of photovoltaic (PV) systems penetration in distribution networks is being challenged by technical barriers, especially in low voltage (LV) networks, such as over-voltages caused by reverse power flows and high PV power injection to the grid. Among other solutions for over-voltage mitigation, active power management can be a highly effective method in LV feeders. However, such methods usually curtail the excess power resulting in a loss of clean and renewable energy and do not take into account the interaction of a prosumer with the grid. To deal with that, this paper proposes a novel active power management methodology for over-voltage mitigation in active LV networks. The methodology calculates the maximum allowed amount of injected power to the grid at each time instant of the day and generates an active power management schedule for the prosumers based on their self-consumption ratio (SCR). This schedule allows prosumers to choose whether to employ either controllable loads or storage systems to manage the generated energy. In this way, injected power to the grid is efficiently handled and over-voltage mitigation is ensured, while the permissible level of PV penetration is increased without requiring large investments by the network operator. The proposed methodology is examined on a LV test network and is compared to other existing techniques for feeder voltage support. The results show that the application of the methodology increases SCR of installations, treating at the same time prosumers in a fairer way compared to existing methods.

1. Introduction

New photovoltaic (PV) systems are connected to the electrical grid with an increasing annual rate over the last decade. In 2016, a record high of 76.6 GWp of PV capacity was installed globally, adding up to a total global PV capacity of 306.5 GWp. The current projections for 2018 show that PV capacity will exceed the 400 GWp threshold, due to the growing solar power competitiveness among other conventional sources [1]. Despite the fact that PV growth is mainly driven by utility-scale PV installations, residential PV systems have been increasing as well, driven by subsidies promoting small-scale PV generation [2]. Furthermore, considering the requirement in Europe that all new buildings should be nearly zero energy buildings (NZEB) from 2020 onwards [3], a considerable amount of PV installations is expected to be connected to the electrical grid.

The transition from centralized generation to distributed renewable energy sources (RES) generation offers great advantages to the environment, yet at the same time poses a series of challenges on the reliable operation of the existing power grids. Concerning low voltage (LV) networks, the main issues are overloading of network lines and

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transformers, reverse power flow and protection systems issues [4,5]. Reverse power flow occurs during periods with high PV power injection and low demand, causing over-voltages along the feeder and violating power quality constraints. These over-voltages are the main restrictive factor for extending PV hosting capacity of a distribution network [6,7].

Several solutions have been proposed in the literature to tackle over-voltages caused by distributed generation. Grid reinforcement is an effective method, however the associated cost is prohibitive [6]. Transformers equipped with on load tap changers (OLTCs) can mitigate over-voltages by regulating the voltage at the substation. However this method is challenged when feeders are hosting different PV capacities [8]. Reactive power control by PV inverters is an effective voltage regulation method in medium-voltage (MV) distribution grids, however the effectiveness of this solution is limited in LV feeders, due to the high R/X ratios of the lines [9].

In contrast, controlling active power is more suitable for voltage regulation in LV grids, due to the resistive nature of the feeders. This feature has been exploited in various studies in the literature. In [10], the authors propose a droop-based active power curtailment (APC) control that uniformly shares the curtailed power among the prosumers. An adaptive active power capping method is developed in [11] to prevent over-voltages caused by high PV penetration, using local voltage and power measurements. The work in [12] presents a distributed control scheme that changes the active and reactive power injected by PV units. An APC strategy is developed in [13] to achieve over-voltage mitigation by determining a voltage bandwidth for each PV system. An APC droop-control is proposed in [14] providing fair curtailment among prosumers. Authors in [15] develop two coordinated PV control strategies to improve the fairness of APC schemes. Although these approaches can efficiently mitigate over-voltages in LV grids, they are based on APC, and thus result in considerable loss of green energy. Obviously, an active power management scheme that can potentially avoid such renewable energy loss would be more attractive, both from economic and policy perspectives.

Existing active power control schemes for voltage regulation usually consider a method to share the responsibility for voltage regulation among prosumers. When undesirable excess power has to be regulated, it is either equally allocated among the prosumers [10,14] or proportionally allocated considering the maximum output power at each PV [11,12,15]. All these methods do not take into account the consumption profile of the prosumers. This neglects the fact that a prosumer who is able to closely match load and generation during high irradiation hours injects only a low amount of power to the feeder, even if he owns a large PV system. Thus, his interaction and impact to the grid is rather limited.

Furthermore, in order to achieve the desired operation of an active distribution system, a central energy management system can be used to provide set points for the input/output power of distributed energy resources (DERs) connected to the grid [16]. These set points may act as a power schedule, which defines the desired injected or absorbed power of DERs at each time instant. The concept of designing a power schedule for DERs has been introduced by several works in the literature. In [17] the authors introduce a short-term dispatch scheduler for the control of DERs, minimizing the overall energy costs, yet this method is applicable to MV networks. In [18] a power scheduling method is proposed to minimize the total distribution system power losses by regulating the power of PVs, a central storage system, transformer OLTCs and controllable loads (CLs), while voltages are kept inside permissible limits. Again, this method is oriented towards MV networks with large PV installations. An operation strategy is developed in [19] for the optimal schedule of LV microgrids regarding multiple technical and economical objectives. An energy consumption scheduling algorithm is presented in [20], aiming both to mitigate the over-voltages and minimize household electricity bills, while all prosumers comply to an equal threshold for energy injection during high irradiation hours. In [21], optimal generation set-points are determined for the minimization of costs for distributed generation units due to their participation in voltage support, taking into account the fair participation of prosumers based on their location and PV size, thus ignoring their actual self-consumption.

In [22], the scheduling of programmable appliances is investigated for minimizing financial losses due to power curtailment, considering a residential PV system with storage. Moreover, a schedule for residential loads of a community is proposed in [23], aiming to minimize prosumers' electricity cost. Authors in [24] developed an optimal scheduling strategy for the combined operation of smart buildings and active distribution networks. A method for the optimal dispatch scheduling of an office building along with electric vehicles is proposed in [25], aiming to reduce electricity costs and power fluctuations at the PCC. In [26], a demand power management is developed utilizing flexible loads and storage systems of a building to compensate the PV generation fluctuations smoothing building interaction with the electrical grid. However, methods in [22–26] are not examined on an extended network to verify that network constraints are fulfilled.

In the above described context, we present a methodology with the following main objectives: (i) the voltage regulation at extended LV networks with high PV penetration and (ii) the increase of self-consumed green energy. To achieve these, we propose an active power management method based on the Self-Consumption Ratio (SCR) of each PV owner [27] and taking into account the intrinsic characteristics of the specific feeder they are located. SCR represents the share of PV produced energy which is consumed on-site. Consequently, it constitutes an indicator for the matching of generation and load of a prosumer throughout a certain period of time [27]. Since SCR highly depends on the demand power, it can be controlled by the prosumer. The methodology constructs an active power profile that can act as a power schedule for the prosumers. The prosumers can comply to this schedule by utilizing either controllable loads or storage systems. Following this approach, the curtailment of renewable energy is efficiently avoided. The effectiveness of the proposed approach is demonstrated on the IEEE European LV Test Feeder [28].

The contributions of the paper are the following:

(1) We introduce the ”marginal SCR” as a metric of a specific distribution feeder. This metric provides the minimum required SCR by all prosumers of the feeder in order not to experience over-voltages. Marginal SCR can be also utilized for distributing network costs in a fairer way.
(2) We propose a novel active power management methodology for over-voltage mitigation in LV feeders with high PV penetration. The method rewards prosumers with high SCR, who do not significantly affect the grid, by not having to change their ”business-as-usual” behavior. Instead, it assigns higher weighting factors to low-SCR prosumers, which implies that they would have to alter their usual behavior and limit their power injection to the grid. In this way, we maximize the utilization of generated PV energy and prevent over-voltages, by transferring the main responsibility to those prosumers that are mostly responsible for over-voltage incidents.

The rest of the paper is organized as follows: Section 2 describes the theoretical background. The methodology for the proposed active power management scheme is described in Section 3, whereas Section 4 describes the system under study that is used to evaluate the applicability and effectiveness of the method. Section 5 presents the results obtained from the examined scenarios, Section 6 discusses the results and finally Section 7 concludes the paper.

2. Theoretical background

This section provides the necessary background for the proposed methodology. The concepts of voltage sensitivity coefficients, SCR and power schedule are briefly presented and discussed, setting the notation