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Single-point reactive power control method on voltage rise mitigation in residential networks with high PV penetration

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ABSTRACT

Voltage rise (VR) due to reverse power flow is an important obstacle for high integration of Photovoltaic (PV) into residential networks. This paper introduces and elaborates a novel methodology of an index-based single-point-reactive power-control (SPRPC) methodology to mitigate voltage rise by absorbing adequate reactive power from one selected point. The proposed index utilizes short circuit analysis to select the best point to apply this Volt/Var control method. SPRPC is supported technically and financially by distribution network operator that makes it cost effective, simple and efficient to eliminate VR in the affected network. With SPRPC none of the previous PV inverters need to upgrade and can retain their unity power factor to not to conflict with current grid codes. Comprehensive 24-h simulation studies are done on a modified IEEE 69-bus Network emulating a traditional residential power system with high r/x ratio. Efficacy, effectiveness and cost study of SPRPC is compared to droop control to evaluate its advantages.

1. Introduction

PV sources are increasingly popular in residential networks driven by dual benefits of PV-customers' and distribution network operator (DNO). DNO's motivating policies towards PV customers makes household electricity cost much lower than coal-based electricity price. As was predicted in Ref. [1], the PV generation in Australia is expected to increase from 320 to 1130 MW/year which means total roof top low voltage (LV) PV generated electricity will increase from 16% to 20% by 2031. Under the premise of this exponential uptake of PV penetration in LV network, DNO must assure that the quality of the provided service to PV customers will not be compromised.

PV integration increase in LV network results in reverse power flow (RPF) that would conflict with the promised quality given to customers [2–4]. According to grid codes, ANSI standard C84.1 [5], EN50160 [6] and IEC61727 [7], the voltage DN nodes must remain within 0.95 and 1.05 pu and missing this criterion would disconnect PV-inverter to serve network protection. Hence, voltage rise (VR) would be a major obstacle for increasing PV penetration into existing LV traditional radial networks which were not designed to handle large amount of RPF towards the source [8,9].

Several alleviative methods have been applied to mitigate VR in distribution network (DN) and were evaluated and categorized into two; PV-inverter side and DNO-side approaches in Ref. [2]. Methods such as active power curtailment (APC), buffering excess active power (BEAP) and reactive power control (RPC) which require modification in inverter technologies are listed in Inverter-side approaches, while under load tap changer (ULTC), reconductoring, active grid voltage control (AGVC) and optimal energy management (OEM) are named as DNO-side approaches.

Although, BEAP prevent the surplus active power curtailment by storing it, and despite the numerous advantages [10], is not employed by residential PV-customers due to high cost. Traditionally, DNOs can reduce the secondary voltage of the upstream transformer by applying ULTC. The inability of the ULTC to change frequently and the induced stress, are the main drawbacks of such method [11–13]. Moreover, it also requires communication

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between the meters and control centre including a transformer, to maintain the feeder voltage within limits [14]. Alternatively, DNO could choose to reinforce the LV network conductor sizes, namely re-conductoring, to reach lower resistance in feeder line. Such practice was applied in some countries because PV penetration increased much faster than inverter development or grid code update, although it has imposed massive costs [15]. In Refs. [16–18] OEM framework was proposed to fulfill the voltage criteria and avoid VR in LV network. Alternative ideas such as [19,20], introduced real-time control to schedule the inverters' active and reactive power which in current state of most LV networks, such methods are less feasible and more expensive considering the required advanced mathematical analysis, dependency on data infrastructure and difficulty of implementation [21–23].

Accordingly, since the mutual benefit of DNO and PV customers, correlates directly to the amount of PV's RPF during the day, APC approaches should also rarely be practiced [23–27]. RPC is recognized as a more viable option for mitigating VR, applied based on droop control [8,28–30]. RPC imposes cost and complexity, and it necessitates to upgrade PV-inverters. Otherwise, they can limit the active power feed-in of PV-inverters, resulting in loss of PV customer revenue [31–34].

According to grid codes such as IEEE standard 1547, PV-inverters are prohibited to interfere with voltage regulation. Although, deliberations are under progress to relieve such constraint and allow individual PVs to contribute in voltage control. Additionally, the major concern of a DNO in high PV integration is to maintain highest possible hosting capacity (HC) for each PV-inverter in sunny hours of the day. It is also, DNO's responsibility to maintain networks' voltage level within grid code criteria. As mentioned earlier, in residential DN, PV-inverters normally do not install storages, and consequently, they would lose revenue of if their inverter switches off due to VR. Consequently, in this paper, a novel methodology is proposed that employ only one PV inverter, and reactive power is suggested to be absorbed centrally. This method is named single point reactive power control (SPRPC), which is an index-based analytic solution for eliminating the VR caused by RPF in a residential DN. By SPRPC short circuit analysis and feeder impedance are utilized to select one PV node through an impedance-voltage rise index (IVRI). The required reactive power to be absorbed is also estimated upon a proposed algorithm to determine the rating of the selected PV-inverter. Considering that, if a PV inverter tends to absorb significant level of reactive power, it is necessary to coordinate a charging mechanism with the DNO to cover the costs associated with extra inverter size and transmitting the additional reactive power, SPRPC is a DNO side approach and would be supported by DNO, technically and financially.

To the knowledge of the authors, this is the first time that literature has managed to employ an index-based RPC methodology from DNO side considering feeder impedance. Previous studies on this topic are extended in the following ways: 1) Technically this method does not breach grid code of voltage regulation and controlling coordination concerns are respected by DNO. 2) Owing to the central fashion of SPRPC, none of the pre-installed PV inverters must be replaced by higher rating inverter which imposes extra costs and hassles to PV-customers. 3) SPRPC mitigates VR to a very acceptable extent in the modified IEEE 69-bus network that cancels or defers the need for DN conductor reinforcement by DNO. 4) Considering that, sunny hours of the days are the times that reactive power capability is most needed and inverter capacity might be occupied mostly by the generated active power of the PV itself, the required reactive power capability of the selected PV-inverter has estimated accurately through a mathematical algorithm which is significantly important. 5) The power losses and transmitting power requirement of SPRPC is less than droop control. 6) According to presented cost study, the associated cost of SPRPC is less than droop. 7) The real verisimilitude models for residential loads and insolation of Sydney, Australia are considered. 8) The study is performed by a powerful DIgSILENT power factory simulator. This enabled the authors to utilize the network effect of the DN in VR mitigation, which mostly neglected in the previous literature. The main purpose of this analysis is to prove that SPRPC, can capably eliminate VR, at essentially no extra cost to the consumer. Comprehensive simulation studies are presented to support its effectiveness.

The remainder of the paper is organized as follows: Section 2 provides a mathematical analysis of the proposed methodology. The test network is introduced, and results of SPRPC are illustrated and compared to droop control in Section 3. Section 4 presents cost study of SPRPC and droop control. Finally, SPRPC methodology is discussed and evaluated in Sections 5 and 6 respectively, where concluding remarks are provided.

2. Analytical SPRPC formulation

The proposed methodology is performed in two analytical steps as follow:

2.1. Mathematical analysis RPC application to VR mitigation due to RPF

Fig. 1 (a) shows a typical pair of distribution nodes with domestic loads, P_{dl} and Q_{dl}, and rooftop grid-connected PV generators to analyse the RPF and the VR phenomenon. The parameters P_m and Q_m represent the net active and reactive power, respectively, at a typical node m which can be determined by Eq. (1). P_r and Q_r are the transmitted active and reactive power between nodes m and n, respectively presented in Eq. (1) which are load nodes in load flow calculations. Vectors depicted in Fig. 1(b), illustrate how voltage U_m raises due to the injected current I_r. Eq. (2) shows load flow major equations that calculates above parameters, where G_{mn} is the real part and B_{mn} is the imaginary part of the element in the bus admittance matrix Y_{BUS} corresponding to the nodes m and n. δ_{mn} is the difference in voltage angle between nodes m and n and the Jacobian matrix (J) represents the partial derivatives of the active

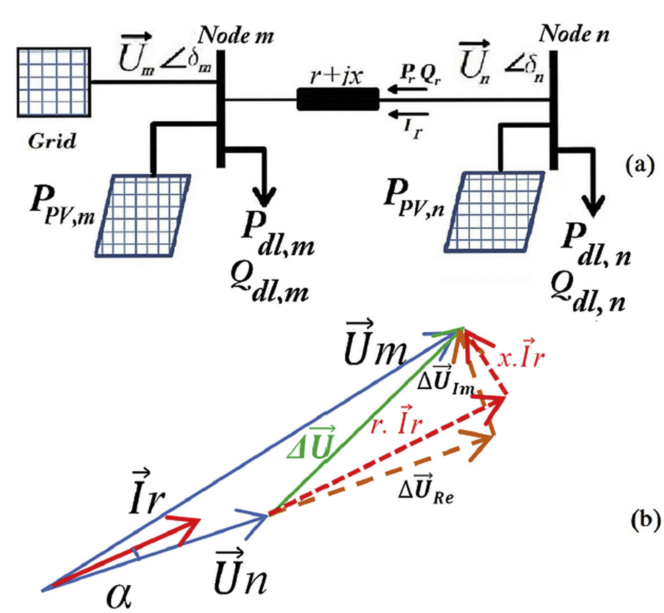

Fig. 1. Voltage vectors of 2 adjacent nodes, m, and n in a DN.