A Center-Free Control Strategy for the Coordination of Multiple Photovoltaic Generators
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Abstract—Coordinated regulation for the outputs from renewable energy sources is an appealing issue in future smart grid. This paper presents a distributed control strategy for multiple photovoltaic generators (PVs), which makes all the PVs have the same reserve ratio with respect to their maximum available power, but also makes their aggregated output support power network by providing power regulation services in real-time. In addition, an estimation method is proposed to get the maximum available power of PV. The proposed control strategy is nearly center-free, i.e., there is no centralized station which collects the output of each PV and sends the power command to each PV, and only uses local communication networks (CNs) to avoid expensive sometimes unreliable, long distance communications. Simulation results based on the IEEE standard 123-bus distribution system are presented and discussed, illustrating the effectiveness of the proposed control strategy.

Index Terms—Communication network, distributed control, network control, photovoltaic, virtual power plant.

I. INTRODUCTION

Compared with conventional energy sources, solar energy has the characteristics of low environmental costs, renewability and worldwide distribution, so it can be expected that there will be more and more photovoltaic generators (PVs) in the future. However, the introduction of a large number of PVs could have negative effects on power networks if the PVs cannot provide adequate technical support. Consequently, as the penetration level of PV rises, it is more and more difficult for the power network to keep the required level of stability and security, especially in a weak power network in which traditional synchronous generators have not enough capacity for power regulation. Therefore, in current or future grids with high penetration of PVs, it is necessary for the PVs’ output to be coordinately controlled to provide some ancillary services such as the load smoothing and the secondary control [1]–[3]. This paper focuses on how to implement a control algorithm to adjust the total output of all PVs in a distribution network in real-time when only one or a small part of PVs receive a command signal that is intended to adjust the total power of all PVs. However, the formulation of the command signal in real-time according to the power system is out of the scope of the paper.

Different schemes can be applied to solve the above coordination control problem. Firstly, a centralized control strategy can be used when the number of the PVs is not large. For example, methods similar to traditional centralized automatic generator control can be used in distribution networks with several distributed generators (DGs) [4], [5]. However, under such scheme, the nature of centralized control requires a CN connecting the central controller to each PV, and the output of each PV needs to be transmitted to the centralized controller in real-time. This scheme is based on an assumption of a global system-wide information structure. However, for a power network having a large number of geographically dispersed PVs, a centralized control scheme with the required information structure is often too expensive to be implemented and it is inflexible for the realization of “plug and play” characteristic.

The second scheme is decentralized, which has wide applications in power engineering. For example, the maximum power point tracking algorithm, the constant voltage and frequency with droop control, etc. [6]–[8]. Decentralized control is inherently robust since the control is only based on local information. However, as the penetration level of PVs increases, it is difficult for such a decentralized scheme to control and dispatch the PVs’ output to support some ancillary services, such as the smoothing of load change and secondary frequency control. Thus, these services will mainly rely on the traditional synchronous generators, which is difficult in a weak power network.

Thirdly, it is known that a distributed control scheme can combine the positive features of both centralized and decentralized controls while limiting their disadvantages [9]. Not like a centralized controller communicating with every PV in the system, a controller under a distributed control scheme sends commands to a part of the PVs and each PV shares its own information with some of their neighboring units. This scheme is proposed in [10]. Through an iteration way, the final output of the PVs will have the same values as those of a centralized control. The convergence property under some adverse conditions such as intermittent communication is provided in [11], showing this distributed scheme is very robust. Similar idea was presented for DGs in [12], where the DGs are controlled to have the same incremental cost. The advantages of these methods are: 1) only local CNs are used, and 2) they don’t need to change the algorithm even there is a disconnection or a new connection of any PV (or DG), such that the “plug and play” characteristic can be easily implemented. One of the disadvantages, however, is that there must have a common point where the total power of
The PVs (or DGs) can be measured easily. Therefore this is only applicable to radial power networks. Moreover, to achieve the consensus of the utilization of all the PVs, the maximum available power of each PV needs to be known in advance, which is an uneasy task in practice.

Motivated by these, an improved distributed control strategy is presented in this paper, which makes the usage of all PVs equal and makes their total output achieve to a given value quickly. Thus, the PVs can constitute a virtual power plant and the ancillary services such as the secondary control can be realized. One feature of the work is that the proposed strategy is nearly center free, i.e., there is no centralized station which collects the output of every PV and sends the power command to every PV. Another feature is that the maximum available power of each PV used in the control strategy is estimated by considering the output characteristic of the PVs, thus the direct measurement or calculation is avoided.

The paper is organized as follows. In Section II, the problem of the coordination of PVs’ output is formulated. The distributed control strategy for the PVs is provided in Section III. The numerical simulations based on the benchmark 123-bus system are provided in Section IV and conclusions are drawn in Section V.

II. PROBLEM DESCRIPTION

Assume there are \( n \) PVs in a power network. For the coordination of the PVs, the main objective of the paper is to develop a distributed control shown in Fig. 1. In this figure, all the PVs in power networks are deliberately divided into \( m \) groups and each group is aggregated to a virtual power plant of large capacity. There is a CN which connects a high level controller and the PV groups. Within each group of PVs, the PVs self-organize themselves through local CNs by sharing information among their neighbors. The PVs within each group are guided by a high level control (which can be a virtual control embedded in one or several groups) to provide the necessary services, such as the power regulation considered in this work. However, the formulation of the high level control according to power network is out of the scope of this paper.

Note that the control structure that we are interested in is different from that of the hierarchical control. In the later one, every PV in one group is connected with a center controller that sends and collects the information of PVs. However, in the control to be proposed later, the PVs share information with their neighbors and the CNs are local and can be designed in a redundant way. Thus, it follows the network control theory that this type of control is more robust with respect to the CNs [13], [14].

Under the proposed control scheme, every PV group can be considered as a virtual generator of large capacity and the output of the generator can be dispatched according to the power network. Consequently, the utilization profile for all the PVs in a group will be determined according to specific needs. In this paper, the objective is the fair utilization profile which makes the PVs operate at an identical reserve ratio, which is fair for all the PVs.

To achieve the fair utilization for all PVs, the reserve ratio, similar to the definition of spinning reserve ratio of the traditional generator, is defined as:

\[
\beta_i = 1 - \frac{P_i}{P_{i,\text{max}}} \quad (1 = 1, 2, \ldots, n)
\]

where the subscript “i” denotes the \( i \)th PV; \( P_i \) and \( P_{i,\text{max}} \) are the active power and the maximum available power under the current environment condition, respectively.

Note that the maximum available power of a PV is related to the irradiance, so the reserve ratio is also related to the irradiance. However, it is much difficult to obtain the reserve ratio since it is difficult to calculate the maximum power for a PV, which is one of the main shortcomings in the algorithm of [10]. For this problem, a method will be used to estimate this variable by considering the specific output characteristic of a PV. The details will be discussed in Section III.

Considering the definition of the reserve ratio, the fair issue of the PVs means that each PV operates at identical reserve ratio, i.e., at the equilibrium there is:

\[
1 - \frac{P_i}{P_{i,\text{max}}} = \ldots = 1 - \frac{P_n}{P_{n,\text{max}}} = 1 - \alpha_0 = \beta_0 \quad (2)
\]

where \( \beta_0 \) is a given command of reserve ratio related to the total required active power output of the PVs (it is used to provide the power regulation service to be discussed in the next problem).

Thus, one of the problems to be solved in this paper is:

Problem 1: Design a distributed control strategy such that each PV operates at an identical reserve ratio.

Clearly, this problem is indeed a consensus problem, which makes the PVs have the same reserve ratio, so the method from the network control theory can be used [9]. That is to say, a PV needs to communicate with its neighbors, as shown in Fig. 1, so the control strategy of a PV has the following type:

\[
\beta_i = w_i (s_{i0}y_0, s_{i1}y_1, s_{i2}y_2, \ldots, s_{im}y_n) \quad (3)
\]

where \( y_0 \) denotes the command information from the high level control; \( y_i \) is the output information of the \( i \)th PV; \( s_{ij} \) is the element of the communication matrix \( s \), which represents the real
time communication topology and information flows among the PVs, as follows:

\[
S = \begin{bmatrix}
    s_{11}(t) & s_{12}(t) & \cdots & s_{1n}(t) \\
    s_{21}(t) & s_{22}(t) & \cdots & s_{2n}(t) \\
    \vdots & \vdots & \ddots & \vdots \\
    s_{n1}(t) & s_{n2}(t) & \cdots & s_{nn}(t)
\end{bmatrix} \in \mathbb{R}^{n \times (n+1)}
\] (4)

where \(s_{ii}(t) = 1\) is satisfied for all \(i\); \(s_{ij}(t) = 1\) if the output information of the \(j\)th PV is known to the \(i\)th PV, and \(s_{ij}(t) = 0\) if otherwise; \(s_{ii}(t) = 1\) if the \(i\)th PV can get information from the high level controller and \(s_{ii}(t) = 0\) if otherwise.

It should be noted that \(s_{ii}(t) = 1\) is satisfied for each PV, which means that each PV can acquire its own output information at any time. The nonzero elements in \(i\)th row of matrix \(S\) determine the information exchange conditions of the \(i\)th PV. The existence of information exchange between the high level controller and a group is up to the first column of matrix \(S\). When all elements of the first column are ones, which means all PVs are connected to the high level controller, the control degenerates to the centralized mode. Similarly, when none of the PVs exchanges information with each other and the high level controller, the control is indeed decentralized. Thus, the centralized and decentralized control modes are two special cases of the proposed control schemes. This is the reason why the distributed control strategy has the ability to combine the positive features of both centralized and decentralized mode while limiting their disadvantages.

Once problem 1 is solved, the PVs can operate at an identical reserve ratio. However, the total power output is still unconsidered. This task is finished in the high level controller, which determines the aggregated output of all the PVs according to the power network, thus the virtual power generator can provide the power regulation service for the distribution network. In this paper, the objective is to make the total power of the PVs meet the power demand, which is stated as:

**Problem 2:** Design a control strategy for the high level controller such that the aggregated power of all the PVs satisfies the power requirement within its limit (i.e., the power command should be less than the maximum available power of all the PVs).

Problem 2 means that on the basis of the solution of problem 1, an additional controller is to be designed to make the total power of the PVs equal the power demand, i.e., there is:

\[
P_{\text{out}} = P_0
\] (5)

where \(P_{\text{out}}\) is the total power of the PVs, \(P_0\) is the power demand given by the network operator, which in turn determines the value of \(\beta_0\).

The goal of problem 2 has an underlying condition, i.e., the power command should be less than the maximum available power of all the PVs such that there is a solution to expression (5). Otherwise, it is reasonable to make the aggregated total power output track the maximum available power. At this case, all the reserve ratios defined in (1) for all the PVs are zeros.

In summary, (2) and (5) describe the problems to be solved in this paper. In essence, it is a consensus problem to make \(\beta\) consensus for all PVs while regulating total power to meet the power demand. To this end, a centralized controller is generally needed to collect the output of each PV to acquire the total power, i.e.,

\[
P_{\text{out}} = \sum_{i=1}^{n} P_i
\] (6)

Expression (6) implies that the measurement of the total power needs the global information, so the global CN is needed unless there is an easy way to get the value. For example, as discussed in [10], for a radial network, the total power can be measured from a point of common coupling (PCC). In this paper, the proposed control strategy will overcome the shortcoming and the details will be presented in Section III.

Once the solutions to the two problems are found, all PVs are organized into several groups, and within each group the PVs have the same reserve ratio. Furthermore, the aggregated output of the groups can be dispatched according to the necessary ancillary services.

### III. DISTRIBUTED CONTROL STRATEGY

#### A. Control Strategy for Fair Utilization and Dispatch Demand

Note that the concept of the reserve ratio is used for power regulation, thus the responses of power converters of the PVs are much faster than those of the consensus control strategy. Therefore, we assume the model for the PVs can be approximated by an inertial link, i.e., the dynamics of the \(i\)th PV can be expressed by:

\[
T_i \beta_i = -\beta_i + \beta_i^{rF}
\] (7)

\[
y_k = P_i
\] (8)

where \(\beta_i^{rF}\) is the reference value of \(\beta_i\), which is also the input signal; \(T_i\) is the approximated inertia time constant.

To make the consensus of all PVs within a group, it follows from (3) that the control for the \(i\)th PV is:

\[
\beta_i^{rF} = u_i(D_{i}y_0, \ldots, D_{i}y_i, \ldots)
\] (9)

where \(u_i\) is the input signal to generate the reference reserve ratio \(\beta_i^{rF}\), and \(D_{ij}\) is defined as

\[
D_{ij} = \frac{s_{ij}}{n} \sum_{j=0}^{n} s_{ij}, \quad i = 1, 2, \ldots, n
\] (10)

where \(s_{ij}\) is the entries of the communication matrix defined in (4).

To achieve the objectives shown in (2) and (5), it follows from the network control theory that the control law of the \(i\)th PV is chosen to be [9], [10]:

\[
u_i = K_0 \left[ -\beta_i + D_{i0}\beta_0 + \sum_{j=1}^{n} D_{ij}\beta_j \right] + \beta_i
\] (11)
where $K_P > 0$ is a given gain.

In problem 2, the total output of the PVs should be allocated to satisfy the relationship in (5). To solve it, the control is given in Fig. 2 and its dynamical equation can be written as:

$$\dot{\beta}_i K_P (P_0 - P_{out})$$  \hspace{1cm} (12)$$

where $K_P > 0$ is the given gain.

One of the conditions, which make the proposed control strategy effective, is that the communication topology must have a global node. Simply speaking, it is to guarantee that every node of the communication topology can communicate with the high level controller either directly or indirectly. Thus, there is at least one PV directly connected to the high level control in a valid CN. The conditions of the CN will be further discussed later in this section.

The PVs directly connecting with the high level controller are called the leaders and the others are the followers. Thus, in a group, say the “ith group,” if there are $N_i$ PVs, i.e.,

$$\sum_{i=1}^{m} N_i = n.$$ and there exists some $j \in \{1, 2, \ldots, N_i\}$ such that the jth PV is connected with the high level controller. Without loss of any generality, we assume No. $N_i$ PV is the leader in the ith group. In order to calculate the total power of the PVs in a group by distributed and local CNs, the following iteration is used via some introduced auxiliary variables $w_{ij}$ [15]:

$$w_{ij}(k+1) = w_{ij}(k) + P_{ij}, \quad j = 2, 3, \ldots, N_i$$

$$w_{ij}(k+1) = P_{ij}$$  \hspace{1cm} (13)

$$w_{ij}(k+1) = P_{ij}$$  \hspace{1cm} (14)

where $P_{ij}$ is the output of the jth PV in the ith group; $k = 0, 1, 2, \ldots$, is the index of the iteration.

For the ith group, $w_{iN_i}$ will converge to the total power of this group (the proof can be easily checked from the network control theory), i.e., $w_{iN_i}(k) \rightarrow \sum_{j=1, 2, \ldots, N_i} P_{ij}$ as $k$ is large enough.

On the other hand, if the dynamics of the iteration algorithm are much faster than those of the proposed consensus algorithm, the total power $P_{out}$ can be calculated by

$$P_{out} = \sum_{i=1}^{m} \sum_{j=1}^{N_i} P_{ij} = \sum_{i=1}^{m} w_{iN_i}.$$  \hspace{1cm} (15)

Thus, it can be assumed that the total power has already been obtained when the required reserve ratio $\beta_0$ is updated along the control strategy. The structure of the above algorithm is shown in Fig. 3.

In the above algorithm the total power output is obtained in a distributed way via local information, so the collection of the global information by a centralized station is avoided in the proposed strategy. Also note that in each group only the information of one PV is directly transmitted to the high level controller, but the cumulative effect via iteration is the same as that in the centralized control. Similarly, if the same skills are used for the $m$ groups as those for the PVs within one group, then only one group is enough to connect with the high level controller. Moreover, if the high level controller is embedded in the controller of some PVs within one group, then the whole control scheme for all the PVs is nearly center free, i.e., there is no centralized station which collects the output of each PV and sends the power command to each PV, and the task that the centralized control with global CNs could finish can also be finished by local CNs. However, we generally set several groups (or several PVs within one group) as the leaders to connect with the high level controller in order to improve the robustness of the CNs and the convergence rate of the iteration algorithm.

### B. Estimation Method for the Maximum Available Power of PVs

In the given control law, $P_{1, \text{max}}$ must be known in advance when to calculate the $\beta_i$. This is a difficult task since the parameters of PV panels are difficult to be obtained in real-time (e.g., several complicated methods are utilized in [16], [17] and the references therein). In fact, this problem is also one of the shortcomings of the approach in [10]. Considering the output characteristic of a PV panel has some specifics, a simple method is given to estimate the maximum available power. The basic idea is as follows:

For a PV, the voltage-power (U-P) and the maximum power characteristic curve (MPCC) are shown in Fig. 4. On the U-P curve, the current operating point of PV panel is $U_i$, where $U_i$ is the output voltage of the PV panel. The operating point, corresponding to the maximum power, is denoted by $P_{i, \text{max}}$, which is also the intersection point of the U-P curve and the MPCC.

As shown in Fig. 4, the rising part of the U-P curve is almost linear [16], [18], so there is:

$$1 - \beta_i = \frac{P_i}{P_{i, \text{max}}} \approx \frac{U_i}{U_{i, \text{max}}}$$  \hspace{1cm} (15)
Since the MPCC can be obtained in advance (similar to the maximum power curve set in wind turbines), the curve can be assumed to be known and it is expressed as follows:

\[ P_i = M_p(U_i) \]  

(16)

where \( M_p(\cdot) \) is the function denoting the MPCC of PV.

As found in Fig. 4, there exists an intersection point (denoted by “C”) of the line OA and the MPCC. Since the line OA is an approximation of the real U-P curve, the point C can be used for the estimation of the maximum power point. Substituting (15) into (16), the given power curve under certain \( \beta_i \) can be denoted by:

\[ P_{\text{in}} = M_p\left(\frac{U_i}{1 - \beta_i}\right) \]  

(17)

The expression (17) shows that the \( P_{\text{in}} \) can be calculated by an additional parameter (the MPCC). The simulation in the next section shows that the estimation error is acceptable, which proves the feasibility of the approximation method. Note that the MPCC is also related to the temperature, so there are a set of curves with different temperature. Fortunately, the temperature changes very slowly, so we can measure the temperature and update the MPCC in a long time interval. Also note that the proposed estimation method is suitable under the assumption that the PV operates at the rising part of the U-P curve. However, there are some advantages if the operation point is at the declining part (right side of the U-P curve). For example, the larger slope of the declining part means the faster response speed. For this case, the estimation method is more complex. More discussion can be found in [3].

Moreover, considering that the traditional double-loop based control is generally used in the inverters of the PVs, it follows from (11), (12) and (17) that the whole control for the \( i \)th PV can be designed as that in Fig. 5, which can be realizable from a practical perspective.

**C. Stability Analysis of the Closed-Loop System**

The proposed control strategy shown in Fig. 5 can be intuitively explained as follows: If the total power \( P_{\text{in}} \) is lower than the command \( P_0 \), it will decrease \( \beta_0 \) and send the command to some PVs to decrease their reserve ratios. Other PVs will converge to the same ratio under the proposed consensus strategy. Thus, the decrease of \( \beta_0 \) results in an increase of \( P_{\text{out}} \) till the total power meets the requirement of the power network.

From the theory of network control, whether the PVs under the proposed control can be consensus and asymptotically stable is determined by the CNs among the PVs. The details of the proof can also be found in our recent work [11]. Specifically, the PVs can be consensus if the communication topology is complete [9], [10]. That is to say, the graph denoting the CNs among the PVs within a group has at least one global node. It also means that all other nodes can acquire the information of the global node through the directed branches of the graph. More details can be founded in [9]. Moreover, the completeness of the CNs also implies that every PV is connected to its neighbors, so the CNs are also valid for calculating the total power \( P_{\text{out}} \) in a distributed way by the algorithm described by (13) and (14).

It should also be noted that the convergence rate of the closed-loop system is related to connectivity of the CN. Generally, more communication channels mean faster convergence rate, but also result in higher costs. So it is important to design some reasonably CNs to make a good compromise between the completeness and the economic issue, which is also one of our future work.

**IV. Numerical Simulation**

In this section, the standard IEEE 123-bus distribution system is used to verify the validity of the center free control strategy. The main voltage of the network is 4.16 kV and its topology is shown in Fig. 6.

Suppose that there are two PV farms connected to the power network and each farm includes five PVs (PV1-PV5 and PV6-PV10, respectively). The initial states of the power flow are as follows:

- PVs: 2 MW + 0.15 Mvar (\( \cos \phi \approx 1 \))
- Loads: 3.55 MW + 1.55 Mvar (\( \cos \phi \approx 0.92 \))
- External grid: An infinite bus (1.0 p.u.);

The communication network among those PVs is denoted by \( s \) in (18), where \( G_i \) denotes the \( i \)th PV generator.
The parameters used in the proposed control strategy are as follows:

In the consensus control, the coefficients used in (11) and (12) for all the PVs are $K_0 = 8$ and $K_p = 1$; the transfer functions of the outer loop PI and the inner loop PI are 2 and 1, respectively; the MPCC of the PVs is expressed by (19) and the temperature is supposed to be 25°C.

It can be verified from (18) that communication matrix satisfies the completeness condition because in every group the second PV can be considered to be the global node. In addition, each PV farm has two channels for receiving the information from the high level controller, i.e., ($G_1$, $G_2$) and ($G_6$, $G_7$). To validate the proposed method, two kinds of disturbances are to be studied: 1) changes of the total power command; 2) changes of the irradiance of some PVs.

### A. Dynamic Response to Changes in $P_0$

The expected disturbance is that the power command $P_0$ decreases by 20% at 0 s, and increases by 30% at 6.0 s, then increases again by 25% at 11 s.

The dynamical response of the two PV farms' reserve ratios are plotted in Fig. 7. In this figure, the subfigure (a) shows that the consensus control makes the reserve ratios of each PV farm converge to a desired constant (at which the fair utilization of all PVs is satisfied and thus it is a solution to the problem 1), even the high level controller does not send the command signal to each PV, e.g., send the signal to PV3 and PV8. Fig. 7(b) shows that the total power can track the command well, implying that the $P_m$ is a solution to the problem 2. Consequently, the two PV farms can be considered to be an aggregated virtual dispatchable generator, which is friendly to the power network.

It should also be noted that when the power command is increased to 2 MW (8.0 p.u., as shown in the subfigure (b) in Fig. 7) at the 11 s, the aggregated power output of the two PV farms can not track the power command. The abnormal results are because that the maximum available power of the two PV farms is smaller than the required one. In this case, the reserve ratios are reasonably reduced to 0, as shown in the subfigure (a) in Fig. 7, which should be a useful signal to system operator that the virtual generator arrives on its maximum power.

To study the method for estimating the PV’s maximum available power, we plot the error between the actual maximum available power and its estimated value. The result is shown in Fig. 7(c). It can be observed from this figure that the estimated power is almost equal to the maximum available power under current conditions in the steady-state. Even during the dynamical process, the error is less than 5%. Thus, the maximum
available power can be estimated well by the proposed method, which avoids the complicated calculation.

Moreover, it follows from the communication matrix shown in (18) that there is no direct information exchange between the two PV farms. In other words, the two farms are weakly coupled. If we change the communication topology by changing $S(5,8)$ and $S(10,3)$ from 0 to 1, which means the coupling between the two farms is strengthened, the corresponding reserve ratio of PV10 and the total power output are shown in Fig. 8. It follows from the figure that under the strong coupling CNs, the system has faster convergence rate than that under the weak one. However, it needs investments on these additional communication links.

B. Dynamic Responses to Changes of Irradiance

Suppose that the initial condition of every PV farm is the same. The disturbance is considered as follows: The irradiance in PV farm 1 (i.e., PV1-PV5) increases by 15% at 0 s and decreases by 25% at 8.0 s. Meanwhile, the irradiance in PV farm 2 (i.e., PV6-PV10) decreases by 10% at 0 s and increases by 20% at 8.0 s.

The corresponding responses under the change of the irradiance are plotted in Figs. 9 and 10, where the real and dash curves are the results of the first and the second PV farms, respectively.

It can be observed from Fig. 9 that when the irradiance of PV farm 1 increases, the corresponding maximum available power of the PVs in farm 1 also rises. According to the fair utilization control strategy, the larger maximum available power implies that the PVs from PV1 to PV5 should make more contribution to $P_r$ than that in farm 2. So the output of PVs in farm 1 increases and the output of farm 2 decreases. Similarly, when the irradiance reduces, the relevant responses are opposite to the above processes.

Moreover, it follows from Fig. 10(a) that the total power can track the required power. Thus, the trajectories of the closed-loop system converge to the solution of problem 2 under the proposed control strategy. Meanwhile, it follows from Fig. 10(b), in which the maximum available power and the corresponding estimation value of PV1 are plotted during the transient process, where the error between the actual available maximum power and its estimated value is negligible in the steady state and is also small during the transient. Thus, the proposed estimation method for the maximum available power of PV is useful.
V. Conclusion

An improved distributed control strategy is proposed for the power settings of a large number of PVs in a power network. The proposed strategy guarantees both fair utilization of the PVs and the requirement of the aggregated power. It is also nearly center free since all the steps in the control strategy can be realized on the basis of local CNs, including the calculation of the aggregated power of PVs and the consensus algorithm among the PVs. Simulations on the IEEE standard 123-bus distribution system validate the features and effectiveness of the proposed control strategy. Future studies will focus on the optimization method for the design of robust and economic CNs.

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Abstract—Coordinated regulation for the outputs from renewable energy sources is an appealing issue in future smart grid. This paper presents a distributed control strategy for multiple photovoltaic generators (PVs), which makes all the PVs have the same reserve ratio with respect to their maximum available power, but also makes their aggregated output support power network by providing power regulation service within the power limit. In addition, an estimation method is proposed to get the maximum available power of PV. The proposed control strategy is nearly center-free, i.e., there is no centralized station which collects the output of each PV and sends the power command to each PV, and only uses local communication networks (CNs) to avoid expensive sometimes unreliable, long distance communications. Simulation results based on the IEEE standard 123-bus distribution system are presented and discussed, illustrating the effectiveness of the proposed control strategy.

Index Terms—Communication network, distributed control, network control, photovoltaic, virtual power plant.

I. INTRODUCTION

C ompared with conventional energy sources, solar energy has the characteristics of low environmental costs, renewability and worldwide distribution, so it can be expected that there will be more and more photovoltaic generators (PVs) in the future. However, the introduction of a large number of PVs could have negative effects on power networks if the PVs cannot provide adequate technical support. Consequently, as the penetration level of PV rises, it is more and more difficult for the power network to keep the required level of stability and security, especially in a weak power network in which traditional synchronous generators have not enough capacity for power regulation. Therefore, in current or future grids with high penetration of PVs, it is necessary, for the PVs’ output to be coordinately controlled to provide some ancillary services such as the load smoothing and the secondary control [1]–[3]. This paper focuses on how to implement a control algorithm to adjust the total output of all PVs in a distribution network in real-time when only one or a small part of PVs receive a command signal that is intended to adjust the total power of all PVs. However, the formulation of the command signal in real-time according to the power system is out of the scope of the paper.

Different schemes can be applied to solve the above coordination control problem. Firstly, a centralized control strategy can be used when the number of the PVs is not large. For example, methods similar to traditional centralized automatic generator control can be used in distribution networks with several distributed generators (DGs) [4], [5]. However, under such scheme, the nature of centralized control requires a CN connecting the central controller to each PV, and the output of each PV needs be transmitted to the centralized controller in real-time. This scheme is based on an assumption of a global system-wide information structure. However, for a power network having a large number of geographically dispersed PVs, a centralized control scheme with the required information structure is often too expensive to be implemented and it is inflexible for the realization of “plug and play” characteristic.

The second scheme is decentralized, which has wide applications in power engineering. For example, the maximum power point tracking algorithm, the constant voltage and frequency droop control, etc. [6]–[8]. Decentralized control is inherently robust since the control is only based on local information. However, as the penetration level of PVs increases, it is difficult for such a decentralized scheme to control and dispatch the PVs’ output to support some ancillary services, such as the smoothing of load change and secondary frequency control. Thus, these services will mainly rely on the traditional synchronous generators, which is difficult in a weak power network.

Thirdly, it is known that a distributed control scheme can combine the positive features of both centralized and decentralized controls while limiting their disadvantages [9]. Not like a centralized controller communicating with every PV in the system, a controller under a distributed control scheme sends commands to a part of the PVs and each PV shares its own information with some of its neighboring units. This scheme is proposed in [10]. Through an iteration way, the final output of the PVs will have the same values as those of a centralized control. The convergence property under some adverse conditions such as intermittent communication is provided in [11], showing this distributed scheme is very robust. Similar idea was presented for DGs in [12], where the DGs are controlled to have the same incremental cost. The advantages of these methods are: 1) only local CNs are used, and 2) they don’t need to change the algorithm even there is a disconnection or a new connection of any PV (or DG), such that the “plug and play” characteristic can be easily implemented. One of the disadvantages, however, is that there must have a common point where the total power of
the PVs (or DGs) can be measured easily. Therefore this is only applicable to radial power networks. Moreover, to achieve the consensus of the utilization of all the PVs, the maximum available power of each PV needs to be known in advance, which is an uneasy task in practice.

Motivated by these, an improved distributed control strategy is presented in this paper, which makes the usage of all PVs equal and makes their total output achieve to a given value quickly. Thus, the PVs can constitute a virtual power plant and the ancillary services such as the secondary control can be realized. One feature of the work is that the proposed strategy is nearly center free, i.e., there is no centralized station which collects the output of every PV and sends the power command to every PV. Another feature is that the maximum available power of each PV used in the control strategy is estimated by considering the output characteristic of the PVs, thus the direct measurement or calculation is avoided.

The paper is organized as follows. In Section II, the problem of the coordination of PVs’ output is formulated. The distributed control strategy for the PVs is provided in Section III. The numerical simulations based on the benchmark 123-bus system are provided in Section IV and conclusions are drawn in Section V.

II. PROBLEM DESCRIPTION

Assume there are \( n \) PVs in a power network. For the coordination of the PVs, the main objective of the paper is to develop a distributed control shown in Fig. 1. In this figure, all the PVs in the power network are deliberately classified into \( m \) groups and each group is aggregated to a virtual power plant of large capacity. There is a CN which connects a high level controller and the PV groups. Within each group of PVs, the PVs self-organize themselves through local CNs by sharing information among their neighbors. The PVs within each group are guided by a high level control (which can be a virtual control embedded in one or several groups) to provide the necessary services, such as the power regulation considered in this work. However, the formulation of the high level control according to power network is out of the scope of the paper.

Note that the control structure that we are interested in is different from that of the hierarchical control. In the later one, every PV in one group is connected with a center controller that sends and collects the information of PVs. However, in the control to be proposed later, the PVs share information with their neighbors and the CNs are local and can be designed in a redundant way. Thus, it follows the network control theory that this type of control is more robust with respect to the CNs [13], [14].

Under the proposed control scheme, every PV group can be considered as a virtual generator of large capacity and the output of the generator can be dispatched according to the power network. Consequently, the utilization profile for all the PVs in a group will be determined according to specific needs. In this paper, the objective is the fair utilization profile which makes the PVs have the same reserve ratio. The reason using the fair utilization is as follows: All investors of PV farms want to generate more power to recover the fund, but the total amount is limited by the power grid. So the same output ratio for each PV is an easy and practical way to achieve the fair issue and balance the requirements of all the PV farms investors. That is to say, the proposed control scheme is designed to make the PVs in a group to operate at an identical output ratio, which is fair for all the PVs.

To achieve the fair utilization for all PVs, the reserve ratio, similar to the definition of spinning reserve ratio of the traditional generator, is defined as:

\[
\beta_i = 1 - \frac{P_i}{P_{i,\text{max}}} \quad (1 - 1, 2, \ldots, n) \quad (1)
\]

where the subscript “\( i \)” denotes the \( i \)th PV; \( P_i \) and \( P_{i,\text{max}} \) are the active power and the maximum available power under the current environment condition, respectively.

Note that the maximum available power of a PV is related to the irradiance, so the reserve ratio is also related to the irradiance. However, it is much difficult to obtain the reserve ratio since it is difficult to calculate the maximum power for a PV, which is one of the main shortcomings in the algorithm of [10]. For this problem, a method will be used to estimate this variable by considering the specific output characteristic of a PV. The details will be discussed in Section III.

Considering the definition of the reserve ratio, the fair issue of the PVs means that each PV operates at identical reserve ratio, i.e., at the equilibrium there is:

\[
1 - \frac{P_i}{P_{i,\text{max}}} = \ldots = 1 - \frac{P_n}{P_{n,\text{max}}} = 1 - \alpha_0 = \beta_0 \quad (2)
\]

where \( \beta_0 \) is a given command of reserve ratio related to the total required active power output of the PVs (it is used to provide the power regulation service to be discussed in the next problem).

Thus, one of the problems to be solved in this paper is:

**Problem 1:** Design a distributed control strategy such that each PV operates at an identical reserve ratio.

Clearly, this problem is indeed a consensus problem, which makes the PVs have the same reserve ratio, so the method from the network control theory can be used [9]. That is to say, a PV needs to communicate with its neighbors, as shown in Fig. 1, so the control strategy of a PV has the following type:

\[
\beta_i = w_i \left( s_{10}y_0, s_{11}y_1, s_{12}y_2, \ldots, s_{1n}y_n \right) \quad (3)
\]

where \( y_0 \) denotes the command information from the high level control; \( y_i \) is the output information of the \( i \)th PV; \( s_{ij} \) is the element of the communication matrix \( s \), which represents the real
time communication topology and information flows among the PVs, as follows:

\[
S = \begin{bmatrix}
  s_{10}(t) & s_{11} & \cdots & s_{1n}(t) \\
  s_{20}(t) & s_{21} & \cdots & s_{2n}(t) \\
  \vdots & \vdots & \ddots & \vdots \\
  s_{n0}(t) & s_{n1}(t) & \cdots & s_{nn}(t)
\end{bmatrix} \in \mathbb{R}^{n \times (n+1)}
\]  

(4)

where \( s_{ij}(t) = 1 \) is satisfied for all \( i \); \( s_{ij}(t) = 1 \) if the output information of the \( j \)th PV is known to the \( i \)th PV, and \( s_{ij}(t) = 0 \) if otherwise; \( s_{ii}(t) = 1 \) if the \( i \)th PV can get information from the high level controller and \( s_{ii}(t) = 0 \) if otherwise.

It should be noted that \( s_{ii}(t) = 1 \) is satisfied for each PV, which means that each PV can acquire its own output information at any time. The nonzero elements in \( i \)th row of matrix \( S \) determine the information exchange conditions of the \( i \)th PV. The existence of information exchange between the high level controller and a group is up to the first column of matrix \( S \). When all elements of the first column are ones, which means all PVs are connected to the high level controller, the control degenerates to the centralized mode. Similarly, when none of the PVs exchanges information with each other and the high level controller, the control is indeed decentralized. Thus, the centralized and decentralized control modes are two special cases of the proposed control schemes. This is the reason why the distributed control strategy has the ability to combine the positive features of both centralized and decentralized mode while limiting their disadvantages.

Once problem 1 is solved, the PVs can operate at an identical reserve ratio. However, the total power output is still unconsidered. This task is finished in the high level controller, which determines the aggregated output of all the PVs according to the power network, thus the virtual power generator can provide the power regulation service for the distribution network. In this paper, the objective is to make the total power of the PVs meet the power demand, which is stated as:

\[
P_{out} = \sum_{i=1}^{n} P_i
\]

(6)

Expression (6) implies that the measurement of the total power needs the global information, so the global CN is needed unless there is an easy way to get the value. For example, as discussed in [10], for a radial network, the total power can be measured from a point of common coupling (PCC). In this paper, the proposed control strategy will overcome the shortcoming and the details will be presented in Section III.

Once the solutions to the two problems are found, all PVs are organized into several groups, and within each group the PVs have the same reserve ratio. Furthermore, the aggregated output of the groups can be dispatched according to the necessary ancillary services.

III. DISTRIBUTED CONTROL STRATEGY

A. Control Strategy for Fair Utilization and Dispatch Demand

Note that the concept of the reserve ratio is used for power regulation, thus the responses of power converters of the PVs are much faster than those of the consensus control strategy. Therefore, we assume the model for the PVs can be approximated by an inertial link, i.e., the dynamics of the \( i \)th PV can be expressed by:

\[
T_i \beta_i = -\beta_i + \beta_i^{ref} \\
y_i = P_i
\]

(7)

(8)

where \( \beta_i^{ref} \) is the reference value of \( \beta_i \), which is also the input signal; \( T_i \) is the approximated inertia time constant.

To make the consensus of all PVs within a group, it follows from (3) that the control for the \( i \)th PV is:

\[
\beta_i^{ref} = u_i(D_{ij}y_i, \ldots, D_{ij}y_i, \ldots)
\]

(9)

where \( u_i \) is the input signal to generate the reference reserve ratio \( \beta_i^{ref} \), and \( D_{ij} \) is defined as

\[
D_{ij} = \frac{s_{ij}}{\sum_{j=0}^{n} s_{kj}}, \quad i = 1, 2, \ldots, n
\]

(10)

where \( s_{ij} \) is the entries of the communication matrix defined in (4).

To achieve the objectives shown in (2) and (5), it follows from the network control theory that the control law of the \( i \)th PV is chosen to be [9], [10]:

\[
u_i = K_0 \left[ -\beta_i + D_{ij} \beta_j + \sum_{j=1}^{n} D_{ij} \beta_j \right] + \beta_i
\]

(11)
where $K_f > 0$ is a given gain.

In problem 2, the total output of the PVs should be allocated to satisfy the relationship in (5). To solve it, the control is given in Fig. 2 and its dynamical equation can be written as:

$$\dot{\beta}_0 K_f (P_0 - P_{out})$$

where $K_f > 0$ is the given gain.

One of the conditions, which make the proposed control strategy effective, is that the communication topology must have a global node. Simply speaking, it is to guarantee that every node of the communication topology can communicate with the high level controller either directly or indirectly. Thus, there is at least one PV directly connected to the high level control in a valid CN. The conditions of the CN will be further discussed later in this section.

The PVs directly connecting with the high level controller are called the leaders and the others are the followers. Thus, in a group, say the “ith group,” if there are $N_i$ PVs, i.e.,

$$\sum_{i=1}^{m} N_i = n,$$

and there exists some $j \in \{1, 2, \ldots, N_i\}$ such that the $j$th PV is connected with the high level controller. Without loss of any generality, we assume No. $N_i$ PV is the leader in the ith group.

In order to calculate the total power of the PVs in a group by distributed and local CNs, the following iteration is used via some introduced auxiliary variables $w_{ij}$ [15]:

$$w_{ij}(k+1) = w_{i(j-1)}(k) + P_{ij}, \quad j = 2, 3, \ldots, N_i$$

$$w_{ij}(k+1) = P_{ij}$$

where $P_{ij}$ is the output of the $j$th PV in the $i$th group; $k = 0, 1, 2, \ldots$, is the index of the iteration.

For the $i$th group, $w_{iN_i}$ will converge to the total power of this group (the proof can be easily checked from the network control theory), i.e., $w_{iN_i}(k) \rightarrow \sum_{j=1}^{i} \ldots N_i - P_j$ as $k$ is large enough. On the other hand, if the dynamics of the iteration algorithm are much faster than those of the proposed consensus algorithm, the total power $P_{out}$ can be calculated by

$$P_{out} = \sum_{i=1}^{m} \sum_{j=1}^{N_i} P_j = \sum_{i=1}^{m} \sum_{j=1}^{N_i} w_i N_j,$$

Thus, it can be assumed that the total power has already been obtained when the required reserve ratio $\beta_i$ is updated along the control strategy. The structure of the above algorithm is shown in Fig. 3.

In the above algorithm the total power output is obtained in a distributed way via local information, so the collection of the global information by a centralized station is avoided in the proposed strategy. Also note that in each group only the information of one PV is directly transmitted to the high level controller, but the cumulative effect via iteration is the same as that in the centralized control. Similarly, if the same skills are used for the $m$ groups as those for the PVs within one group, then only one group is enough to connect with the high level controller. Moreover, if the high level controller is embedded in the controller of some PVs within one group, then the whole control scheme for all the PVs is nearly center free, i.e., there is no centralized station which collects the output of each PV and sends the power command to each PV, and the task that the centralized control with global CNs could finish can also be finished by local CNs. However, we generally set several groups (or several PVs within one group) as the leaders to connect with the high level controller in order to improve the robustness of the CNs and the convergence rate of the iteration algorithm.

### B. Estimation Method for the Maximum Available Power of PVs

In the given control law, $P_{i\text{max}}$ must be known in advance when to calculate the $\beta_i$. This is a difficult task since the parameters of PV panels are difficult to be obtained in real-time (e.g., several complicated methods are utilized in [16], [17] and the references therein). In fact, this problem is also one of the shortcomings of the approach in [10]. Considering the output characteristic of a PV panel has some specifics, a simple method is given to estimate the maximum available power. The basic idea is as follows:

For a PV, the voltage-power (U-P) and the maximum power characteristic curve (MPCC) are shown in Fig. 4. On the U-P curve, the current operating point of PV panel is $A(U_i, P_i)$, where $U_i$ is the output voltage of the PV panel. The operating point, corresponding to the maximum power, is denoted by $B(U_{i\text{max}}, P_{i\text{max}})$, which is also the intersection point of the U-P curve and the MPCC.

As shown in Fig. 4, the rising part of the U-P curve is almost linear [16], [18], so there is:

$$1 - \beta_i = \frac{P_i}{P_{i\text{max}}} \approx \frac{U_i}{U_{i\text{max}}}$$

where $\beta_i$ is the required reserve ratio, $P_i$ and $U_i$ are the output power and voltage of the PV panel, respectively.
Since the MPCC can be obtained in advance (similar to the maximum power curve set in wind turbines), the curve can be assumed to be known and it is expressed as follows:

$$P_i = M_p(U_i)$$  \hspace{1cm} (16)

where $M_p(U_i)$ is the function denoting the MPCC of PV.

As found in Fig. 4, there exists an intersection point (denoted by “C”) of the line OA and the MPCC. Since the line OA is an approximation of the real U-P curve, the point C can be used for the estimation of the maximum power point. Substituting (15) into (16), the given power curve under certain $\beta_i$ can be denoted by:

$$P_{i,max} = M_p \left( \frac{U_i}{1 - \beta_i} \right)$$  \hspace{1cm} (17)

The expression (17) shows that the $P_{i,max}$ can be calculated by an additional parameter (the MPCC). The simulation in the next section shows that the estimation error is acceptable, which proves the feasibility of the approximation method. Note that the MPCC is also related to the temperature, so there is a set of curves with different temperatures. Fortunately, the temperature changes very slowly, so we can measure the temperature and update the MPCC in a long time interval. Also note that the proposed estimation method is suitable under the assumption that the PV operates at the rising part of the U-P curve. However, there are some advantages if the operation point is at the declining part (right side of the U-P curve). For example, the larger slope of the declining part means the faster response speed. For this case, the estimation method is more complex. More discussion can be found in [3].

Moreover, considering that the traditional double-loop based control is generally used in the inverters of the PVs, it follows from (11), (12) and (17) that the whole control for the $i$th PV can be designed as that in Fig. 5, which can be realizable from a practical perspective.

C. Stability Analysis of the Closed-Loop System

The proposed control strategy shown in Fig. 5 can be intuitively explained as follows: If the total power $P_{out}$ is lower than the command $P_{0i}$, it will decrease $\beta_i$ and send the command to some PVs to decrease their reserve ratios. Other PVs will converge to the same ratio under the proposed consensus strategy. Thus, the decrease of $\beta_0$ results in an increase of $P_{out}$ till the total power meets the requirement of the power network.

From the theory of network control, whether the PVs under the proposed control can be consensus and asymptotically stable is determined by the CNs among the PVs. The details of the proof can also be found in our recent work [11]. Specifically, the PVs can be consensus if the communication topology is complete [9], [10]. That is to say, the graph denoting the CNs among the PVs within a group has at least one global node. It also means that all other nodes can acquire the information of the global node through the directed branches of the graph. More details can be found in [9]. Moreover, the completeness of the CNs also implies that every PV is connected to its neighbors, so the CNs are also valid for calculating the total power $P_{out}$ in a distributed way by the algorithm described by (13) and (14).

It should also be noted that the convergence rate of the closed-loop system is related to connectivity of the CN. Generally, more communication channels mean faster convergence rate, but also result in higher costs. So it is important to design some reasonably CNs to make a good compromise between the completeness and the economic issue, which is also one of our future work.

IV. NUMERICAL SIMULATION

In this section, the standard IEEE 123-bus distribution system is used to verify the validity of the center free control strategy. The main voltage of the network is 4.16 kV and its topology is shown in Fig. 6.

Suppose that there are two PV farms connected to the power network and each farm includes five PVs (PV1-PV5 and PV6-PV10, respectively). The initial states of the power flow are as follows:

- PVs: 2 MW + 0.15 Mvar ($\cos \varphi \approx 1$)
- Loads: 3.55 MW + 1.55 Mvar ($\cos \varphi \approx 0.92$);
- External grid: An infinite bus (1.0 p.u.);
- The communication network among those PVs is denoted by $s$ in (18), where $G_i$ denotes the $i$th PV generator
(i = 1, 2, ..., 16). The CN is also depicted by the dash lines in Fig. 6.

The parameters used in the proposed control strategy are as follows:

In the consensus control, the coefficients used in (11) and (12) for all the PVs are $K_0 = 8$ and $K_p = 1$; the transfer functions of the outer loop PI and the inner loop PI are $10 + 10/s$ and $5 + 100/s$, respectively; the MPCC of the PVs is expressed by (19) and the temperature is supposed to be $25^\circ$C.

$$S = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_1 \\ 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_2 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_3 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_4 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_5 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & G_6 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & G_7 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & G_8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & G_9 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & G_{10} \end{bmatrix}$$

$$P_{\text{max}}(U_i) = \begin{cases} 0.727U_i , & 0 < U_i \leq 22 \\ 36U_i - 556 , & 22 < U_i \leq 25 \\ 98U_i - 2356 , & 25 < U_i \leq 26 \\ 137U_i - 3370 , & 26 < U_i \leq 28 \\ 466 , & U_i > 28 \end{cases}$$

(18)

(19)

It can be verified from (18) that communication matrix satisfies the completeness condition because in every group the second PV can be considered to be the global node. In addition, each PV farm has two channels for receiving the information from the high level controller, i.e., $(G_1, G_2)$ and $(G_6, G_7)$. To validate the proposed method, two kinds of disturbances are to be studied: 1) changes of the total power command; 2) changes of the irradiance of some PVs.

A. Dynamic Response to Changes in $P_0$

The expected disturbance is that the power command $P_0$ decreases by 20% at 0 s, and increases by 30% at 6.0 s, then increases again by 25% at 11 s.

The dynamical response of the two PV farms’ reserve ratios are plotted in Fig. 7. In this figure, the subfigure (a) shows that the consensus control makes the reserve ratios of each PV farm converge to a desired constant $(\beta_0)$ (at which the fair utilization of all PVs is satisfied and thus it is a solution to the problem 1), even the high level controller does not send the command signal to each PV, e.g., send the signal to PV3 and PV8. Fig. 7(b) shows that the total power can track the command well, implying that the $\beta_0$ is a solution to the problem 2. Consequently, the two PV farms can be considered to be an aggregated virtual dispatchable generator, which is friendly to the power network.

It should also be noted that when the power command is increased to 2 MW (8.0 p.u., as shown in the subfigure (b) in Fig. 7) at the 11 s, the aggregated power output of the two PV farms can not track the power command. The abnormal results are because that the maximum available power of the two PV farms is smaller than the required one. In this case, the reserve ratios are reasonably reduced to 0, as shown in the subfigure (a) in Fig. 7, which should be a useful signal to system operator that the virtual generator arrives on its maximum power.

To study the method for estimating the PV’s maximum available power, we plot the error between the actual maximum available power and its estimated value. The result is shown in Fig. 7(c). It can be observed from this figure that the estimated power is almost equal to the maximum available power under current conditions in the steady-state. Even during the dynamical process, the error is less than 5%. Thus, the maximum
available power can be estimated well by the proposed method, which avoids the complicated calculation.

Moreover, it follows from the communication matrix shown in (18) that there is no direct information exchange between the two PV farms. In other words, the two farms are weakly coupled. If we change the communication topology by changing \( S(5,8) \) and \( S(10,3) \) from 0 to 1, which means the coupling between the two farms is strengthened, the corresponding reserve ratio of PV10 and the total power output are shown in Fig. 8. It follows from the figure that under the strong coupling CNs, the system has faster convergence rate than that under the weak one. However, it needs investments on these additional communication links.

B. Dynamic Responses to Changes of Irradiance

Suppose that the initial condition of every PV farm is the same. The disturbance is considered as follows: The irradiance in PV farm 1 (i.e., PV1-PV5) increases by 15% at 0 s and decreases by 25% at 8.0 s. Meanwhile, the irradiance in PV farm 2 (i.e., PV6-PV10) decreases by 10% at 0 s and increases by 20% at 8.0 s.

The corresponding responses under the change of the irradiance are plotted in Figs. 9 and 10, where the real and dash curves are the results of the first and the second PV farms, respectively.

It can be observed from Fig. 9 that when the irradiance of PV farm 1 increases, the corresponding maximum available power of the PVs in farm 1 also rises. According to the fair utilization control strategy, the larger maximum available power implies that the PVs from PV1 to PV5 should make more contribution to \( P_I \) than that in farm 2. So the output of PVs in farm 1 increases and the output of farm 2 decreases. Similarly, when the irradiance reduces, the relevant responses are opposite to the above processes.

Moreover, it follows from Fig. 10(a) that the total power can track the required power. Thus, the trajectories of the closed-loop system converge to the solution of problem 2 under the proposed control strategy. Meanwhile, it follows from Fig. 10(b), in which the maximum available power and the corresponding estimation value of PV1 are plotted during the transient process, where the error between the actual available maximum power and its estimated value is negligible in the steady state and is also small during the transient. Thus, the proposed estimation method for the maximum available power of PV is useful.
V. CONCLUSION

An improved distributed control strategy is proposed for the power settings of a large number of PVs in a power network. The proposed strategy guarantees both fair utilization of the PVs and the requirement of the aggregated power. It is also nearly center free since all the steps in the control strategy can be realized on the basis of local CNs, including the calculation of the aggregated power of PVs and the consensus algorithm among the PVs. Simulations on the IEEE standard 123-bus distribution system validate the features and effectiveness of the proposed control strategy. Future studies will focus on the optimization method for the design of robust and economic CNs.

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