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Prevention of distribution network overvoltage by adaptive droop-based active and reactive power control of PV systems

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ABSTRACT

Proliferation of grid-connected photovoltaic systems (PVSs) causes technical problems due to their variable and non-dispatchable generated power. High penetration of PVS in distribution networks can result in overvoltage in some operating conditions. Although this situation occurs rarely, it limits the installed capacity of PVS. In this paper, adaptive droop-based control algorithms are presented to regulate active and reactive power of PVS, with the objectives of loss minimization and increasing the PVS capacity installation without unallowable overvoltage. Operating voltage range of the PVS is divided into several intervals, and a specific control algorithm is presented for each of them. Reactive power control of PVS is used as the first action, and active power curtailment as the final remedy for voltage rise prevention. The proposed adaptive droop-based algorithms make the system operation smooth and highly stable. The required active power curtailment is shared equally between all PVSs, so that they have equal opportunity to sell their extra generation. Decentralized control with only local measurements is the other feature of the proposed methods. Efficiency of the proposed methods is demonstrated through simulation of different scenarios on the IEEE 33-bus distribution network.

1. Introduction

Photovoltaic systems (PVSs) and other renewable sources are growing rapidly in recent years because of environmental concerns, sustainable resources, and reduction of their production cost. International Energy Agency predicts that until 2050, 11% of the total electrical energy will be achieved by PVSs [1]. PVSs are used both as grid-connected and stand-alone structures. Small-scale PVSs connected to distribution network (DN) are so far the dominant form of these systems.

The use of DN-connected PVS is not without technical problems. Overvoltage is one of the most restricting factors in increasing the installed capacity of PVSs in DNs. Distribution networks have been usually designed with the assumption that there is no generation in the network, and thus the real power flow is from the upstream feeder to downstream loads. Increasing the penetration of PVS in DN can result in overvoltage, especially at the end of the feeder. The reverse flow of power from load buses to the substation provokes an impact on the feeder voltage profile, increasing bus voltages. This is usually pointed out as a major concern regarding DG penetration [2].

Probability of overvoltage occurrence in distribution networks (DN) depends on many parameters such as feeder impedance, difference between the load level and PV generation in DN, etc. Generally, the difference between the load and PV generation in DN plays the main role. Increasing the penetration of PVS and irradiance level in DN with a constant load level increases the reverse active power flow; and therefore, raises the probability of overvoltage occurrence, especially during the time periods that the feeder load is low and PV generation is high. Accordingly, various standards on the acceptable voltage range and power quality restrict the penetration of PVS in DN. Although a consensus is yet to be reached regarding DG penetration limits in distribution systems, various limits are found in the literature, ranging from 5% to up to 100% of the load [3,4]. Also, a commonly used rule of thumb in the U.S. allows distributed PV systems with peak powers up to 15% of the peak load on a feeder (or section thereof) to be permitted without a detailed impact study [5]. IEEE Std 1547 establishes criteria and requirements for some relevant aspects. For instance, the DG shall not cause the voltage to go outside steady-state limits; and in case of extra voltage rise at the connection points of DGs, they should be tripped off. However, this standard does not define the maximum DG capacity that may be interconnected to a single point of common coupling or connected to a given feeder. In a study done by National Renewable Energy Laboratory (NREL) [6] to model the effects of various PV penetrations across the wide spectrum of U.S.

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distribution feeder architectures, a publicly available taxonomy of 24 radial distribution feeder models developed at Pacific Northwest National Laboratory (PNNL) [7] are employed. The results show that the penetration level is even limited to 34% because of overvoltage occurrence in some DNs [6]. However, increasing the penetration level of PV systems as clean and sustainable resources is highly desired. Thus, providing a technique to overcome this problem makes it possible to increase the penetration level of PVSs in DNs without violating standard voltage limits.

Different approaches are presented to solve the problem of voltage rise due to high penetration of PVSs in radial DNs. Energy storage equipment such as batteries are proper means for this purpose. These equipment can store additional production of PVS and deliver it to the network during high load periods [8,9]. Financial burden of these equipment is the main obstacle of this approach. A straightforward way to prevent the voltage rise is increasing the cross-section of the lines conductors [10], which is the most expensive way. Voltage and reactive power control equipment such as switched capacitors, automatic voltage regulators and under-load tap changer (ULTC) are considered in some literature to prevent overvoltage [11,12]. Operation and control of this equipment are based on conventional DN, in which real power flow is from the upstream feeder to downstream loads. Reverse power flow at high penetration of PVS, rapid changes of solar irradiance due to passing clouds [13] and other constraints such as operating range, resolution and switching rate [14,15] are the factors that limit the efficiency of these equipment in preventing overvoltage in the new DNs. In contrast, reactive power control (RPC) capability of PVS faces none of these limitations [16].

Reactive power control is a common method to regulate voltage in transmission networks. Although due to the low X/R in DN, effectiveness of reactive power reduces [17], it is yet effective for voltage regulation. Regarding that the use of free capacity of PVS inverter for reactive power does not impose any significant impact on the PVS, it can be used for voltage regulation in DN [18]. While the IEEE 1547 standard forbids using reactive power capability of inverter-based DGs for DN voltage regulation, increasing penetration of PVS will likely lead to re-examination of this policy [19]. Accordingly, several literatures have adapted this trend and have suggested control algorithms for this purpose. Ref. [15] proposes an optimal method for coordinated control of switched capacitors and reactive power of inverters proportional to their speed. Ref. [16] has summarized different PVS reactive power control techniques to prevent the voltage rise and to minimize losses. In [20] reactive power of PVS inverters is used for loss reduction and maintaining the voltage profile in an acceptable range. Ref. [21] controls the reactive power of inverters to prevent overvoltage based on sensitivity analysis and proportional to bus voltages.

During high irradiance and PV generation levels, reactive power capacity of PVS inverter reduces. Once the capacity limit is reached, overvoltage prevention by reactive power will not be possible. In this situation, reduction of PV active power generation is inevitable. Real power curtailment as a method for regulating the voltage in acceptable range is considered in [22–25]. Reference [22,23] uses a droop-based active power curtailment (APC) method. In the proposed method in [22] all PVSs participate in voltage-rise prevention fairly. Necessity to know the maximum power point (MPP) of PV arrays and accurate characteristics of the network to determine droop coefficients are the main drawbacks of the proposed method. Besides, none of these methods have used RPC capability of PVS inverter. In [24] fair active power reduction of PVS has been proposed to prevent overvoltage. Requirement of complete communication link between all units, complex implementation and non-proved performance are the main weak points of this method. In [25], voltage-based droop control of renewable system active and reactive power generation is presented to avoid ON–Off oscillations caused by overvoltage, and its benefits in comparison to ON–Off control are studied in detail.

Due to zero cost and efficiency of RPC of PVS in voltage regulation and loss minimization, in this paper an adaptive RPC is presented to suppress overvoltage and to minimize losses. Using the proposed RPC method, available reactive power capacity of all PVSs is fully utilized for overvoltage prevention before the feeder voltage violates standard limits. Since the available reactive power capacity of PVS inverters is restricted with increasing irradiance and PV real power generation, the proposed RPC method is complemented by a fair adaptive droop-based APC method, as a final remedy to prevent the voltage rise in extreme cases when the reactive capacity of PVSs is exhausted.

The rest of the paper has been organized as follows. In Section 2, voltage variation and losses in DN are analyzed in detail. The overall control objectives are discussed in Section 3. The proposed RPC of PVS for voltage control and loss minimization is presented in Section 4. Adaptive droop-based method for fair APC to prevent overvoltage is developed in Section 5. In Section 6, performance of the proposed methods is evaluated through simulation. Conclusions are drawn in the last section.

2. Modeling of voltage variation and power loss

Voltage variation and power loss in DN are two important issues which are analyzed through a sample radial DN shown in Fig. 1. The network comprises n buses, and at each bus one load and one PV system is considered.

Therefore, the net total active and reactive power injections at each bus are

$$\begin{aligned} P_{t_i} &= P_{Pv_i} - P_{C_i} \\ Q_{t_i} &= Q_{Pv_i} - Q_{C_i} \end{aligned} \tag{1}$$

where P_{C_i} and Q_{C_i} are active and reactive power consumptions of the load, respectively. P_{Pv_i} and Q_{Pv_i} are the active and reactive powers generated by the PVS.

Active and reactive power flows in each piece of the line are related to the active and reactive power injections (RPIs) at all buses. Ignoring power losses in the line results in,

$$\begin{aligned} P_{L_i} &\approx P_{L_{i-1}} + P_{t_{i-1}} \\ Q_{L_i} &\approx Q_{L_{i-1}} + Q_{t_{i-1}} \end{aligned} \tag{2}$$

in which P_{L_i} and Q_{L_i} are active and reactive power flows in the ith line segment, respectively. In these equations, power flow to downstream of the feeder is assumed positive. With these definitions and considering all variables in per-unit, active power losses in each line segment is computed as follows:

$$P_{\text{Loss}-i} = r_i \frac{(P_{L_i}^2 + Q_{L_i}^2)}{V_i^2} \tag{3}$$

Although power loss is a small part of the total power injection to DN, because of high investment cost of the PVS, it is desired to minimize it. The total active power loss in the network is the sum of losses in all line segments.

$$P_{\text{Loss}-\text{total}} = \sum_{i=1}^{n} P_{\text{Loss}-i} = \sum_{i=1}^{n} r_i \frac{(P_{L_i}^2 + Q_{L_i}^2)}{V_i^2} \tag{4}$$

Also, the voltage difference between two adjacent buses is related to power flow and impedance of the line segment as follows.

$$V_i \approx V_{i-1} - \frac{r_i P_{L_i} + x_i Q_{L_i}}{1} \tag{5}$$