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Fan, Bo; Wang, Xiongfei

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Distributed Privacy-Preserving Active Power Sharing and Frequency Regulation in Microgrids

Bo Fan, *Member, IEEE*, and Xiongfei Wang, *Senior Member, IEEE*

Abstract—To avoid potential privacy threats and associated cyber-security issues in microgrids, this letter presents a distributed active power sharing and frequency regulation method with *preserved privacy* of local information. In the proposed approach, the transmitted data including the active power outputs and capacities are protected by adding noises to the original ones. Theoretical analysis and verification studies are performed to illustrate the advantages of the proposed method.

Index Terms—Frequency regulation, power sharing, privacy-preserving algorithm, distributed control.

I. INTRODUCTION

A MICROGRID generally comprises loads, distributed generators (DGs), and energy storage systems [1]. Usually, the DGs are connected to the microgrid through power electronic devices and regulated by hierarchical controllers to achieve various objectives including active power sharing and frequency regulation [2].

Traditionally, active power sharing is achieved by droop control. Centralized or distributed controllers are then utilized to compensate for the frequency deviations caused by the droop control [3]–[5]. However, the DGs' sensitive local data, such as power outputs, power capacities, utilization levels, etc., are directly transmitted through communication networks without privacy protection. In [6], a distributed optimal control is developed for microgrids to protect the DGs' privacy. Although the proposed method can preserve privacy to some extent, the accurate local frequency data is transmitted among the DGs during both the transient- and steady-state, which can be further used to infer the other local information, such as the real power generation of DGs.

To preserve the privacy of DGs, all information transmitted through the communication network should be protected. For this purpose, distributed average consensus algorithms are developed in [7], [8]. However, these algorithms are originally designed for ad-hoc networks where the data transmitted have no physical meanings. In microgrids, the transmitted data are essentially physical ones and have their physical impact. Hence, instability issues such as supply-demand imbalance may occur if these methods are directly applied. Besides, when using these methods, only average power sharing can be achieved. Since the DGs' capacities in microgrids are generally different from each other, the DGs with smaller

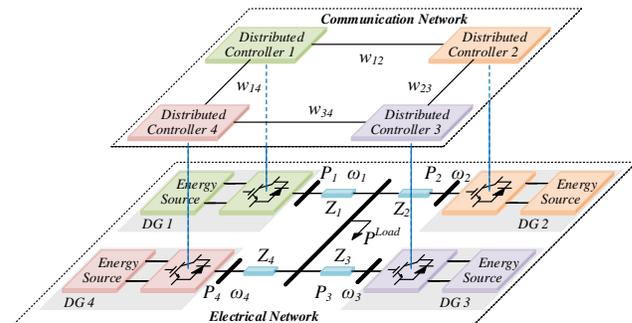


Fig. 1. Topology of a typical microgrid.

capacities may be overloaded and the whole microgrid may suffer from the instability problem under the average power sharing scheme. To the best of the authors' knowledge, how to achieve the proportional active power sharing and frequency regulation in microgrids with *preserved privacy* of local information is still an open question.

To this end, this letter presents a distributed privacy-preserving consensus (PPC)-based control method to achieve these control objectives. First, the original control problem is transformed into an equivalent active power reference generation problem which can be solved by obtaining the global active power utilization level. Further, a distributed PPC algorithm is proposed to acquire this global variable. With the noise added to the transmitted data, the privacy of DGs' local information is protected. Theoretical analyses illustrate that accurate proportional active power sharing and frequency regulation can be achieved. Finally, verification studies are conducted to demonstrate the merits of the proposed PPC-based method. Additionally, the presented methodology can be extended to other control problems in microgrids with preserved privacy.

The main contributions of this study are summarized as:

- 1) A distributed controller is firstly proposed to achieve the proportional active power sharing and frequency regulation in the microgrids with preserved privacy;
- 2) The transmitted data including the power outputs and capacities is protected by adding noises to the original ones. The instability impact that may be caused by using the traditional PPC-based methods is alleviated through the designed power reference generation technique and control structure;
- 3) Theoretical analyses and verification studies are performed to showcase the advantages of the proposed method. Both control objectives are proved to be accurately achieved in the steady-state.

II. PROBLEM FORMULATION

A typical cyber-physical microgrid composed of a communication network and an electrical one is illustrated in

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B. Fan and X. Wang are with the Department of Energy Technology, Aalborg University, Aalborg 9220, Denmark (e-mail: bof@et.aau.dk; xwa@et.aau.dk).

Fig. 1 [9]. The former is used for information sharing among the distributed controllers. The latter is a physical grid for delivering electrical energy from DGs to loads. Each DG is equipped with a distributed controller to generate the active power reference for its local droop controller.

For DG i , $i \in \{1, 2, \dots, N\} \triangleq \mathcal{V}_E$ with N being the number of DGs, its local P-f droop control is expressed as

$$\omega_i = \omega_0 - m_i(P_i - P_i^r) \quad (1)$$

where ω_0 is the nominal frequency. ω_i is the DG's frequency. P_i is the active power output, with P_i^r being its reference. m_i is the droop coefficient, which is selected properly to ensure the system stability when there exist equilibria [4], [5].

Two control objectives are considered in this study, i.e., the proportional active power sharing and frequency regulation [4], defined in the sequel.

Proportional Active Power Sharing is achieved if the total active power demand is shared proportionally according to DGs' capacities P_i^M in the steady-state, i.e.,

$$P_i/P_i^M = P_j/P_j^M, \quad \forall i, j \in \mathcal{V}_E. \quad (2)$$

Usually, the proportional active power sharing is considered in microgrids to avoid the possible overload of the DG(s) when the total active power demand is no larger than the total capacity of the microgrid. Otherwise, load shedding must be taken to avoid the supply-demand imbalance.

Frequency Regulation is achieved if all the DGs' frequencies are equal to the nominal one in the steady-state, i.e.,

$$\omega_i = \omega_0, \quad \forall i \in \mathcal{V}_E. \quad (3)$$

Additionally, the privacy of the local information, i.e., the active power outputs and capacities of DGs, is required to be protected during the realization of these objectives.

III. ACTIVE POWER REFERENCE GENERATION

In this section, the control problem defined in Section II is transformed into an equivalent active power reference generation problem based on the global active power utilization level [1]. For a microgrid, the active power supply-demand balance can be expressed as $\sum_{i \in \mathcal{V}_E} P_i = P^{Load} + P^{Loss}$ where P^{Load} and P^{Loss} are the load active power requirement and the total active power loss of the transmission lines. Thereafter, the global active power utilization level K^U can be defined as

$$K^U = \frac{P^{Load} + P^{Loss}}{\sum_{i \in \mathcal{V}_E} P_i^M} = \frac{\sum_{i \in \mathcal{V}_E} P_i}{\sum_{i \in \mathcal{V}_E} P_i^M}. \quad (4)$$

Moreover, select the active power references of the DGs' droop controllers as

$$P_i^r = K^U P_i^M. \quad (5)$$

Next, the active power outputs and frequencies of DGs in the steady-state are analyzed based on the droop control (1) with the active power references given by (5).

Taking the summations of both sides of (5) and substituting (4) into the resulting equation yield

$$\sum_{i \in \mathcal{V}_E} P_i^r = \frac{\sum_{i \in \mathcal{V}_E} P_i}{\sum_{i \in \mathcal{V}_E} P_i^M} \sum_{i \in \mathcal{V}_E} P_i^M = \sum_{i \in \mathcal{V}_E} P_i. \quad (6)$$

Since all the DGs' frequencies are identical in the steady-state, i.e., $\omega_i = \omega_j, \forall i, j \in \mathcal{V}_E$, combining (1) and (6) yields

$$\begin{aligned} 0 &= \sum_{i \in \mathcal{V}_E} P_i^r - \sum_{i \in \mathcal{V}_E} P_i = \sum_{i \in \mathcal{V}_E} (P_i^r - P_i) \\ &= \sum_{i \in \mathcal{V}_E} m_i^{-1}(\omega_i - \omega_0) = (\omega_i - \omega_0) \sum_{i \in \mathcal{V}_E} m_i^{-1}. \end{aligned} \quad (7)$$

Considering the fact that the droop coefficients $m_i, \forall i \in \mathcal{V}_E$ are positive, one has $\sum_{i \in \mathcal{V}_E} m_i^{-1} > 0$. Then (7) gives $\omega_i = \omega_0, \forall i \in \mathcal{V}_E$. Hence, all DGs' frequencies are equal to the nominal value ω_0 in the steady-state. Furthermore, combining (1) and (5) gives $P_i/P_i^M = P_i^r/P_i^M = K^U, \forall i \in \mathcal{V}_E$. Therefore, the ratios of all DGs' active outputs to their capacities are identical to the global utilization level.

From the above steady-state analysis, it can be noticed that if the global utilization level K^U is known to all DGs, then the control objectives can be achieved simply by selecting the active power references of the droop control by (5). Besides, the active power supply-demand balance can be maintained. However, K^U is a global variable whose calculation requires all the active power outputs and capacities of DGs. The privacy of these sensitive data is jeopardized.

IV. PPC-BASED DISTRIBUTED CONTROL

In this section, a PPC algorithm is presented to accurately obtain the global utilization level K^U which is further used to update the active power references by (5) and achieve the control objectives.

A. Control Development

First, rewrite (4) as $K^U = \frac{\sum_{i \in \mathcal{V}_E} P_i/N}{\sum_{i \in \mathcal{V}_E} P_i^M/N}$. Since the numerator and denominator are the average values of the active power outputs and capacities, respectively, they can be obtained through the traditional average consensus algorithm [10].

For clarity, define two states, \bar{P}_i and \bar{P}_i^M , for DG i , $i \in \mathcal{V}_E$. Let $\bar{P}_i(0)$ and $\bar{P}_i^M(0)$ be the actual sampled active power output and capacity data, respectively. Further, denote $\bar{P}_i(k)$ and $\bar{P}_i^M(k)$ as the states of DG i at periodic discrete-time instants $t = kT_C, k = 0, 1, 2, \dots$, where T_C is the communication period for the distributed controllers. Notice that only the data $\bar{P}_i(0)$ and $\bar{P}_i^M(0)$ are sensitive and should be protected since they contain the actual information of DGs.

For brevity, only the acquirement of the numerator $\sum_{i \in \mathcal{V}_E} P_i/N$ is presented in detail, and that of the denominator is similar and therefore omitted here. According to [10], the traditional consensus algorithm can be expressed as $\bar{P}_i(k+1) = w_{ii}\bar{P}_i(k) + \sum_{j \in \mathcal{N}_i} w_{ij}\bar{P}_j(k)$, where w_{ij} being the Metropolis weights [7], and \mathcal{N}_i denotes the set of the neighbors of DG i . Notice that at $k = 0$, the actual active power output data $P_j = \bar{P}_j(0)$ of DG $j, j \in \mathcal{N}_i$ is directly transmitted to its neighbor DG i . To protect the sensitive data $\bar{P}_i(0)$, a random noise $d_i(k)$ is added to the sensitive data before it is sent to its neighbor DGs as follows

$$\bar{P}_i^+(k) = \bar{P}_i(k) + d_i(k). \quad (8)$$

The PPC algorithm is then given as

$$\bar{P}_i(k+1) = w_{ii}\bar{P}_i^+(k) + \sum_{j \in \mathcal{N}_i} w_{ij}\bar{P}_j^+(k). \quad (9)$$

TABLE I
MICROGRID AND CONTROL PARAMETERS

| Quantity | Value | Quantity | Value |
|----------------------------------|-------|---------------------|-------------------------|
| Nominal frequency (Hz) | 50 | Z_i (Ω) | $2Z^b, 3Z^b, Z^b, 4Z^b$ |
| Nominal voltage (V) | 311 | m_i (10^{-4}) | 1.57, 2.09, 3.14, 6.28 |
| Nominal power (kW) | 10 | P_i^M (p.u.) | 0.4, 0.3, 0.2, 0.1 |
| T_U (ms) | 100 | T_C (ms) | 4 |
| $w_{12}, w_{23}, w_{34}, w_{41}$ | 1/3 | α, ρ | 5000, 0.6 |

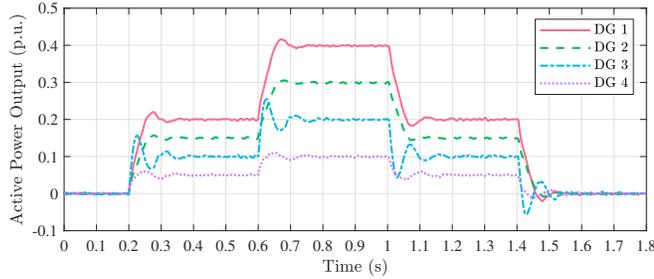


Fig. 3. Active power outputs P_i of DGs.

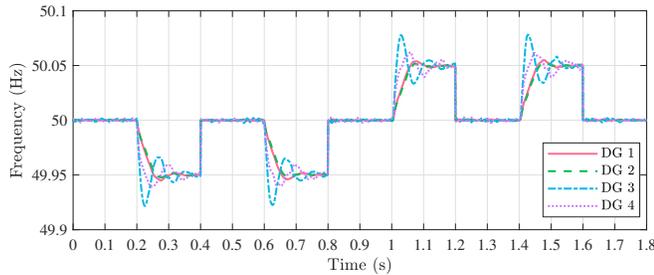


Fig. 4. Frequencies $\omega_i/2\pi$ of DGs.

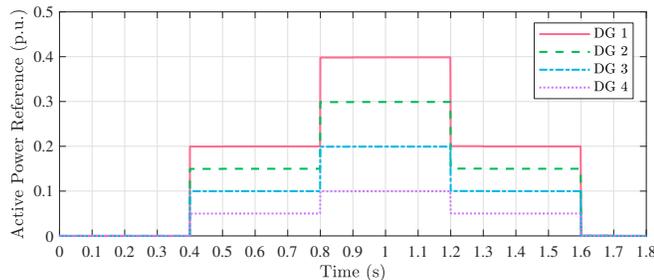


Fig. 5. Active power references P_i^r of DGs.

$j\omega L_b$ with $R_b = 0.1 \Omega$, $L_b = 1$ mH. The base power for the calculation of the per unit (p.u.) power value is 10 kW. Two 5 kW resistive loads are connected to the system at 0.2 s and 0.6 s, respectively, and disconnected at 1 s and 1.4 s afterward.

The corresponding results are shown in Figs. 3-6. From Figs. 4 and 5, one can notice that when the DGs' active power references update at 0.4 s, 0.8 s, 1.2 s, and 1.6 s, the DGs' frequencies can restore to the nominal value. As shown in Fig. 3, the proportional active power sharing is achieved. Fig. 6 illustrates the comparison results between the sampled power outputs and the power outputs with noise. The transmitted data are totally different from their original ones in both the power outputs and their trends. The privacy of this sensitive information is thus protected.

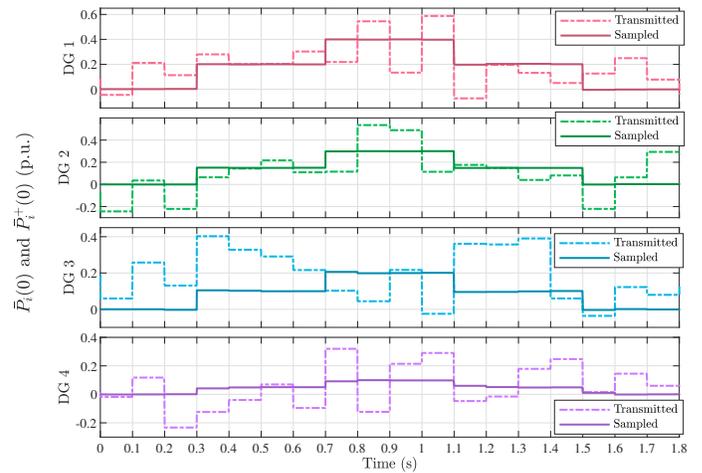


Fig. 6. Comparison between the sampled power outputs $\bar{P}_i(0)$ and the transmitted power outputs with noise $\bar{P}_i^+(0)$.

VI. CONCLUSION

This letter presents a PPC-based algorithm to achieve active power sharing and frequency regulation in microgrids. By virtue of the global utilization level, the original control problem is transformed into an equivalent active power reference generation problem. A PPC-based algorithm is then presented to obtain the global utilization level in a distributed way with *preserved privacy*. Finally, verification studies are carried out to show the merits of the proposed approach.

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