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Overvoltage and Overloading Prevention Using Coordinated PV Inverters in Distribution Network

G. Mokhtari*, *Student Member, IEEE*, G. Nourbakhsh*, *Member, IEEE*, G. Ledwich*, *Senior Member,* IEEE A. Ghosh**, *Fellow, IEEE*,

Abstract— **Overvoltage and overloading due to high utilization of PVs are the main power quality concerns for future distribution power systems. This paper proposes a distributed control coordination strategy to manage multiple PVs within a network to overcome these issues. PVs reactive power is used to deal with over-voltages and PVs active power curtailment are regulated to avoid overloading. The proposed control structure is used to share the required contribution fairly among PVs, in proportion to their ratings. This approach is examined on a practical distribution network with multiple PVs.**

***Index Terms*— Consensus algorithm, overloading, overvoltage, PV.**

I. INTRODUCTION

Power quality challenges caused by high utilization of PV sources are the main concerns for utilities around the world [1]. The main concerns include over-voltages and overloading [2-8] in the period of high generation. These problems constitute the major cause of renewable energy capacity limitation in future distribution systems planning.

As listed in literature, using resources in distribution network such as PVs active and reactive power [9], controllable loads [10, 11], DSTATCOMs[12] and energy storage units [13] has promising features to avoid such issues.

This paper proposes an effective approach for regulating PV active and reactive power, according to the network voltage and loading requirements.consensus algorithm is used as the coordination strategy to avoid over-voltages and overloading in distribution network. PVs active power curtailment are regulated to keep the injected power in acceptable range while the contribution of PVs reactive power are coordinated to reduce overvoltage in the network. The main contributions of the this work include: 1- designing of a new internal control structure for PVs to adapt for coordination, and 2- Applying the consensus control strategy to share the contribution fairly among PVs in distribution network.

II. PROPOSED APPROACH

Consensus algorithm is a promising distributed control approach to manage a network with multiple devices. References [14, 15] manage multiple robots using this control algorithm. In reference [16], this algorithm harmonise unmanned devices for fire monitoring. This algorithm has also been applied to power system as well. Reference [10] uses this algorithm as a supplementary control to coordinates batteries within low voltage network and avoid voltage rise issue. In reference [14], this algorithm is used to coordinate storage units for loading management in distribution network. The main feature of this algorithm is its sharing ability among multiple devices.

This algorithm was applied in this paper using the following scheme. Every PV is supported by a control agent who determines the reference value for active and reactive power. There also exists a communication system among the control agents of neighboring PVs. Additionally, a higher control agent, named the leader, is used to initiate the coordination of PVs. The structure for leader control agent is shown in Fig. 1. For the purpose of managing the voltage at all buses, critical bus voltage (V_c) is assigned as the controlling variable and the aim is to keep this bus voltage less than a critical limit ($V^{critical}$).

The injected apparent power to the upper voltage level network is termed S, where a part of the control strategy is to keep this value less than $S^{critical}$, for overloading prevention.

The structure of PV control agent is shown in Fig. 2. Every PV control agent has parameters named information state based on consensus algorithm. The information state for active power is shown by p_i and for reactive power is shown by q_i.

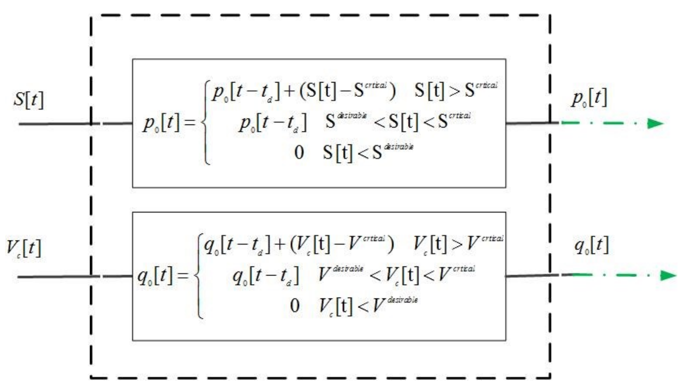


Fig. 1: Proposed control structure for leader.

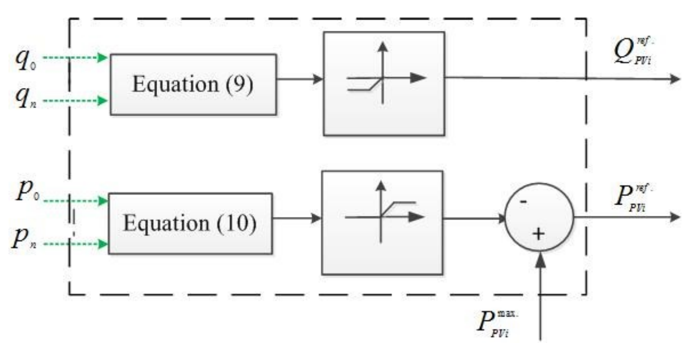


Fig. 2: Proposed control structure for control agent of each PV.

In our proposed approach, reactive power absorption using PV inverters are utilized to avoid overvoltages. The control design goal is to reduce the critical bus voltage less than $V^{critical}$, when this limit is violated. In other words, when critical bus voltage violates $V^{critical}$, the PVs coordination needs to be initiated, and when the critical bus voltage is less than $V^{desireable}$

*Ghassem Mokhtari, Ghavameddin Nourbakhsh and Gerard Ledwich with the School of Electrical Engineering and Computer Science, Science and Engineering Faculty, Queensland University of Technology, Brisbane, Australia.

**Arindam Ghosh with School of Electrical Engineering and Computing, Faculty of Science and Engineering, Curtain University of Technology, Perth, Australia.

^{ble}, the coordination needs to be stopped. Additionally, a relationship describing the sharing of reactive power among inverters, similar to equation (1) in this paper, needs to be achieved.

$$\frac{Q_{PV1}}{Q_{PV1}^{\max.}} = \frac{Q_{PV2}}{Q_{PV2}^{\max.}} = \ldots = \frac{Q_{PVn}}{Q_{PVn}^{\max.}} \tag{1}$$

where Q_{PVi} is the reactive power of ith PV and $Q_{PVi}^{\max.}$ is the maximum available reactive power of the same PV.

In order to achieve these goals, the information state for reactive power of leader is determined as equation (2), when the critical bus voltage passes $V^{critical}$ limit.

$$q_0[t] = q_0[t-t_d] + k_q.(V^{critical} - V_c[t]) \tag{2}$$

In addition, based on consensus algorithm [16], the information state of reactive power for each PV is determined as:

$$q_i[t] = \sum_{k=0}^{n} c_{ik}[t-t_d].q_k[t-t_d] \tag{3}$$

where $c_{ik}[t]$ is a coefficient which depends on communication structure as shown in (4) [14]:

$$c_{ik}[t] = \frac{l_{ik}[t-t_d]}{\sum_{j=0}^{n} l_{ij}[t-t_d]} \tag{4}$$

where l_{ij} equals to 1 if there is communication link between ith and jth control agents, and zero otherwise.

Correspondingly, to manage the loading of the network, a set of similar goals need to be achieved for the associated controllable variables. Consequently, equations (5) and (6) need to be achieved for the purpose of this control design.

$$S(t) < S^{critical} \tag{5}$$

$$\frac{P_{PV1}}{P_{PV1}^{\max.}} = \frac{P_{PV2}}{P_{PV2}^{\max.}} = \ldots = \frac{P_{PVn}}{P_{PVn}^{\max.}} \tag{6}$$

where P_{PVi} is the active power of ith PV and $P_{PVi}^{\max.}$ is the maximum available active power for the same PV.

In order to meet the noted goals, it is proposed that information state of active power for control agents need to be updated in the same time step as in equations (7) and (8), respectively.

$$p_0[t] = p_0[t-t_d] + k_p.(S[t] - S^{critical}) \tag{7}$$

$$p_i[t] = \sum_{k=0}^{n} c_{ik}[t-t_d].p_k[t-t_d] \tag{8}$$

The reference values for active and reactive power of PVs are updated as functions of information state, shown in equations (9) and (10).

$$Q_{PVi}^{ref.}[t] = q_i[t] \times Q_{PVi}^{\max.} \tag{9}$$

$$P_{PVi}^{ref.}[t] = P_{PVi}^{\max.} \times (1 - p_i[t]) \tag{10}$$

It is worth nothing that to avoid curtailments for PVs (equation (10)), storage units can be added beside PV units and the reference value for storage active power ($P_{Bi}^{ref.}$) can be determined as equation (11).

$$P_{Bi}^{ref.}[t] = p_i[t].P_{PVi}^{\max.} \tag{11}$$

III. Case Studies

A network with multiple PVs is used to examine this approach. The details of this network are listed in reference [17]. The network and communication structure is shown in Fig. 3. The value of load in each node and PV rating are listed in Table I and II, respectively. In this application, the generation profile shown in Fig. 4 is considered for each PV. The threshold limits for voltage and network loading are listed in Table III and IV, respectively.

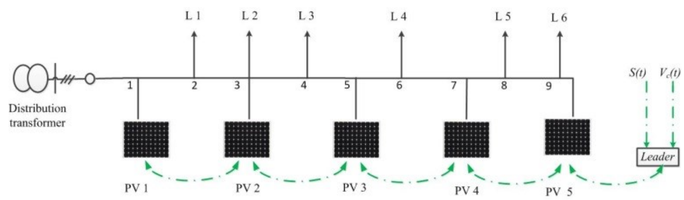


Fig. 3: Distribution network schematic diagram.

Table I: Load information.

Load	L1	L2	L3	L4	L5	L6
Active power (kW)	34.6	36.5	47.4	39.5	41.3	27.3
Reactive power (kVAR)	9.2	5.8	9.7	6.3	12.2	7.8

Table II: PV ratings.

PV	PV1	PV2	PV3	PV4	PV5
Active power (kW)	550	600	500	450	650
Reactive power (kVAR)	275	300	250	225	325

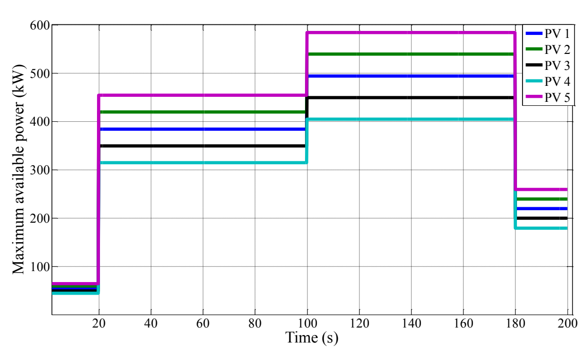


Fig. 4: PVs Generation profile.

Table III: Voltage limits in the proposed approach.

Parameter	Voltage (kV)	Voltage (pu)
$V^{permissible}$	16	1.06
$V^{critical}$	15	1.05
$V^{desirable}$	14	1.04

Table IV: Network loading limits in the proposed approach.

Parameter	Power (kVA)	Power (pu)
$S^{permissible}$	2000	2
$S^{critical}$	2000	2
$S^{desirable}$	1500	1.5

Fig. 5 shows the bus voltages and injection to the higher grid when no control is applied. It can be seen that there is overvoltage in buses 6, 7, 8 and 9 between t=100 s and t=180 s. Furthermore, the injection to the higher grid, as seen in Fig. 5, is more than its permissible limit (2000 kVA) in the same period.

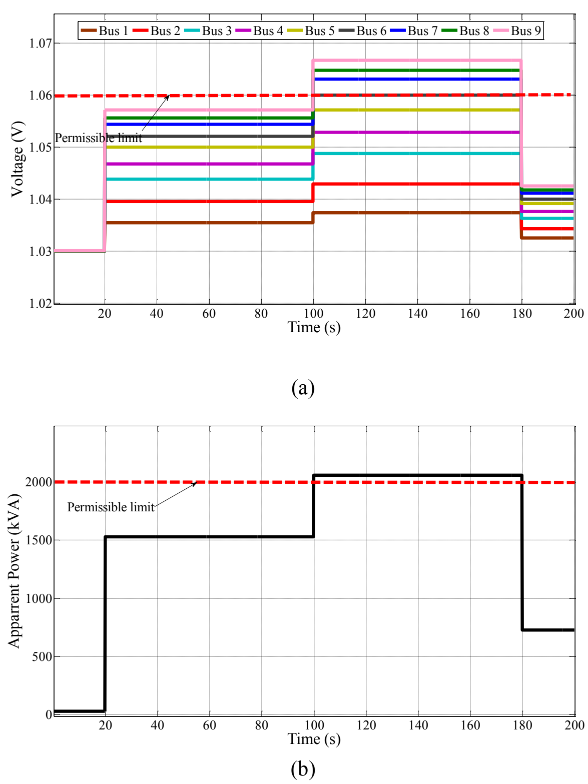


Fig. 5: Traditional operation (a) Bus voltages, (b) network loading.

Using the proposed control approach, the results in Fig. 6 show the bus voltages (a), network loading (b), PVs active power (c), and PVs reactive power (d), in different time steps. As shown in this figure, between 0 s and 20 s, all voltages and loading are in acceptable range and PVs are injecting their maximum active power with no required coordination. However, at t=20 s, the PVs injection rise and the critical bus voltage passes $V^{critical}$. Consequently, leader control agent initializes the coordination of PV inverters reactive power to reduce the voltage. At t=68 s, the critical bus voltage become less than $V^{critical}$ while fair sharing of PVs reactive power is achieved, as listed in Table V. Then, at t= 100 s, the critical limit for both voltage and network loading is violated and coordination for managing both issues are initiated. Same as, and in addition to the last case, leader control agent also initializes the coordination of PV active and reactive power. The required contribution is listed in Table V and VI. Finally, at t=180 s, all the voltages and network loading go to the desirable range and PVs start to maximize their injection without any coordination.

Table V: PVs reactive power in different time interval.

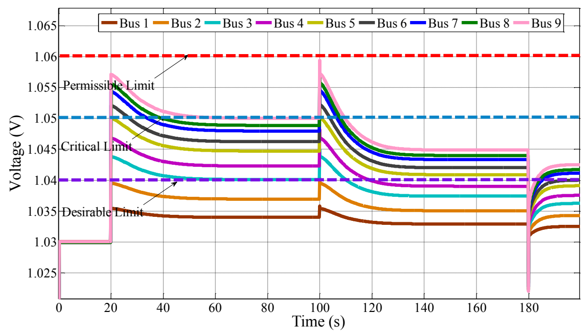
	Q_{PV1}	Q_{PV2}	Q_{PV3}	Q_{PV4}	Q_{PV5}	$\frac{Q_{PVi}}{Q_{PVi}^{max.}}$
0-20s	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0*
20-100s	*130.45*	*142.32*	*118.61*	*-106.74*	*154.17*	*0.47*
100-180s	*240.67*	*262.55*	*218.79*	*196.91*	*284.43*	*0.87*
180-200s	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0*

Table VI: PVs active power in different time interval.

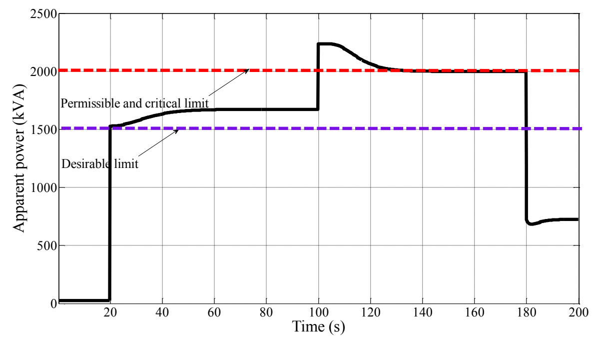
	P_{PV1}	P_{PV2}	P_{PV3}	P_{PV4}	P_{PV5}	$\frac{P_{PV1}}{P_{PV1}^{max.}}$
0-20s	*55.00*	*60.00*	*50.00*	*45.00*	*65.00*	*1.00*
20-100s	*385.00*	*420.00*	*350.00*	*315.00*	*455.00*	*1.00*
100-180s	*397.23*	*433.34*	*361.12*	*325.00*	*469.46*	*0.80*
180-200s	*220.00*	*240.00*	*200.00*	*180.00*	*260.00*	*1.00*

IV. Conclusion

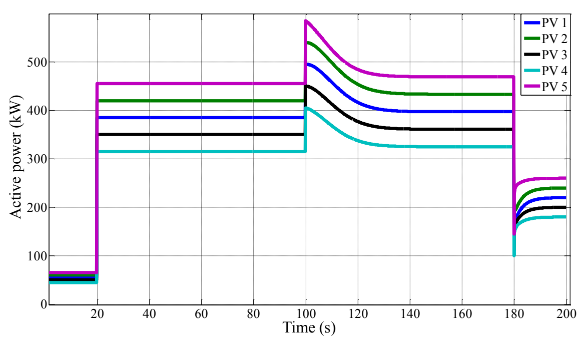
This paper proposed a distributed control coordination technique to manage the voltage rise and overloading in presence of high PV penetration in distribution systems. In this method, the resources including PVs active and reactive power were used to overcome these issues. PVs active power curtailment was coordinated to avoid overloading while PVs reactive power was utilized to deal with overvoltages. This approach was examined by applying the method to a distribution network with multiple PVs, and the results given in this paper confirm that the methodology is suitable for the intended outcome. Therefore, this method successfully proved to be effective in resolving overvoltage and loading issues arising from increased PV penetration in distribution systems.



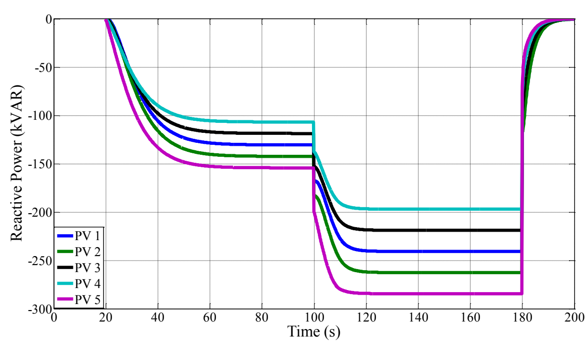
(a)



(b)



(c)



(d)

Fig. 6: Proposed control approach results, (a) bus voltages, (b) network loading, (c) PVs active power, and (d) PVs reactive power.

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