Consensus-Based Approach for Active Power Control and Reserve Estimation in Distributed PV Systems

Preprint

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Consensus-Based Approach for Active Power Control and Reserve Estimation in Distributed PV Systems

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***Abstract*—With the increased adoption of distributed energy resources (DERs) in power systems, DERs are expected to contribute to power system reliability services and enhance power system stability. This paper presents a distributed consensus control approach for the real-time active power reserve estimation and power management in distributed photovoltaic (PV) systems. The proposed method estimates the cumulative active power reserve from numerous PV generators using only the sparse communication network for a DER aggregator to provide active power regulation services. It also can be used by DER aggregators to manage curtailment in distributed PV systems to maintain stipulated reserves and to provide power system frequency regulation. Using the proposed approach, the DER aggregator requires only measurements at the feeder substation, and it does not require information from individual DER units, thereby improving system resilience. The proposed distributed consensus control method is validated on the IEEE 123-node test bed using PSCAD simulations.**

***Index Terms*—Distributed energy resources, consensus control, PV generators, real-time estimation, active power reserve.**

I. Introduction

Distributed energy resources (DERs)—which can include solar photovoltaics (PV), fuel cells, energy storage systems, electric vehicles (EVs), etc.—are being added to electric grids [1]. For instance [2], Pacific Gas & Electric Company expects to host more DERs, including hundreds of thousands of new PV systems, numerous EVs, and more than 400 MW of behind-the-meter distributed energy storage by 2030 [3]. With the accelerated installation of DERs, it has become urgent to establish strategic controls and communications among DERs to manage power and provide grid reliability services in a collaborative manner. Two DER aggregation projects, with Holy Cross Energy and Stone Edge Farm Estate Vineyards & Winery [1], demonstrated real-world applications where aggregated DERs allow rural microgrids to become virtual power plants and provide grid auxiliary services.

Current centralized control systems work well when there are a limited number of controllable DERs in the system. To host massive amounts of new DERs while maintaining reliable real-time system controls, a distributed and hierarchical control architecture with a sparse communication network is a suitable candidate. As discussed in many works in the literature, the distributed control scheme intends to divide a complex control problem into simple and local agents' consensus over a peer-to-peer communication network. As a result, each distributed controller requires less control complexity and fewer system measurements. It also avoids a single point of failure on the central controller and improves control system reliability [4].

Distributed consensus control of DERs for the frequency and voltage restoration of an islanded microgrid is mostly discussed in the literature [4], [5]. Some papers [6], [7] also used distributed controlled DERs and responsive loads to improve the secondary frequency response of a bulk power system. These papers demonstrate the advantages of using a distributed control architecture in terms of control reliability and scalability. The system regulation performance of a distributed control approach is comparable to that of a centralized control approach; however, several issues need to be resolved to control massive numbers of distributed PV systems in a distribution feeder to fully exploit the PV's potential to provide system auxiliary services.

PV systems have the control flexibility to operate with curtailment and provide operational reserve. To evaluate the capability of a PV system to provide auxiliary services, it is essential to estimate the maximum power point (MPP) of a PV generator during deloaded operation. This function can be achieved for a single PV array [8] or a utility-scale PV plant [9] using irradiance and temperature measurements. Reference [8] experimentally validated the real-time MPP estimation to ensure that sufficient reserved power is available for grid frequency regulation. Different from a centralized PV power plant, behind-the-meter PV generators are generally distributed in a relatively large geographic area; therefore, it is difficult to estimate the cumulative operational reserve of aggregated PV systems. On the other hand, there is no dedicated unit to collect

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system information and measurements from individual PV generators under the distributed control framework. Limited by the sparse communication topology, PV generators can only exchange information with their neighbors. Similarly, the DER aggregator can only send reference values and receive feedback from several selected PV generators that have established communication links; therefore, it is difficult for a DER aggregator to determine the amount of the current operational reserve in a distribution feeder and to control distributed PV generators to deliver the required auxiliary services.

This paper proposes a distributed consensus control with a real-time active power reserve estimator to coordinate the feeder active power control of distributed PV generators. The real-time estimator evaluates the overall PV active power reserve in a distribution feeder, such that the DER aggregator can adjust the deloaded ratio in response to the system power management and frequency regulation requirement. The proposed consensus control method for distributed PV generators is validated on the IEEE 123-node test bed using PSCAD simulations.

II. Distributed Consensus Control of PV Generators

PV generators that are part of the distributed consensus control system are connected by a sparse communication network providing peer-to-peer communications. The communication network can be described by an undirected graph [4]. Denote a_{ij}=a_{ji}=1, if there is a link allowing information to flow between the i^{th} PV generator and the j^{th} PV generator; otherwise, a_{ij}=a_{ji}=0. The italicized i and j represent the i^{th} and the j^{th} PV generator (that participate in distributed control), respectively, in the studied distribution system. For the effective distributed system control, the communication graph should be designed as strongly connected [10].

The consensus control objective of this paper is to balance the deloaded ratios of PV generators and to further adjust the feeder's active power reserve and power consumption accordingly. This can be achieved with a consensus protocol where the control input depends on the difference between in the deloaded ratios between the local PV generator, $P_i/P_{i,\max}$, and the neighboring PV generator, $P_j/P_{j,\max}$. $P_{i,\max}$ and $P_{j,\max}$ are local MPP estimations [8], and P_i and P_j are PV active power outputs. The distributed consensus control protocol for the i^{th} PV generator is given in (1):

$$\dot{P}_{i,\text{ref}} = -k_p \sum_{j=1}^{N} a_{ij} \left(\frac{P_i}{P_{i,\max}} - \frac{P_j}{P_{j,\max}} \right) - g_i \left[\frac{P_i}{P_{i,\max}} - \beta_{\text{ref}} \right] \quad (1)$$

where β_{ref} is the reference value of the PV's deloaded ratio defined by the DER aggregator. k_p represents the consensus control gain, and $P_{i,\text{ref}}$ denotes the active power reference of the i^{th} PV generator. For the i^{th} generator, g_i=1 if it can receive the reference signal from the DER aggregator; otherwise, it is denoted as g_i=0. For N number of PV generators that participate in the system distributed consensus control, at least one PV generator should receive the reference signal, β_{ref}, which means $\sum g_i \geq 1$.

By using the consensus control protocol in (1), the PV generators that participate in the system distributed control can maintain the same deloaded ratio. Even if $P_{i,\max}$ or $P_{j,\max}$ changes because of the variation of solar irradiance, the power output of all PV generators can be adjusted to reconverge to the referenced deloaded ratio. As a result, the deloaded agreement of the PV generators can be maintained and described as in (2):

$$\beta_{\text{ref}} = \frac{P_1}{P_{1,\max}} = \cdots = \frac{P_i}{P_{i,\max}} = \cdots = \frac{P_N}{P_{N,\max}} \quad (2)$$

Rewrite (2), and the reference value of the deloaded ratio, β_{ref}, also can be derived as in (3):

$$\beta_{\text{ref}} = \frac{P_{\text{ref}}}{\sum_{i=1}^{N} P_{i,\max}} \quad (3)$$

where P_{ref} denotes the desired value of the cumulative PV power output. When consensus is reached, and ignoring the feeder's power loss, P_{ref}=$\sum P_i$ holds.

As mentioned in the previous section, the distributed control structure does not have a dedicated centralized unit that has information access to individual PV generators. Each PV generator can access only its own and the neighboring generators' information. Specifically, if a_{ij}=1 and a_{ik}=0, the i^{th} and the j^{th} generators can exchange P_i, P_j, $P_{i,\max}$, and $P_{j,\max}$ (and other system status, if required), whereas the i^{th} and the k^{th} generators cannot exchange any information. Similarly, for PV generators with or without direct communication links with the DER aggregator, if g_i=1 and g_k=0, the aggregator can receive power and estimation feedback, P_i, $P_{i,\max}$, from the i^{th} PV generator but not P_k, $P_{k,\max}$ from the k^{th} PV generator; hence, the cumulative MPP of PV generators, which is also the denominator of the deloaded ratio in (3), cannot be determined under the original distributed consensus control framework. Further, the number of PV generators in a distribution system can also be unknown or varying from the perspective of the DER aggregator because PV users can either opt in or opt out of feeder power management. This results in a DER aggregator being unable to determine how to adjust the PV active power reserve based on the available capacity in response to the requirement for system auxiliary services.

III. Real-time Estimation of Active Power Reserve in Distributed PV Generators

A. *System real-time estimation*

To solve these issues, this section proposes a real-time estimator to evaluate the cumulative PV active power reserve of a distribution system based only on power measurements at the feeder substation. Fig. 1 illustrates a distribution feeder using distributed consensus control with a real-time estimator [11]. Both the red and green circles represent distributed PV generators; the red circles denote PV generators that are physically close to the DER aggregator and can receive

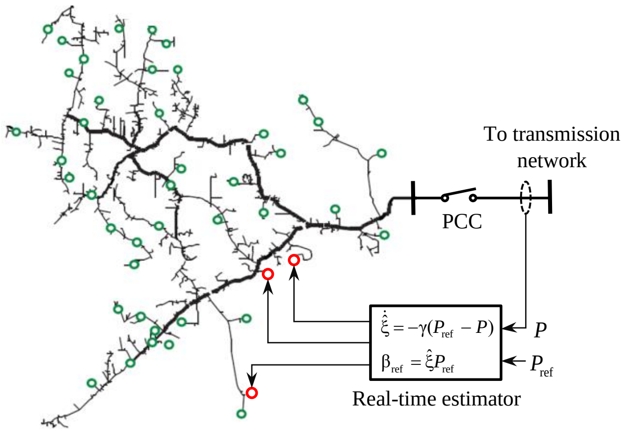

Fig. 1: The framework of the distributed consensus control for PV generators with a real-time estimator [11].

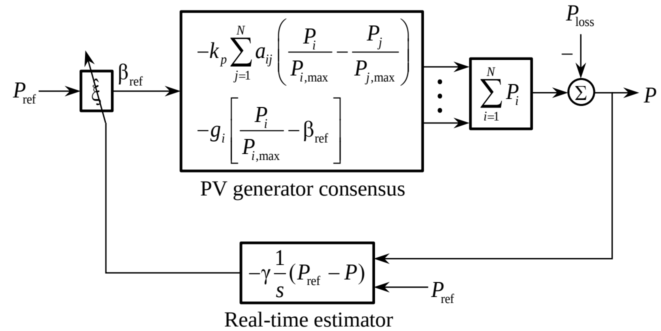

Fig. 2: System diagram of the distributed consensus control considering power line loss.

the reference signal, β_{ref}. The green circles represent PV generators that have no direct communication with the aggregator. Only the communication links between the DER aggregator and selected PV generators are shown in Fig. 1 for simplicity. Denote that ξ and $\hat{\xi}$ are the inverse of the unknown MPP and its estimated value in a feeder, respectively. To accurately determine the deloaded ratio, β_{ref}, for feeder power management and to prepare the system for frequency regulation, the estimated $\hat{\xi}$ should adaptively converge to a real value so that the cumulative PV power output, P, can be adjusted properly. The actual PV power output, P, can be derived as in (4) under real-time estimation:

$$P = \hat{\xi} P_{\text{ref}} \cdot \frac{1}{\xi} \tag{4}$$

Intuitively, an overestimation of the PV active power reserve (overestimation of cumulative MPP) results in less than the required actual power output from the PV generators, so the deloaded ratio, β_{ref}, is adjusted based on the incorrect estimation. Then, the cost function in (5) can be developed to describe the power output error:

$$J = \frac{1}{2}\xi^2 (P - P_{\text{ref}})^2 = \frac{1}{2}(\hat{\xi} P_{\text{ref}} - \xi P_{\text{ref}})^2 \tag{5}$$

To minimize the cost function and to converge the estimated MPP to the real value, the gradient method [12] is used to design the adaptive law. The estimated MPP can be updated according to (6):

$$\dot{\hat{\xi}} = -\gamma (P_{\text{ref}} - P) \tag{6}$$

where parameter γ gives the gain of the adaptive law. As a result, the real-time estimator of (6) can estimate the PV active power reserve of a distribution system. Then, proper β_{ref} can be calculated and distributed by the DER aggregator to adjust the PV cumulative power output, and to further achieve feeder power management.

B. Considering feeder power loss

Because PV generators are generally behind-the-meter sources in a distribution feeder, the cumulative PV power might not be observable considering power line losses. The complete system diagram of distributed consensus control with a real-time estimator is then derived as shown in Fig. 2. The cumulative PV power output, P, measured at the point of common coupling (PCC) is less than the actual power output of the PV generators, $\sum P_i$, because of the existence of the power line losses, P_{loss}, in the distribution system. This issue also can be interpreted as a case where the real-time estimator is overestimating the active power reserve available from the PV generators; therefore, the real-time estimator can adjust the estimated MPP based on the power difference, $P_{\text{ref}} - P$, and automatically exclude P_{loss} from the cumulative MPP. Then the reference PV deloaded ratio, β_{ref}, should be slightly higher than the theoretical calculation responding to the same power management command. In fact, it is beneficial for DER aggregators to estimate the effective active power reserve from the PV generators (excluding P_{loss}) that can be used for system auxiliary services, such as primary frequency regulation.

IV. CASE STUDIES

This section validates the effectiveness of the proposed distributed consensus control with a real-time estimator using a modified IEEE 123-node test bed in PSCAD. There are 100 distributed PV generators installed in the feeder. SunPower SPR-415E-WHT-D is selected as the simulated PV module [13]. The capacities of the PV generators range from 2 kW to 40 kW, and their MPPs vary with respect to irradiance. Overall, the distributed PV generators can output a maximum power of 1.45 MW with irradiance of 1000W/m^2. In reality, the DER aggregator might not have accurate or the most current information on how many and how much capacity of the PV generators are in the feeder. To construct the real-time estimator, the power consumption is measured at substation bus 150. The consensus control gain k_p is selected as 5 pu, and the gain of the adaptive law γ is 0.1 pu.

Fig. 3 describes the illustrative communication topology of the distributed control system. The stability of the distributed control under a strongly connected graph is well proved [10]. Therefore, the design of communication topology is not the focus of this paper. A simple and representative ringlike communication network is considered. Note that the proposed distributed consensus control is applicable to distributed systems with strongly connected communication topology.

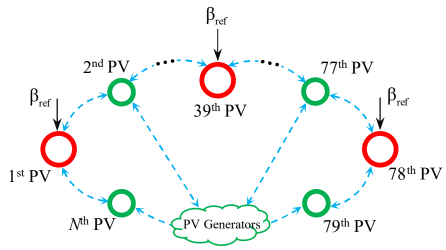

Fig. 3: Illustrative communication topology of the distributed consensus control, selecting adjacent PV generators to establish communication links

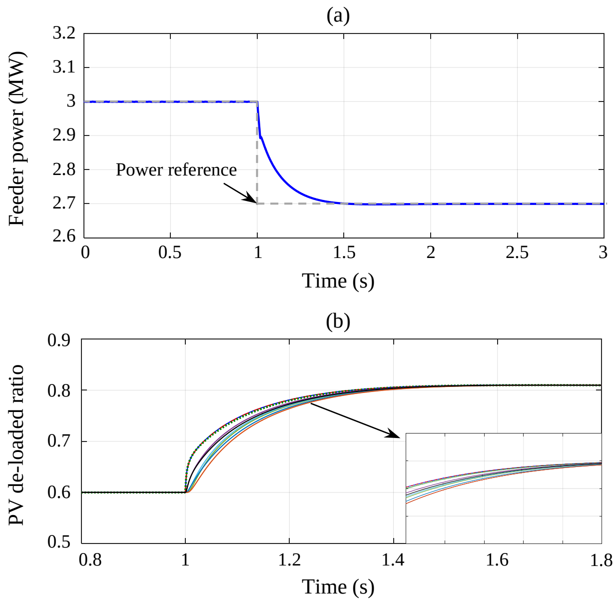

Fig. 4: Power management of the distribution feeder under the distributed consensus control. (a). Power consumption of the distribution feeder; (b). PV deloaded ratio.

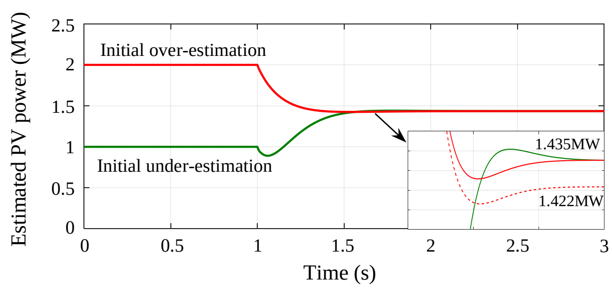

Fig. 5: Estimated cumulative MPP of the PV generators.

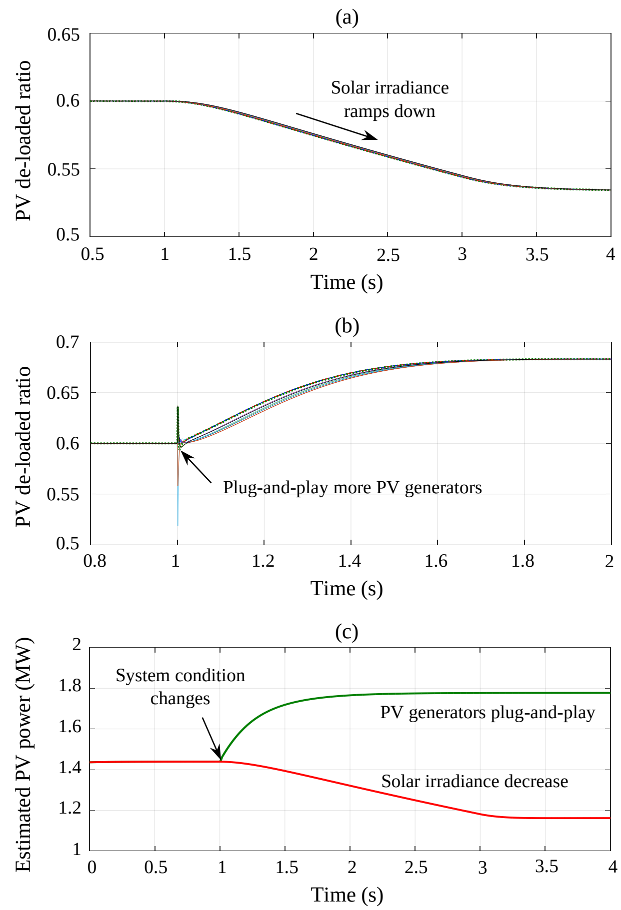

Fig. 6: PV consensus using distributed control with a real-time estimator. (a). PV deloaded ratios with decreased solar irradiance; (b). PV deloaded ratios when more PV generators are connected; (c). estimated MPP of the PV generators.

Specifically, three PV generator units are selected to have direct communication links with the DER aggregator, which are marked as red circles. The green circles represent the PV generators that communicate only with other units.

A. Power management of distribution feeder

Fig. 4 presents the case study when using the distributed consensus control for the power management of a distribution feeder. Initially, the distribution feeder is consuming 3 MW, and the PV deloaded ratio is kept at 60%. The active power reserve in each PV generator can be exploited as resources to manage the power consumption of the feeder. At 1 s of the simulation time, the DER aggregator is required to reduce the feeder's power consumption to 2.7 MW. As a result, the active power reserve of the PV generators can be released by collaboratively increasing the deloaded ratios of the PV generators to a new equilibrium, at 81%. For simplicity, the deloaded ratios of only 10 PV generators are presented.

The proposed real-time estimator is implemented in this case study to estimate the PV active power reserve, as shown in Fig. 5. Regardless of the initial over- or underestimation, the real-time estimator can calculate the actual overall MPP of the PV generators such that the system regulator can evaluate the system condition and further determine how much power can be adjusted for the power management and grid services. The dashed red line in Fig. 5 presents the case where the power loss in the feeder is deliberately increased. As analyzed, the real-time estimator slightly underestimates the cumulative MPP of the PV generators. In fact, the power line losses in the feeder should be excluded because it cannot effectively modify the power flow at the feeder substation.

B. Variation of solar irradiance and DER plug-and-play

This section verifies the estimation performance of the real-time estimator under varying system conditions. Fig. 6 (a) shows the consensus of the PV deloaded ratios when the solar irradiance ramps down to 800W/m^2 on a portion of the

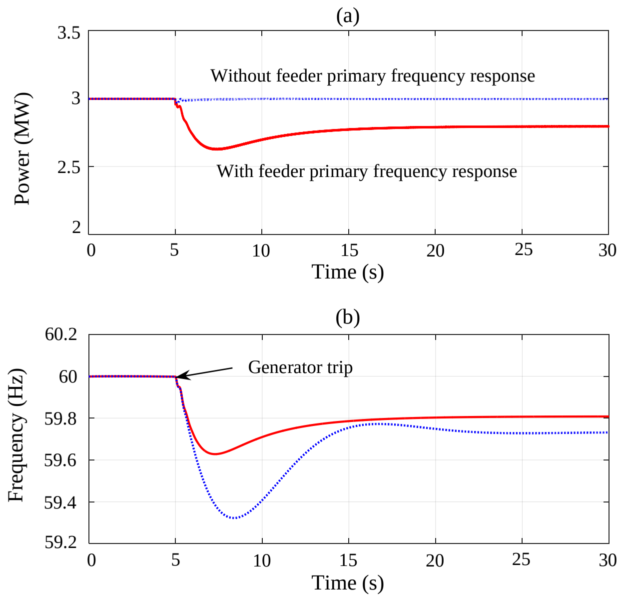

Fig. 7: Primary frequency control. Solid red: PV generators participating in primary frequency control; dashed blue: original case. (a). Power responses of the distribution feeder; (b). power system frequency response.

distributed PV generators. Because some PV generators are generating less power and have less reserve with the initial deloaded ratio, the distributed consensus protocol decreases the deloaded ratio reference, β_{ref}, to maintain the same level of active power reserve in the system. Fig. 6 (b), on the other hand, presents the consensus of the PV deloaded ratios when 10 more PV generators are connected to the feeder. As presented, the distributed consensus protocol increases the PV deloaded ratios responding to the fact that more cumulative PV power is available, and less curtailment is needed for the same level of system active power reserve. In both case (a) and case (b) of Fig. 6, the real-time estimator can accurately update the cumulative MPP of the PV generators, as presented in Fig. 6 (c). This further demonstrates that the proposed distributed consensus control is robust and scalable. The PV generators can plug-and-play into the feeder and start contributing to the system power management and further participate in grid auxiliary services.

C. Power system primary frequency regulation

This section verifies the performance of the proposed distributed consensus control on power system primary frequency regulation using a massive number of distributed PV systems, as shown in Fig. 7. The IEEE 14-bus test bed is considered as part of the transmission network. The IEEE 123-node bus distribution feeder is scaled up to represent a 90-MW load. 5% droop coefficient is implemented on each feeder. In this case, the distribution feeder reduces its power consumption based on the regulation command. As a result, the power system frequency trajectory is improved by the primary frequency response of the distribution feeder. The reduced power consumption is compensated by the deloaded PV generators. Specifically, the PV generators respond to the power reference by releasing their active power reserve while maintaining the consensus of the deloaded ratios. This case study demonstrates the capability of using distributed consensus control with a real-time estimator to enable a distribution feeder to provide critical grid reliability services.

V. Conclusion

This paper presents a distributed consensus-based approach for the real-time active power reserve estimation and active power management in distributed PV systems. The proposed approach achieves the active power reserve estimation and control for numerous PV generators using only the sparse communication network, such that a DER aggregator can provide active power regulation services with enhanced control system resilience. Specifically, the real-time active power reserve estimator requires only the power measurement at the feeder substation, without gathering information from individual DERs. Simulation results show that the real-time estimator can accurately estimate the active power reserve, and the distributed consensus control framework has good scalability to allow DERs to plug-and-play. The performance of the distributed controlled PV generators on improving the power system frequency trajectory is also validated.

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