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Sequential Volt/Var Controller for PV Smart Inverters in Distribution Systems

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Abstract— **Increased photovoltaic (PV) penetration in distribution systems helps improve the system's performance by reducing the active power loss, in addition to the environmental benefits. However, high PV generation during light loading periods results in reverse power flows in the system. In turn, the voltage increases at the nodes located further from the main substation. This paper proposes a reactive power control method to coordinate the participation of different PV smart inverters in solving the overvoltage problem. The proposed control method operates at the lateral level based on the measured voltage at the lateral's end-node (or most downstream PV system). The lateral controller sequentially dispatches power factor commands to the smart inverters. This method maintains the coordination between the PV systems at different operating conditions keeping the reactive power requirement as low as possible. The proposed control method is compared to the volt/var control method from the IEEE standard 1547 and shows an improved performance in terms of reactive power requirement and active power loss.**

Keywords—distribution system, overvoltage, PV generation, smart inverter, volt/var control

I. INTRODUCTION

Climate change and other environmental factors are deriving the world to rely on renewable and clean energy sources, especially wind and photovoltaic generation [1]. Despite the economical, technical, and environmental advantages of photovoltaic (PV) systems, they introduce challenges to the operation of the electric grid in different aspects [2]. Reverse power flow in distribution systems is one of the major challenges that can lead to an overvoltage problem [3]. In a conventional radial distribution system, the power flows from the substation downstream to the loads leading to lower voltage levels at the loads than at the substation. With the integration of PV systems and for the periods when the PV generation is high (sunny periods) while the loading level is low (off peak periods), the surplus PV generation will flow upstream to the main substation. This reverse power flow and because the main substation voltage is tied to the main grid (i.e., can be assumed fixed), the voltage levels at the loads, especially far from the substation, become higher than the substation voltage. This case may result in voltage violation where the voltage exceeds the allowable operating voltage limit [4]. This paper focuses on the methods that solve the overvoltage problem using the PV smart inverters rather than other conventional devices such as voltage regulators.

The IEEE standard 1547-2018 for interconnection of distributed energy resources (DERs) with associated electric power systems interfaces considered the participation of the distributed resources in voltage regulation [5]. Different voltage control modes/methods were reported. The volt/var droop control method is the widely recognized one. The DER absorbs/injects reactive power following its terminal voltage magnitude and according to a predefined characteristics relating the voltage magnitude to the reactive power [5]. The IEEE standard 1547 described a default setting for the volt/var controller which has been tested against a variety of operating scenarios in [6] and worked well for managing the voltage. However, there are limitations and drawbacks associated with the volt/var droop control method including increased thermal overloading of the network lines and transformers [7].

In [8], the volt/var droop settings for different PV systems were coordinated by solving a multi-objective optimization problem at a critical operating point. The study showed that unequal reactive power share between the PV systems is much better than equal reactive power share. A hybrid reactive power control method has been proposed in [9]. The method combines both reactive power control based on voltage Q(V) and power factor control based on active power PF(P). Two reactive power control methods using not only local measurements but also shared information from remote PV systems were proposed in [10]. These two methods relied on either low or high bandwidth communication means. Ceylan *et al* [11] presented a lateral controller to control the smart inverters installed along the lateral. This central lateral controller uses the voltage at the lateral's end and the active power generation from all PV systems together with the system voltage sensitivity matrix to organize the operation of the smart inverters. Depending on constant offline calculated sensitivity matrix was a shortfall that leaded to errors. Proper communication facility is needed to transfer the instantaneous active power generation from the PVs to the controller. In [12], the authors considered the presence of energy storage system with the PV system. To overcome voltage violation, the PV generation is used to charge the energy storage during the peak generation periods and this energy is discharged during the peak loading periods. Other methods considered controlling the PV active power generation for voltage regulation [13]. It is worth to mention that some methods studied the coordination between the PV smart inverters and the conventional voltage regulation devices such as voltage regulators and capacitor banks [14].

The previous literature shows that the penetration of PV systems to the distribution network and the accompanied voltage problems require further research work. This paper proposes a coordinating volt/var controller for PV systems in distribution network to solve the potential overvoltage problem. The proposed controller operates at the lateral level and coordinates the reactive power of different PV systems. The control method is based on the sequential operation of the smart inverters to solve the overvoltage problem while minimizing the reactive power requirement and accordingly the associated active power loss.

II. DROOP CONTROL METHOD

In this section, the IEEE 1547 volt/var control method is briefly presented as it will be used in a comparison with the proposed method. The IEEE standard 1547-2018 requires the distributed resources to participate in the voltage regulation using different control methods [5]. The volt/var droop control method which uses the characteristics shown in Fig. 1 is commonly used with the PV smart inverters [6, 15]. The droop setting is defined by the four main points indicated in Fig. 1. The PV system operates in an over excited mode injecting reactive power to the system during undervoltage situation. When there is an overvoltage problem, the PV system absorbs reactive power from the system (under excited mode). Based on the setting values, there may be a dead band where the PV system is not absorbing/injecting any reactive power.

III. PROPOSED CONTROL METHOD

The proposed control method aims to use as minimum reactive power as possible to overcome the voltage violation problem in the system under different operating conditions. Employing arbitrary/default droop setting from the IEEE standard 1547 [6, 7] can solve the overvoltage problem but can result in using more reactive power than necessary leading to increased active power loss due to reactive power flow. Optimizing the droop setting between different PV systems [8] helps reducing the power loss due to reactive power flow. However, the coordination between the PV systems operation is usually carried out at a single operating point (ideally a critical point). Therefore, the minimum reactive power utilization may not be satisfied at all operating conditions.

The proposed method operates at the lateral level coordinating the reactive power of different PV systems along the lateral. The lateral controller firstly activates one PV system trying to solve the voltage problem. If it was not able to individually solve the problem, then the lateral controller activates the next PV system and so on. The nodal voltage sensitivity to reactive and active power variation increases while going downstream (away from the substation in radial systems) [16]. Therefore, the lateral controller starts by activating the most downstream PV system. Also, the lateral end-node is often suffering from the highest voltage rise when the PV generation is high while the system loading is low. The proposed lateral controller uses the voltage at the lateral end-node (or the most downstream PV system) as an indication for the voltage violation.The proposed controller monitors the lateral end-node voltage (or the most downstream PV system) and accordingly dispatches power factor (PF) commands to the smart inverters of the PV systems along the lateral as shown in Fig. 2.

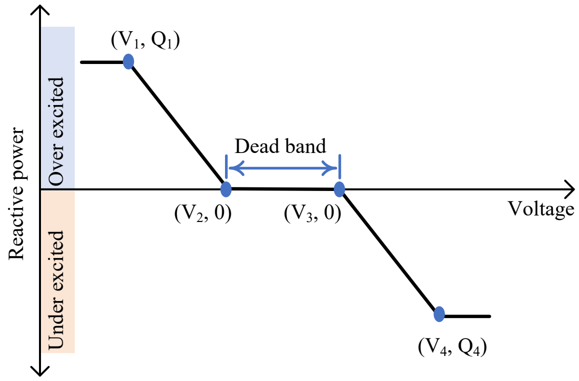

Fig. 1. IEEE 1547 volt/var droop control characteristics.

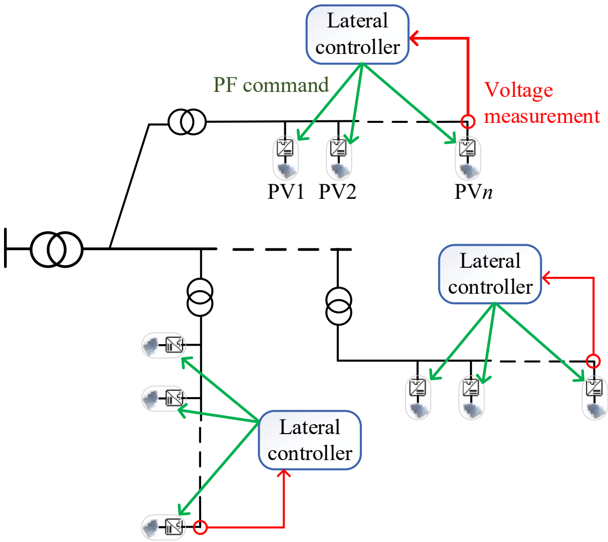

Fig. 2. Proposed lateral volt/var controller.

Algorithm 1: Procedure of the proposed controller

```
Run Power Flow
Monitor the lateral's end-node voltage ($V_E$)
if $V_E$ > Limit
    for K = $n$ : -1 : 1
        i = 0
        while $|PF_K| > 0.9$ && $V_E$ > Limit
            $PF_K(i+1) = -(|PF_K(i)| - \Delta PF)$
            Run Power Flow
            Monitor the voltage ($V_E$)
            i ++
        end
    end
end
```

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Dispatching PF commands to the inverters has two advantages. Firstly, it helps maintaining the PF value. Secondly, it eliminates the need for measuring the PV system active/reactive power. When the monitored voltage exceeds the accepted voltage limit, the lateral controller sends a new PF command to the most downstream smart inverter (PV*n* in Fig. 2). The PF command is such that the PV system operates in an under excited mode (absorbs reactive power) to bring the voltage down to the accepted limit.

The overvoltage problem mainly occurs at high PV generation and low loading conditions as previously mentioned. To comply with the IEEE standard 1547 [5], the minimum PF value used is 0.9. Accordingly, the PF of the most downstream inverter is recursively changed until the monitored voltage falls within limits, or the inverter operates at PF value of 0.9. In the latter case, if the monitored voltage is still exceeding the voltage limit, the lateral controller dispatches an PF command to an upper stream PV system. This sequential process continues until the voltage returns to the accepted operating range. Algorithm 1 illustrates the implementation procedure of the proposed controller. In the algorithm, n refers to the number of PV systems installed along the lateral. The PF value is negative such that the PV system is under excited i.e., absorbs reactive power to solve the overvoltage problem. The accepted voltage limit depends on the code employed and the system voltage level [17].

There are two possible options for updating the operating PF. The first one is to use a fixed step change (for instance ΔPF=0.01). The other option is to use a variable change in the PF depending on the voltage deviation value from the accepted voltage limit. In this paper, the fixed step change is employed. The proposed controller has different advantages compared to the local droop controllers and other controllers working at the lateral level [11] as follows.

1. Unlike the local droop controllers, droop settings are not required.
2. The operation of the PV systems is coordinated irrespective to the operating condition.
3. The PV system operating PF can be maintained to the standard limits.
4. Measuring the PV system active/reactive power is not required reducing the required communication bandwidth.

IV. SIMULATION STUDY

The radial test system shown in Fig. 3 is used for the simulation study [8, 18]. The system represents a low voltage lateral with five buses connected to a medium voltage grid through a distribution transformer. The system parameters are given in Table 1 [8, 18]. The test system, including the PV systems, was simulated using the Open Distribution System Simulator (OpenDSS) [19]. The proposed controller was built using MATLAB and interfaced to the OpenDSS. The OpenDSS is used to solve the power flow problem following the control commands dispatched from the modelled controller. The interaction between the OpenDSS and MATLAB is done through the OpenDSS COM interface as shown in Fig. 4. More information about the OpenDSS operation and interaction to MATLAB can be found in [19].

TABLE I. TEST SYSTEM PARAMETERS

Element	Parameters
Medium voltage grid	20kV, 100MVA, X/R=1
Distribution transformer	20/0.4 kV, 250kVA, Z=4%
Cable impedance	0.346+j0.0754 Ω/km

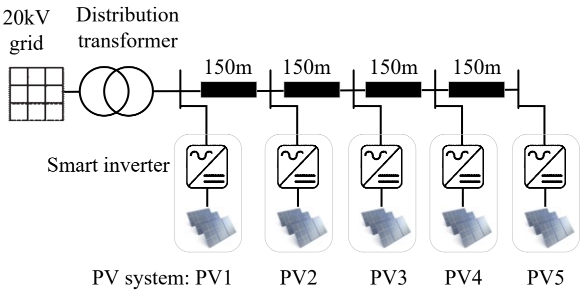

Fig. 3. Distribution lateral with PV systems.

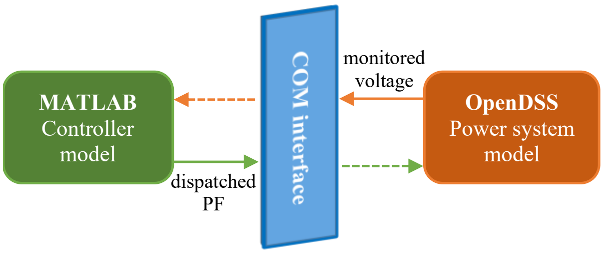

Fig. 4. Interaction between OpenDSS and MATLAB.

A. *Performance of the proposed controller*

With the system operating at no load, the PV generation level represents the net load-generation value that flows upstream to the main substation. For simplicity, the generation from the five PV systems is assumed equal. The power generation for each PV changed from 13kW to 17kW in a step of 1kW. While the PV systems were operating at unity power factor, the voltage profiles at different total net load-generation levels are shown in Fig. 5. According to the ANSI C84.1, the allowable upper service voltage limit is 1.05pu for systems operating 600V or below [17]. As is clear, the voltage at the lateral end exceeds the limit for the net load-generation levels of 75kW, 80kW, and 85kW.

The proposed control method has been applied to the system and the corresponding voltage profiles are shown in Fig. 6. The overvoltage problem has been solved for different conditions. It is worth noting that the proposed controller did not request the PV systems to act for the net load-generation levels of 65kW and 70kW where the voltage was originally within the limits. To solve the overvoltage problem, when exists, the PV systems were running under excited absorbing reactive power from the system. The absorbed reactive power by different PV systems at different load-generation levels is shown in Fig. 7. No reactive power was absorbed for the first two cases (65kW and 70kW) where there was no voltage violation. Only PV5 acted and absorbed reactive power to solve the overvoltage problem for the 75kW case. Both PV4 and PV5 were required to absorb reactive power for the 80kW case while four PV systems (PV2 to PV5) were needed to participate to solve the problem for the 85kW case. The operating power factor for any PV system was maintained at or above 0.9 which can be seen in Fig. 8.

B. Comparison with the IEEE 1547 volt/var method

In this subsection, the proposed control method is technically compared to the volt/var droop control method in the IEEE standard 1547 [5]. It is important to firstly mention that the IEEE 1547 droop control method has an economic advantage of using local voltage measurement only without any need for communication. On the other hand, the proposed control method requires communication at the lateral level. However, due to simplicity of required data transfer (end-node voltage and dispatched PF commands) and short distance extension of the lateral, a low bandwidth communication channel would suffice.

Regarding the droop setting of the IEEE 1547 volt/var control method, it has been shown in [11] that arbitrary droop setting provides similar performance to voltage sensitivity-based droop setting. Also, the default droop setting was evaluated in [6] to improve the system performance. Accordingly, in this paper, the same droop setting was used for the five PV systems. Regarding the under excited region in Fig. 1, the default setting from the IEEE 1547 was used for V_3 as 1.02pu while V_4 was set to the upper voltage limit as 1.05pu. The over excited region of the droop characteristics followed the default IEEE 1547 default setting. The maximum reactive power limits Q_1 and Q_4 in Fig. 1 were set to 44% and −44% of the inverter rated power, respectively [5].

The voltage profiles when applying the volt/var droop control method are shown in Fig. 9 for different load-generation levels. The overvoltage problem has been solved except for the 85kW case. Changing the used droop setting would help overcoming this case but this is not the aim of the comparison in this subsection. Therefore, the 85kW case has been discarded from the comparison.

The total reactive power absorbed by all the PV systems for different net PV generation is shown in Fig. 10 for both proposed and IEEE droop control methods. The proposed control method requires less reactive power than the IEEE droop control method especially when the voltage violation is not significant and can be solved with lower interference of the PV systems. When the overvoltage problem necessitates the participation of all PVs systems, it is expected that the two control methods provide close performance. This can be seen in Fig. 10 as the two performance lines are approaching each other. The reason behind the lower reactive power requirement by the proposed control method can be interpreted from comparing the voltage profiles in Fig. 6 and Fig. 9. The proposed method solved the overvoltage problem and brought the voltage to/near the limit. On the other hand, the droop control method solved the overvoltage and brought the voltage below the limit more than necessary which in turn required more reactive power absorption from the system.

The more the reactive power flow, the more the resulting active power loss due to reactive power flow. The percentage increase in active power loss, calculated using (1), due to reactive power flow in the system is shown in Fig. 11 for both proposed and droop control methods. The droop control method resulted in at least 6% increase in the active power loss at the time that the proposed method can prohibit the increase in active power loss if unnecessary. This comparison proves the technical advantages of the proposed control method over the standard volt/var droop control method.

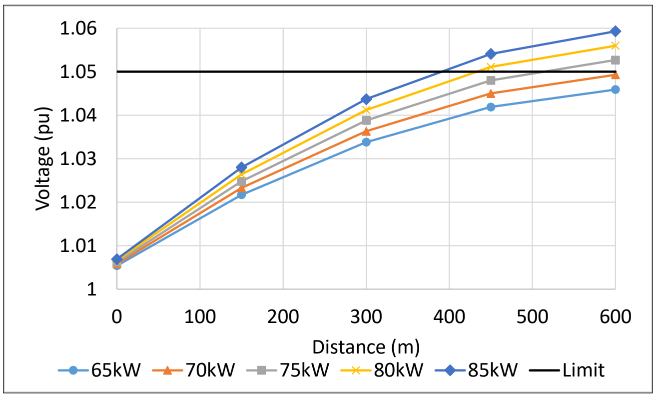

Fig. 5. Voltage profiles at unity power factor.

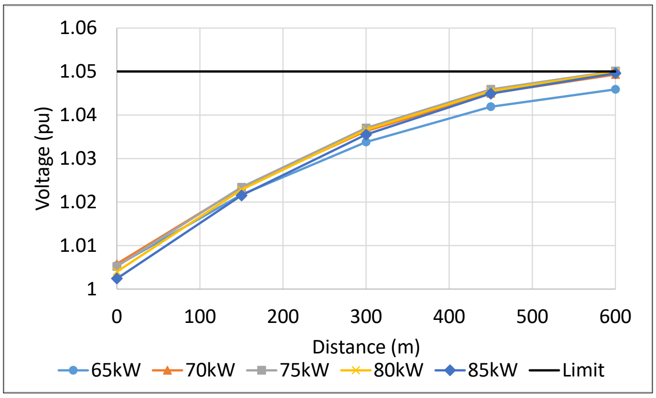

Fig. 6. Voltage profiles when applying the proposed control method.

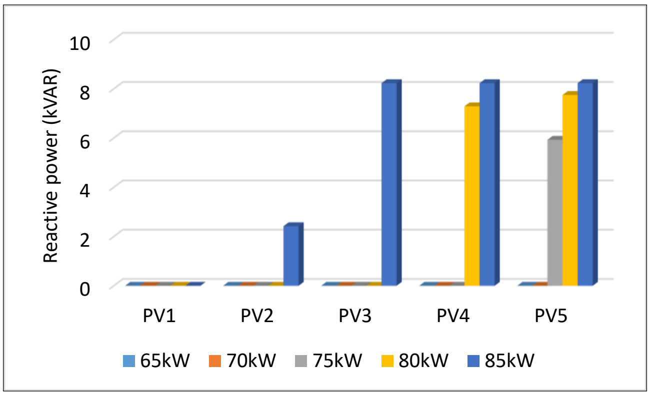

Fig. 7. Reactive power for different PV systems when applying the proposed control method.

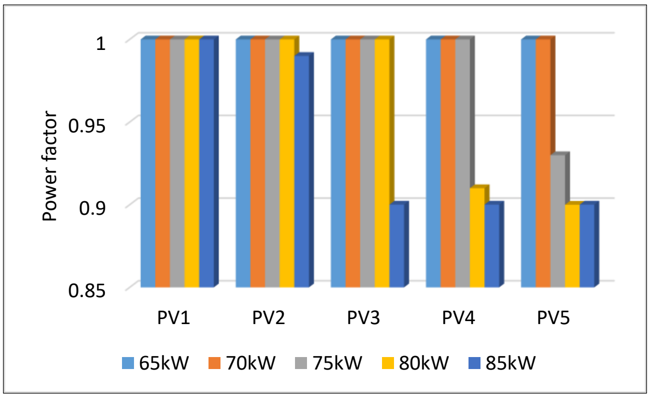

Fig. 8. Operating power factor for different PV systems when applying the proposed control method.

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$$P_{LOSS+} = (P_{LOSS} - P_{LOSS\text{-}PF=1}) / P_{LOSS\text{-}PF=1} \times 100 \qquad (1)$$

where, P_{LOSS+}, P_{LOSS}, and $P_{LOSS\text{-}PF=1}$ are the percentage increase in active power loss, the current active power loss, and the active power loss when operating at unity power factor.

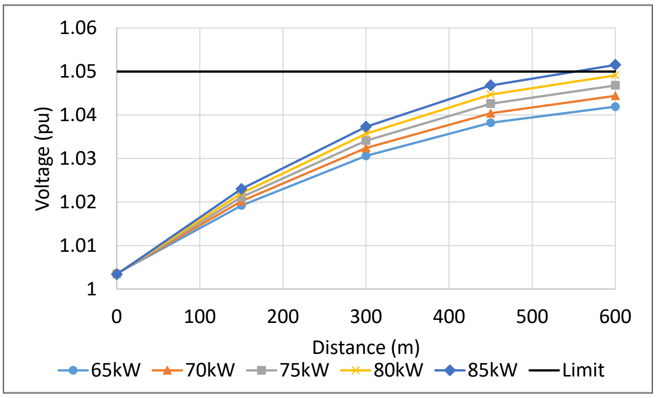

Fig. 9. Voltage profiles when applying the IEEE volt/var droop control.

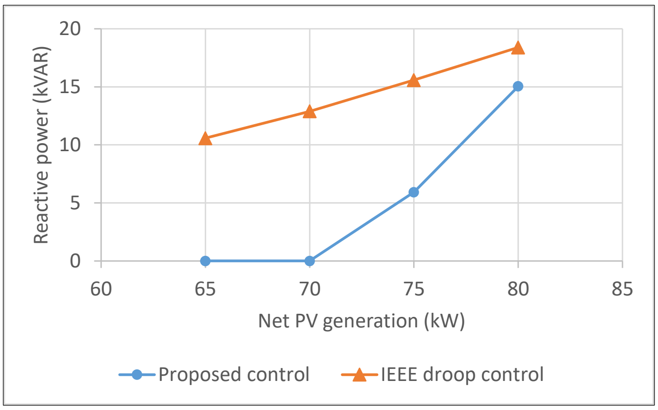

Fig. 10. Reactive power requirement by the proposed and the IEEE droop control methods.

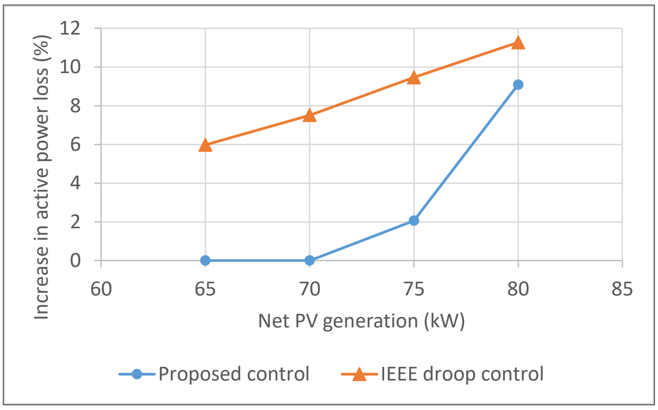

Fig. 11. Percentage increase in active power loss due to reactive power flow for the proposed and the IEEE droop control methods.

V. CONCLUSION

High PV generation especially during off peak load periods may result in overvoltage. Recent distributed energy resources integration standards consider the reactive power capability of PV smart inverters for the voltage regulation. Uncoordinated reactive power share from different PV systems can overcome the overvoltage problem but not optimally in terms of the associated active power loss. A coordinating lateral controller has been proposed in this paper to manage the reactive power share from different PV systems installed along the lateral. The controller sequentially activates the reactive power sharing through sending power factor commands to the PV systems starting from the most downstream one. This process helps utilizing as low reactive power as possible to mitigate the overvoltage problem. Accordingly, the active power loss due to the reactive power flow is kept low. Unlike the volt/var droop control methods, the proposed controller does not require setting the droop characteristics. The comparison between the proposed control method and the IEEE standard 1547 volt/var control method emphasized the better performance of the proposed method in terms of lower reactive power requirement and lower active power loss due to the reactive power flow. It is worth to mention that the proposed method requires communication between the lateral controller and the PVs along the lateral but just to transfer the PF commands from the controller to the PV systems, so a low bandwidth communication channel would suffice. The digital communication platform required to support the controller proposed in this paper represents a separate research topic.

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