

# Broadcast Gossip Algorithms for Distributed Peer-to-Peer Control in AC Microgrids

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**Abstract**—This paper focuses on a fully distributed peer-to-peer control scheme for voltage regulation and reactive power sharing of multiple inverter-based distributed energy resources (DERs) in ac microgrids. The proposed peer-to-peer control strategy is fully distributed enabled through broadcast gossip communication, where each DER unit only requires local voltage and current measurement from its own and some (but not all) nearby neighbors for the voltage and reactive power sharing control. Employing the broadcast gossip communication protocol with attractive scalability and reliability properties, the control inputs can be updated to restore the voltage magnitudes at the point of common coupling to a desired value ensuring an accurate reactive power sharing for each DER. Since the proposed distributed controllers are implemented on local DERs, the central controller and hierarchy are no longer required. Accordingly, the microgrid system stability is preserved in the peer-to-peer requirements of line switches, which in turn, enables a plug-and-play operation of DERs and their robustness against microgrid topology change scenarios. Simulation studies in a modified IEEE 34-bus test network demonstrate the effectiveness and applicability of the proposed control strategy.

**Index Terms**—Autonomous microgrid, broadcast gossip protocol, distributed peer-to-peer control, reactive power sharing, voltage regulation.

Manuscript received July 5, 2018; revised November 14, 2018; accepted January 23, 2019. Date of publication February 8, 2019; date of current version April 20, 2019. Paper 2018-ESC-0613.R1, presented at the 2018 IEEE Industry Applications Society Annual Meeting, Portland, OR, USA, September 23–27, 2018, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Energy Systems Committee of the IEEE Industry Applications Society. This work was supported in part by the National Natural Science Foundation of China under Grants 61773158 and 51709215, in part by the Australia Research Council under Grant 170102303, and in part by the Natural Science Foundation of Hunan Province under Grant 2018JJ2051. (Corresponding author: Fei Wang.)

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Digital Object Identifier 10.1109/TIA.2019.2898367

## I. INTRODUCTION

MICROGRIDS are among the viable solutions to achieve an effective integration of loads, energy storage systems, and distributed energy resources (DERs) into the low- and medium-voltage distribution networks via dc/ac interface inverters [1]–[3]. The microgrids will enable an autonomous operation in the advent of disturbances or planned outages [4]–[7], where proper control for maintaining the voltage and frequency stability and power sharing is more challenging than that in conventional power systems.

Due to the line impedance effect, the voltage droop controller is unable to share reactive power demand among even identical DERs operating in parallel. In contrast with the high-voltage networks, where the reactive power sharing among generators is usually not a major concern—since the generators' voltages are maintained constant by the excitation system through capacitive compensation of both loads and transmission lines [8]–[10], the voltage regulation in microgrids can be accomplished through a secondary control [3], [11]. However, the microgrids characteristics (e.g., low ratings of DERs, small electrical distances between DERs, and the lack of static compensation) call for an accurate reactive power sharing mechanism among DERs to avoid overloading conditions that can adversely affect their operation [14], [15], and consequently, influences the microgrid stability.

The rapid developments in the information and communication technologies provide an opportunity to achieve communication network-based distributed control for voltage regulation and reactive power sharing of autonomous microgrids. Contrary to a centralized secondary control architecture for reactive power sharing that requires each unit to communicate with a central controller, a distributed voltage controller mandates all DERs to communicate with all others directly [16]. Moreover, since the controller regulates the DER voltages to their nominal values, it is unable to share reactive power between heterogeneous DERs connected through varying line impedances. Considering the influence of uncertain communication topologies on the microgrid system stability, a distributed pinning control strategy is proposed in [17] to regulate the power output of a large number of DERs in ac microgrids. It is demonstrated in [18] that the distributed control is able to enhance the voltage regulation and maintain the proportional load sharing for microgrids via low-bandwidth communication. Centered on the pinning control of multi-agent systems, a novel finite-time

distributed frequency/voltage synchronization strategy is proposed in [19] accompanied by a distributed active power sharing regulator. Subsequently, in [20], a distributed averaging PI controller has been proposed for secondary frequency and voltage control in autonomous microgrids using decentralized proportional droop/integral control and distributed averaging technique. In addition, Castilla *et al.* [21] has addressed the adverse impacts that the drifts of the processors clocks produce on the operation of the secondary control and stability of the autonomous microgrids.

However, due to the inherent distributed characteristic of the microgrid systems consisting of various DERs with different objectives, it is desirable that the control system coordinating these DERs operates in a highly distributed manner. Therefore, a non-hierarchical peer-to-peer control architecture seems to be an effective alternative for controlling DERs in the distribution grid. Such a peer-to-peer control method is based on peer-to-peer communication networks [23], [24], where there is no hierarchy and no central controller. The DER units cooperate toward a common goal, but the control remains local. In this architecture, the requirement of bidirectional communications is necessary for activating and integrating the local control of each DER unit. This allows to keep the control of the DERs local and distributed, thereby eliminating the large-scale impact of any single point of failure.

Motivated by the above considerations and in order to overcome the drawbacks of droop control such as voltage deviations and inaccurate reactive power sharing, this paper presents a distributed peer-to-peer control scheme employing a broadcast gossip algorithm that will regulate average voltage value of integrated DERs while keeping an accurate reactive power sharing among DERs. Different from the existing distributed control approaches (e.g., time delay [11], switching topology [15], and noisy communication channel [22]), the distributed peer-to-peer control strategies via broadcast gossip algorithms have many salient properties, among which one can highlight a better robustness to unreliable communication, no synchronized clock requirement at the DER unit, distributed computations, etc. [21], [22]. Thus, a broadcast gossip algorithm with attractive scalability and reliability properties [7], [8] is applied to indirectly discover the global information, and recognize an updating method for global information sharing. Accordingly, the main contributions of this paper are summarized as follows.

1) Compared with the existing distributed cooperative algorithms that only achieve the power sharing or voltage control [18]–[21], the proposed control scheme ensures a precise voltage regulation while keeping an accurate reactive power sharing of DERs in a distributed manner. In addition, the proposed distributed control algorithm for reactive power sharing also optimizes the power quality during autonomous operation, i.e., minimizes the reactive power flows between the DERs while achieving reactive power sharing.

2) Since all DERs merely need a partial and limited knowledge of the problem parameters from their neighbors and perform only based on local measurements, the proposed distributed peer-to-peer control scheme is centered only on local DER controllers, offering further reliability and robustness.

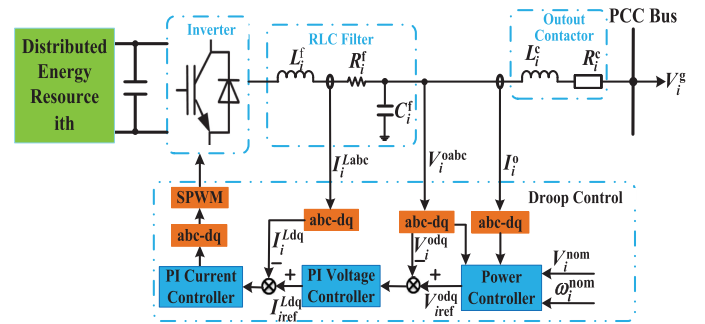


Fig. 1. Circuit structure of the inverter-based DER<sub>*i*</sub> unit connected to a PCC bus.

Different from the traditional hierarchical control schemes for microgrids [5], [13]–[15], there is no hierarchy and no central controller in our proposed framework, which is a totally distributed implementation of droop control, and distributed gossip control, which enhances the redundancy and enables a plug-and-play functionality in microgrids.

3) Furthermore, the proposed peer-to-peer algorithm is fully distributed which promotes independent decision making, and lowers the need to signal the overhead network. Thus, the introduced methods also make it easier to meet the requirements of line switches and plug-and-play operation of intermittent DERs in low-inertia microgrid systems. The effectiveness of the proposed distributed gossip control mechanism is validated under different scenarios of load variations, plug-and-play operations, and communication link failures.

The rest of this paper is organized as follows: Section II presents the basics of droop control for DER units, the generic models of the microgrids, and fundamental principles of the graph theory. Two novel distributed peer-to-peer control algorithms are elaborated to achieve the microgrid voltage regulation and reactive power sharing in Section III, where the fundamentals of the broadcast gossip algorithm are also presented. Section IV is devoted to numerical case studies to verify the effectiveness of the proposed algorithms. And finally, Section V concludes this paper.

## II. MICROGRID ARCHITECTURE AND SYSTEM MODEL

In this paper, non-linear dynamics of each DER unit in a microgrid are formulated on its own direct-quadratic (d–q) reference frame. This microgrid reference frame is considered as the common reference frame and the dynamics of other DERs are transformed to this common reference frame with angular frequency  $\omega^{\text{com}}$ . Then the active and reactive powers can be decoupled via an abc/dq transformation.

### A. Local Control of Inverter-Based DERs

The control process of three-phase inverter-based DER<sub>*i*</sub> unit consists of three control loops (i.e., the droop-based power controller, PI voltage controller, and PI current controller) as shown in Fig. 1, where,  $L_i^f$ ,  $R_i^f$ , and  $C_i^f$  represent the inductance, resistance, and capacitance of the output filter, respectively. And  $L_i^c$  and  $R_i^c$  represent the inductance, and resistance of the output

connector between DER<sub>*i*</sub> unit and the point of common coupling (PCC) bus, respectively. The virtual impedance loop  $Z_i^V$  is employed so as to keep the  $Q$  versus  $V$  and  $P$  versus  $\omega$  droop characteristic for power controller.

The nominal frequency  $\omega_i^{\text{nom}}$  of droop-based power controller is utilized by the pulsewidth modulation (PWM) inverter as the frequency reference. Meanwhile, the following voltage and current controllers will be employed to regulate the voltage reference of the inverter [6]. According to the references provided by the power controller,  $V_{i\text{ref}}^{\text{od}}$  and  $V_{i\text{ref}}^{\text{oq}}$ , the controller outputs are given by

$$I_{i\text{ref}}^{\text{od}} = \left( k_i^{\text{PV}} + \frac{k_i^{\text{IV}}}{s} \right) (V_{i\text{ref}}^{\text{od}} - V_i^{\text{od}}) - \omega_i^{\text{nom}} C_i^{\text{f}} V_i^{\text{oq}} + F I_i^{\text{od}} \quad (1)$$

$$I_{i\text{ref}}^{\text{oq}} = \left( k_i^{\text{PV}} + \frac{k_i^{\text{IV}}}{s} \right) (V_{i\text{ref}}^{\text{oq}} - V_i^{\text{oq}}) - \omega_i^{\text{nom}} C_i^{\text{f}} V_i^{\text{od}} + F I_i^{\text{oq}} \quad (2)$$

where  $k_i^{\text{PV}}$  and  $k_i^{\text{IV}}$  are, respectively, the proportional and integral gains of the PI voltage control loop, and  $F$  is the feed forward gain. The feed-forward quantities ( $F I_i^{\text{od}}$ ,  $F I_i^{\text{oq}}$ ) and cross decoupled quantities ( $\omega_i^{\text{nom}} C_i^{\text{f}} V_i^{\text{oq}}$ ,  $\omega_i^{\text{nom}} C_i^{\text{f}} V_i^{\text{od}}$ ) are utilized to realize a decoupled current control in the d-q axis. Therefore,  $V_i^{\text{od}}$  and  $V_i^{\text{oq}}$  are able to be controlled separately.

Furthermore, according to the references  $I_{i\text{ref}}^{\text{od}}$  and  $I_{i\text{ref}}^{\text{oq}}$ —supplied by the PI voltage controller—the output of the PI current control loop can be expressed as

$$V_{i\text{ref}}^{\text{od}} = \left( k_i^{\text{PI}} + \frac{k_i^{\text{II}}}{s} \right) [I_{i\text{ref}}^{\text{od}} - I_i^{\text{od}}] - \omega_i^{\text{nom}} L_i^{\text{f}} i_i^{\text{Lq}} + V_i^{\text{Id}} \quad (3)$$

$$V_{i\text{ref}}^{\text{oq}} = \left( k_i^{\text{PI}} + \frac{k_i^{\text{II}}}{s} \right) [I_{i\text{ref}}^{\text{oq}} - I_i^{\text{oq}}] - \omega_i^{\text{nom}} L_i^{\text{f}} i_i^{\text{Ld}} + V_i^{\text{Iq}} \quad (4)$$

where  $k_i^{\text{PI}}$  and  $k_i^{\text{II}}$  are the proportional and integral gains of the current controller based on PI control, respectively. The feed-forward quantities ( $V_i^{\text{Id}}$ ,  $V_i^{\text{Iq}}$ ) and cross decoupled quantities ( $\omega_i^{\text{nom}} L_i^{\text{f}} i_i^{\text{Ld}}$ ,  $\omega_i^{\text{nom}} L_i^{\text{f}} i_i^{\text{Lq}}$ ) are separately utilized to realize a current control in the d-q axis.

Regarding the power control,  $R_{ij}$  and  $X_{ij}$  represent the line impedance and inductance, respectively. And  $V_i$  and  $V_j$  represent the root-mean-square value of DER<sub>*i*</sub> and DER<sub>*j*</sub> units, with their phases  $\vartheta_i$  and  $\vartheta_j$ , respectively. For inductive lines (if  $X \gg R$ ) of reactance  $X_{ij}$ , connecting DER<sub>*i*</sub> to DER<sub>*j*</sub>, the active and reactive power injections  $P_i$  and  $Q_i$  at DER<sub>*i*</sub> unit are given by

$$P_i = \sum_{j=1}^N \frac{V_i V_j}{X_{ij}} \sin(\vartheta_i - \vartheta_j)$$

$$Q_i = V_i^2 \sum_{j=1}^N X_{ij}^{-1} - \sum_{j=1}^N \frac{V_i V_j}{X_{ij}} (\vartheta_i - \vartheta_j). \quad (5)$$

If  $\vartheta_{ij} = \vartheta_i - \vartheta_j$  is small, then (1) can be simplified as follows:

$$P_i = \sum_{j=1}^N \frac{V_i V_j}{X_{ij}} \vartheta_{ij}$$

$$Q_i = V_i^2 \sum_{j=1}^N X_{ij}^{-1} - \sum_{j=1}^N \frac{V_i V_j}{X_{ij}}. \quad (6)$$

As shown by (6), the active power flowing from DER<sub>*i*</sub> to DER<sub>*j*</sub> via a highly inductive line impedance can be controlled by regulating the phase  $\vartheta_{ij}$ . The reactive power supplied by DER<sub>*i*</sub> unit can be controlled by regulating the voltage magnitude of DER<sub>*i*</sub> unit. This is the basis of the conventional  $Q$  versus  $V$  and  $P$  versus  $\omega$  droop controls. Thus, the droop technique employed for DERs during the multiple loop control processes can be given by

$$V_i = V_i^{\text{nom}} - n_i^Q Q_i$$

$$\omega_i = \omega_i^{\text{nom}} - m_i^P P_i \quad (7)$$

where  $V_i^{\text{nom}}$  and  $\omega_i^{\text{nom}}$  are chosen from the nominal set points of voltage and frequency of the DER<sub>*i*</sub> unit, respectively;  $Q_i$  and  $P_i$  are the measured reactive and active power at the DER terminal;  $n_i^Q$  and  $m_i^P$  are the associated droop coefficients that are usually selected based on the reactive and active power ratings. According to the traditional droop control strategy using d-q transformation, the voltage reference values of DER<sub>*i*</sub> unit are determined by the power control loop and can be abstracted as follows [19]:

$$V_i^{\text{od}} = V_i^{\text{nomd}} - n_i^Q Q_i$$

$$V_i^{\text{oq}} = 0 \quad (8)$$

where  $V_i^{\text{nomd}}$  is chosen from the nominal voltage set point of the DER<sub>*i*</sub> unit, while  $n_i^Q$  is the voltage droop gain.  $Q_i$  is the measured reactive power at the DER terminal.  $V_i^{\text{od}}$  is the actual output voltage and  $V_i^{\text{nom}}$  (i.e.,  $V_i^{\text{nom}} = \sqrt{(V_i^{\text{nomd}})^2 + (V_i^{\text{nomq}})^2}$  with  $V_i^{\text{nomq}} = 0$ ) is the control input computed by (16).

## B. Dynamic Model of Microgrids

Consider an autonomous microgrid hosting an  $N$  number of inverter-based DERs, where all variables are referred to a common reference frame  $\omega^{\text{com}}$ . The mathematical equations of the microgrid equivalent circuit can be obtained by considering the small-signal model of inverter-based DER (as described in Section II-A), the output LC filter, and the output connector. Such differential equations are derived as follows [23]:

$$\dot{I}_i^{\text{Ld}} = -\frac{R_i^{\text{f}}}{L_i^{\text{f}}} I_i^{\text{Ld}} + \omega_i I_i^{\text{Lq}} + \frac{1}{L_i^{\text{f}}} V_i^{\text{Id}} - \frac{1}{L_i^{\text{f}}} V_i^{\text{od}}$$

$$\dot{I}_i^{\text{Lq}} = -\frac{R_i^{\text{f}}}{L_i^{\text{f}}} I_i^{\text{Lq}} + \omega_i I_i^{\text{Ld}} + \frac{1}{L_i^{\text{f}}} V_i^{\text{Iq}} - \frac{1}{L_i^{\text{f}}} V_i^{\text{oq}}$$

$$\dot{V}_i^{\text{od}} = \omega_i V_i^{\text{oq}} + \frac{1}{C_i^{\text{f}}} I_i^{\text{Ld}} - \frac{1}{C_i^{\text{f}}} I_i^{\text{od}}$$

$$\begin{aligned}
\dot{V}_i^{\text{oq}} &= -\omega_i V_i^{\text{od}} + \frac{1}{C_i^{\text{f}}} I_i^{\text{Lq}} - \frac{1}{C_i^{\text{f}}} I_i^{\text{oq}} \\
\dot{I}_i^{\text{od}} &= -\frac{R_i^{\text{c}}}{L_i^{\text{c}}} I_i^{\text{od}} + \omega_i I_i^{\text{oq}} + \frac{1}{L_i^{\text{c}}} V_i^{\text{od}} - \frac{1}{L_i^{\text{c}}} V_i^{\text{gd}} \\
\dot{I}_i^{\text{od}} &= -\frac{R_i^{\text{c}}}{L_i^{\text{c}}} I_i^{\text{oq}} + \omega_i I_i^{\text{od}} + \frac{1}{L_i^{\text{c}}} V_i^{\text{oq}} - \frac{1}{L_i^{\text{c}}} V_i^{\text{gq}}. \quad (9)
\end{aligned}$$

Equations (1)–(7) and (9) engender a dynamical model of the inverter-based DER<sub>*i*</sub> unit, the output LC filter, and the output line impedance. The corresponding microgrid dynamical model can be given in a compact form as

$$\begin{aligned}
\dot{x} &= Ax + Bu \\
y &= Cx + Du \quad (10)
\end{aligned}$$

where

$$\begin{aligned}
x &= [P \quad Q \quad I^{\text{Ld}} \quad I^{\text{Lq}} \quad V^{\text{od}} \quad V^{\text{oq}} \quad I^{\text{od}} \quad I^{\text{oq}}]^T \\
u &= [\omega^{\text{com}} \quad V_i^{\text{gd}} \quad V_i^{\text{gq}}] \\
y &= [V_{\text{ref}}^{\text{od}} \quad -V_{\text{ref}}^{\text{od}} \quad V_{\text{ref}}^{\text{oq}} \quad -V_{\text{ref}}^{\text{oq}} \quad I_{\text{ref}}^{\text{od}} \quad -I_{\text{ref}}^{\text{od}} \quad I_{\text{ref}}^{\text{oq}} \quad -I_{\text{ref}}^{\text{oq}}].
\end{aligned}$$

The proposed fully distributed gossip control scheme selects the control input  $V_i^{\text{od}}$  in (12) to synchronize the average terminal voltage value of all DERs to the desired value  $V^{\text{DES}}$ . Note that the DER output voltage magnitude  $V_i^{\text{od}}$  can achieve synchronization via adjusting the control input  $V_i^{\text{nomd}}$ . Meanwhile, a proper reactive power sharing among DERs would also be possible by the subsequent controller (14).

### C. Graph Theory

The peer-to-peer communication network among  $N$  number of DERs can be described by a graph:  $\mathcal{G} = (\mathcal{V}, \mathcal{E}, A)$  with a set of nodes  $\mathcal{V} = (\mathcal{V}_1, \dots, \mathcal{V}_N)$  and a set of edges  $\mathcal{E} = \mathcal{V} \times \mathcal{V}$ . Each graph node represents a DER unit, and edges represent communication links for data exchange. If communication links are bidirectional,  $(\mathcal{V}_i, \mathcal{V}_j) \in \mathcal{E} \Rightarrow (\mathcal{V}_j, \mathcal{V}_i) \in \mathcal{E} \forall i, j$ , the graph is said to be undirected. Otherwise, it is directed. A graph is said to have a spanning tree, if there is a root node, such that there is a direct path from the root to any other node in the graph. A matrix called adjacency matrix  $A = \{a_{ij}\}_{N \times N}$  where  $a_{ij}$  can be defined as follows:

$$a_{ij} = \begin{cases} 1, & \text{if } (V_i, V_j) \in E \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

## III. PROPOSED FULLY DISTRIBUTED PEER-TO-PEER CONTROL VIA BROADCAST GOSSIP ALGORITHMS

The proposed fully distributed peer-to-peer control scheme for autonomous microgrids is achieved via a broadcast gossip algorithm that will regulate average voltage value of integrated DERs to the desired values while keeping an accurate reactive power sharing of DERs in a distributed manner.

### A. Distributed Peer-to-Peer Control in Microgrids

Different from the conventional power control with centralized models, this paper proposes a fully distributed peer-to-peer control scheme for each DER unit via broadcast gossip

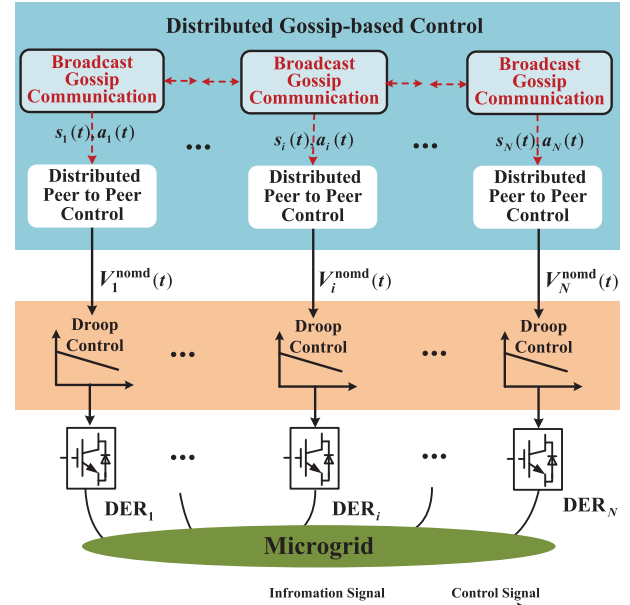


Fig. 2. Proposed fully distributed peer-to-peer control structure via a broadcast gossip algorithm.

algorithms. The basic idea of the proposed distributed control method is to share information among each DER and its neighbors through sparse communication networks.

The block diagram of the proposed peer-to-peer control scheme is illustrated in Fig. 2. The proposed scheme involves communication layer via a broadcast gossip algorithm and distributed peer-to-peer control layer. The broadcast-based gossip communication layer is mainly responsible for local information exchanges with neighbors to indirectly achieve the global information cooperatively by the broadcast gossip algorithm (which will be presented in detail in Section III-B) and then sending it to the distributed control layer. The peer-to-peer control layer sends the corresponding reference signal  $V_i^{\text{nomd}}$  (illustrated with solid lines) to the droop control to realize the voltage regulation and reactive power sharing reasonably.

In order to provide a flat voltage profile across the entire microgrid, the proposed distributed voltage average method is able to compensate the voltage deviations caused by droop control in each local DER. Thus, each DER unit is required to measure the voltage error, and try to compensate the voltage deviation caused by the  $Q$  versus  $V$  droop. The main advantage of the proposed method compared to the conventional techniques is that the remote sensing used by the distributed voltage control is not necessary; so just the DER terminal voltage, which can substantially vary among different terminals, is required. In this case, the voltage regulation is achieved as follows:

$$V^{\text{Ave}} = \frac{1}{N} \sum_{i=1}^N V_i^{\text{od}} \quad (12)$$

$$\dot{V}_i^{\text{od}} = \left( k_i^{\text{PAveV}} + \frac{k_i^{\text{IAveV}}}{s} \right) [V^{\text{DES}} - V^{\text{Ave}}] \quad (13)$$

where  $N$  is the total number of DERs,  $k_i^{\text{PAve}V}$  and  $k_i^{\text{IAve}V}$  are the proportional and integral terms for DER<sub>*i*</sub> unit, respectively.  $\dot{V}_i^{\text{od}}$  is the voltage output variation of DER<sub>*i*</sub> unit, resulted from the PI control of the error between microgrid voltage reference ( $V^{\text{DES}}$ ) and the DERs average voltage ( $V^{\text{Ave}}$ ).

Although several methods have been proposed to enhance the *reactive power sharing*, it is difficult to accurately achieve it in a high R/X microgrid [5], [6]. That is because the voltage is a local variable and the impedances between the DERs and PCC bus are different. Different from the existing literature, a novel distributed peer-to-peer control is proposed that offers a possible solution for power sharing locally; that is each DER exchanges the measured  $Q$  with other DERs indirectly to acquire average reactive power as the same reference. Thus, the distributed control for reactive power sharing can be expressed as

$$Q^{\text{Ave}} = \frac{1}{N} \sum_{i=1}^N Q_i \quad (14)$$

$$\dot{Q}_i = \left( k_i^{\text{PAve}Q} + \frac{k_i^{\text{IAve}Q}}{s} \right) [Q^{\text{Ave}} - Q_i] \quad (15)$$

where  $k_i^{\text{PAve}Q}$  and  $k_i^{\text{IAve}Q}$  are the proportional and integral terms for DER<sub>*i*</sub> unit, respectively.  $Q^{\text{Ave}}$  is the average reactive power for all DERs which acts as a reactive power reference and  $\dot{Q}_i$  is the control signal issued by the proposed distributed peer-to-peer control module, aiming to share the reactive power between the DERs.

The voltage control and reactive power sharing can be achieved by employing (9)–(12) and  $Q$  versus  $V$  droop control principles. Combining the above equations with (4) yields

$$\dot{V}_i^{\text{nomd}} = \dot{V}_i^{\text{od}} + n_i^Q \dot{Q}_i \quad (16)$$

which then results in

$$V_i^{\text{nomd}} = \int (\dot{V}_i^{\text{od}} + n_i^Q \dot{Q}_i) dt \quad (17)$$

where  $V_i^{\text{nomd}}$  is the distributed control input for voltage regulation and reactive power sharing. Through the local adjustment of the distributed control input, steady-state voltage errors will be eliminated while sharing reactive power between DERs accurately will be made possible.

In the communication layer, distributed broadcast-based gossip algorithm is implemented for information sharing and averaging among a set of distributed DERs. It helps discovering the average values of measured voltage  $V^{\text{Ave}}$  and the total reactive power generation  $Q^{\text{Ave}}$ , which will be explained in detail in the following section.

## B. Broadcast Gossip Algorithm

In a traditional setting, several control methods must be managed through a central controller for voltage regulation and reactive power sharing. It requires communication between the central controller and the DERs by facilitating the global voltage information for average voltage reference  $V^{\text{Ave}}$  and reactive power reference  $Q^{\text{Ave}}$ . However, a central control mechanism

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### Algorithm 1: Broadcast-Based Gossip Push-Sum Algorithm.

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#### Initialization:

Set  $s_i(0) = a_i V_i^{\text{od}}(0)$  and  $a_i(0) = a_i$  for all  $\{i = 1, \dots, N\}$ ;

#### Iterative:

- 1: **for** each time step  $t$ , **do**
  - 2: Let  $\{(\tilde{s}_r, \tilde{a}_r)\}$  be all pairs sent to DER<sub>*i*</sub> at time  $t - 1$
  - 3:  $\sum_r \tilde{s}_r \rightarrow s_i(t)$  and  $\sum_r \tilde{a}_r \rightarrow a_i(t)$
  - 4:  $\{s_{i,i}(t) + (V_i^{\text{od}}(t) - V_i^{\text{od}}(t - 1))\} \rightarrow s_{i,i}(t)$
  - 5: Each *i*th DER send  $\frac{1}{2}s_i(t)$  and  $\frac{1}{2}a_i(t)$  to another random *j*th DER and to itself
  - 6:  $\frac{s_i(t)}{a_i(t)}$  is the average voltage estimate of the *i*th DER of all voltages  $V^{\text{od}} = \langle V_1^{\text{od}}, V_2^{\text{od}}, \dots, V_N^{\text{od}} \rangle$  at time  $t$
  - 7: **end for**
- 

is 1) complex; 2) not reliable to a single point failure; and 3) limits the systems' scalability.

A broadcast gossip method is proposed to be employed for disseminating the locally measured voltages and reactive powers to all DERs in the microgrid. Broadcast gossip protocols for group DERs communication have attractive scalability and plug-and-play properties. In particular, an advantage of the proposed broadcast gossip method is that each DER will know its corresponding local information without any communication (e.g., the local voltage and the output reactive power) at the local-droop control stage, while it does not have direct access to the global information. It can only communicate with its immediate neighboring DERs via a sparse communication network. Thus, the main challenge in the design of a distributed gossip control method is to discover the average voltage reference  $V^{\text{Ave}}$  and reactive power reference  $Q^{\text{Ave}}$  through information exchange between the distributed DERs based on broadcasts.

As explained earlier, the proposed broadcast gossip control is implemented in a peer-to-peer fashion, thereby eliminating any single point of failure that a more centralized method will inherently prone to. The information sharing algorithm should be dynamic and should disseminate the latest available voltage measurements as new data comes in. Besides, it should be resilient to packet losses or delays. This paper employs the broadcast-based gossip push-sum algorithm [24], [25] for approximating the average voltage and reactive power values across a microgrid. The algorithm is adapted so that it can be used for dynamic dissemination of the states of all DERs to any other DER. The algorithmic procedure is presented in Algorithm 1. The accuracy of the estimates depends on the number of asynchronous iterations of the push-sum algorithm. Here, the adopted approach proceeds with the local estimate in each DER (which is more realistic in practice), but it does not need to assume that after each push-sum algorithm, one of the local estimates is broadcasted to all the other DERs.

At all times  $t$ , each vector  $s_i(t)$  and  $a_i(t)$ , respectively, represents a sum, and the weight of this sum for the terminal voltage  $V_i^{\text{od}}$  or reactive power output  $Q_i$  of each DER<sub>*i*</sub> unit. Taking the terminal voltage case as an example, the estimate of the voltage

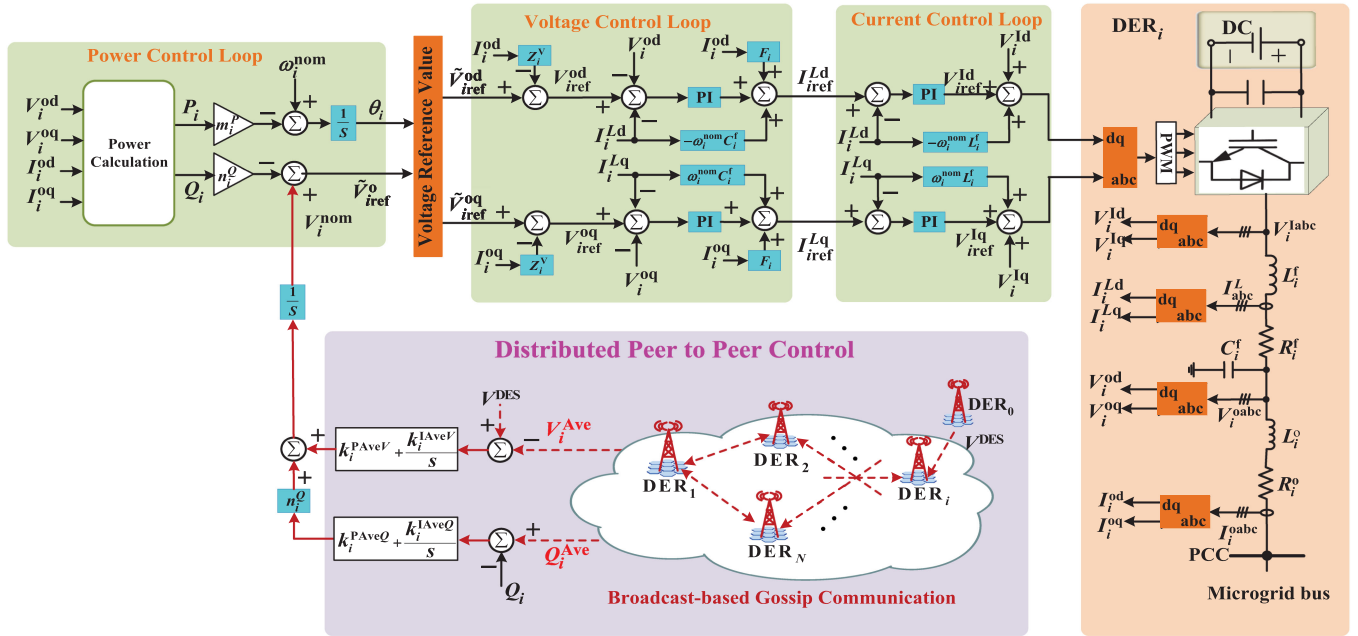


Fig. 3. Proposed distributed peer-to-peer control scheme for  $DER_i$  unit in a microgrid via a broadcast gossip algorithm.

reference value  $V^{Ave}$  can be then calculated as  $\frac{s_i(t)}{a_i(t)}$  at all times  $t$ . These values are always transmitted in pairs, so if a packet gets lost, all the other pairs continue to have a correct estimate of the voltages.  $a_i$  denotes a unit vector with 1 on the  $i$ th position and 0 elsewhere. Each  $DER_i$  unit follows the protocol given in Algorithm 1. In operation 5, the  $i$ th element of vector  $s_i(t) = s_{i,i}(t)$ , is updated with the  $V_i^{od}(t)$  difference between the current step  $t$  and previous time step  $t-1$ , so the latest available measurements are always being spread.

The reactive power reference  $Q^{Ave}$  can also be estimated in the same way by the gossiping Algorithm 1. Regarding the implementation of the proposed broadcast-based gossip algorithm, take a communication network implemented by CAN Bus with PROFIBUS protocols as an example, where the average transmission distance among DERs is 400 m—i.e., the communicating rate is 500 kps. Suppose that there are six pieces (each piece 64 b) of data to be communicated from each DER with six neighboring DERs. Also, assume that the maximum number of iterations is 50, then there are 76.8 kb indirectly inferred global information (i.e., peer-to-peer local communication) to be exchanged in each process. Therefore, the global information can be exchanged seven times per second via peer-to-peer local information exchanges, which is enough to ensure the communication accuracy.

The overall control structure diagram for the proposed distributed peer-to-peer control strategy via a broadcast gossip algorithm is illustrated in Fig. 3. As it can be seen, the virtual leader  $DER_0$  sends the desired voltage,  $V^{DES}$ , to the pinned DERs (which can access the virtual leader directly). A pinned DER will exchange its own information with its neighboring DERs across the sparse communication network. After the dynamical evolution, the control inputs,  $\bar{V}_i^{od}$  in (13) and  $\bar{Q}_i$  in

(15), can be calculated and then used to generate the local voltage reference,  $V_i^{nom}$ , that will be used in the PI voltage controller in the droop control layer. Simultaneously, the voltage control loop generates the current reference,  $I_{iref}$ , for the PI current controller. Ultimately, the current errors are computed to generate the inverter's outputs PWM mode for the  $DER_i$  unit.

*Remark 1:* During the droop control period, the droop control reference  $V_i^{nomd}$  (i.e.,  $V_i^{nom} = \sqrt{(V_i^{nomd})^2 + (V_i^{nomq})^2}$  with  $V_i^{nomq} = 0$ ) of each DER is computed by the integrators (17) with the distributed average voltage controller (12) and reactive power controller (14). Then, during the distributed control period, the control outputs  $V_i^{od}$  and  $Q_i$  (after low-pass filtering) of each DER unit will be sent to their neighbors through a sparse communication network, by which each DER unit shares its own information with its neighbors, consequently the voltage  $V_i^{od}$  and reactive power  $Q_i$  for different DERs will autonomously realize consensus to get the average value of voltage output  $V^{Ave}$  and reactive power  $Q^{Ave}$ . In addition, the external given reference  $V^{DES}$  will be sent to some particular DERs (e.g., only one  $DER_i$  unit), which is located at the root nodes of the sparse communication network. Accordingly, all DERs across the entire system can regulate their voltage values to their consensus average voltage value, while achieving an accurate reactive power sharing.

*Remark 2:* The results in [6], [9], [12], [13], and [18] merely consider the trade-off strategies between voltage regulation and reactive power sharing, thus fail to achieve both at the same time. However, the proposed distributed gossip control strategy is modeled such that the control objectives of voltage restoration and reactive power sharing are synchronously guaranteed. Furthermore, different from the existing methods [5], [9], and [14], our proposed distributed control strategy can realize such

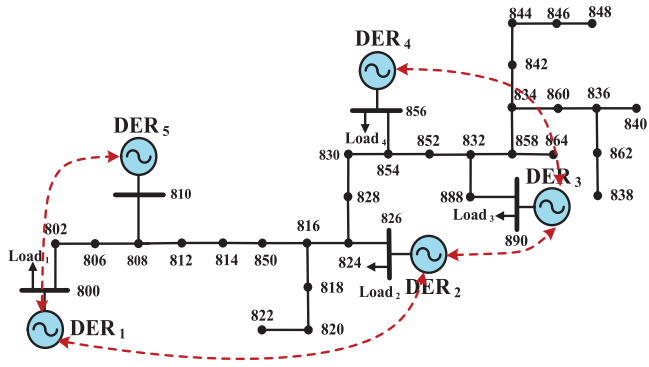


Fig. 4. Modified IEEE 34-bus test microgrid with DERs and local loads considering a communication network (the red dot lines).

control objectives through peer-to-peer communication, which is also inherent with good interference suppression, in a distributed way and within an expected time frame for indirectly discovering the global information in microgrid systems.

*Remark 3:* Since all DERs merely need a partial and limited knowledge of parameters from their neighbors and perform only based on local measurements, the proposed distributed gossip scheme only needs to implement on local DER controllers, which can be more reliable and robust. Compared with the traditional hierarchical control structures in microgrids [5], [13]–[15], there is no hierarchy and no central controller in our proposed framework, which is a totally distributed implementation of droop control and gossip controls. This enhances the redundancy and enables the plug-and-play functionality in microgrids, which in turn, ensures its robustness against topological variations caused by cyber or physical links switching or failures.

#### IV. SIMULATION RESULTS AND DISCUSSIONS

A modified IEEE 34-bus test microgrid system is selected to verify the effectiveness of the proposed distributed peer-to-peer control algorithm and to investigate the effects of DER control variables on the power flow. Fig. 4 shows the basic diagram of the test system which consists of the physical (black solid lines) and communication (red dot lines) networks. In this test system, there are five DERs in a non-parallel configuration and four loads connected to the microgrid. It is assumed that each DER unit can access the required information from its neighbors through a communication network. The communication topology of the microgrid is depicted in the red part in Fig. 4. The specifications of the DERs, lines, and loads are summarized in Table I.

If designed properly, a virtual impedance can lead to an acceptable system transient and steady-state response by increasing the damping capabilities. It, however, affects the inverters' voltage regulation (which will cause voltage drops). In this paper, the method suggested in [26] and [27] is adopted to evaluate the virtual impedance. The values of  $k_i^{\text{PAveV}}$ ,  $k_i^{\text{IAveV}}$ ,  $k_i^{\text{PAveQ}}$ , and  $k_i^{\text{IAveQ}}$  in (13) and (15) are selected through experiential adjustments according to the simulation results. Within certain limits, when the value of  $k_i^{\text{PAveV}}$  and/or  $k_i^{\text{PAveQ}}$  is higher, the

TABLE I  
PARAMETERS OF THE TEST SYSTEM

	DER <sub>1</sub> & DER <sub>2</sub> & DER <sub>5</sub>	DER <sub>3</sub> & DER <sub>4</sub>	
$V_{\text{DC}}$	800(V)	$V_{\text{DC}}$ 680(V)	
$k^{\text{P}}$	$1 \times 10^{-5}$	$k^{\text{P}}$ $0.5 \times 10^{-5}$	
$k^{\text{Q}}$	$3 \times 10^{-4}$	$k^{\text{Q}}$ $6 \times 10^{-4}$	
$k_i^{\text{PV}}$	10	$k_i^{\text{PV}}$ 8	
$k_i^{\text{IV}}$	100	$k_i^{\text{IV}}$ 110	
$k_i^{\text{PI}}$	5	$k_i^{\text{PI}}$ 4	
$k_i^{\text{II}}$	200	$k_i^{\text{II}}$ 180	
$R^{\text{c}}$	0.001( $\Omega$ )	$R^{\text{c}}$ 0.001( $\Omega$ )	
$L^{\text{c}}$	0.2(mH)	$L^{\text{c}}$ 0.2(mH)	
$R^{\text{f}}$	0.1( $\Omega$ )	$R^{\text{f}}$ 0.1( $\Omega$ )	
$C^{\text{f}}$	25( $\mu\text{F}$ )	$C^{\text{f}}$ 25( $\mu\text{F}$ )	
$Z^{\text{V}}$	0.2707( $\Omega$ )	$Z^{\text{V}}$ 0.4399( $\Omega$ )	
Load <sub>1</sub>	Load <sub>2</sub>	Load <sub>3</sub>	Load <sub>4</sub>
12(kVar)	14(kVar)	12(kVar)	13(kVar)
$k_i^{\text{PAveV}}$	$k_i^{\text{IAveV}}$	$k_i^{\text{PAveQ}}$	$k_i^{\text{IAveQ}}$
0.01	0.6	0.001	0.3

voltage can be restored faster. However, it cannot be too large so as to maintain system stability. When the value of  $k_i^{\text{IAveV}}$  and/or  $k_i^{\text{IAveQ}}$  is larger, the steady-state deviation is lower. However, it cannot be too large either so as to maintain system stability.

#### A. Convergence of the Broadcast Gossip Algorithm

Fig. 5 illustrates the local information to be shared in the simulated scenarios. Based on the communication topologies in Tables II and III, the broadcast gossip Algorithm 1 is executed with a time step of 50 ms, meaning that each DER unit sends a  $(\tilde{V}_r, \tilde{A}_r)$  pair to its neighbor each 50 ms. Accordingly,  $V^{\text{Ave}}$  and  $Q^{\text{Ave}}$  can converge to new corresponding average values. Consequently, the global information on the total voltage  $NV^{\text{Ave}}$  and total reactive power  $NQ^{\text{Ave}}$  is indirectly shared in a distributed way to all distributed DERs for decision making. Finally, based on the indirectly shared global information realized through the proposed broadcast gossip algorithm, the distributed peer-to-peer control can be implemented to achieve a cooperative voltage recovery while sharing the reactive power accurately.

The proposed broadcast gossip algorithm method is employed for information sharing, the processes of which are shown in Fig. 5 within five steps. It can be observed from Fig. 5 (c) and (d) that when the DER<sub>1</sub> is plugged out from the microgrid system, the proposed broadcast gossip method can flexibly and successfully adapt the switching communication topologies caused by the plug-and-play operations.

#### B. Load-Change Dynamic Performance

In this case study, the performance of the proposed distributed peer-to-peer control method is verified under sudden load change scenarios by using directed communication network topology of five DERs described in Table II. The simulations are conducted in the following stages:

1) At  $t = 0$  s (simulation initialization period). Only the droop control is activated.

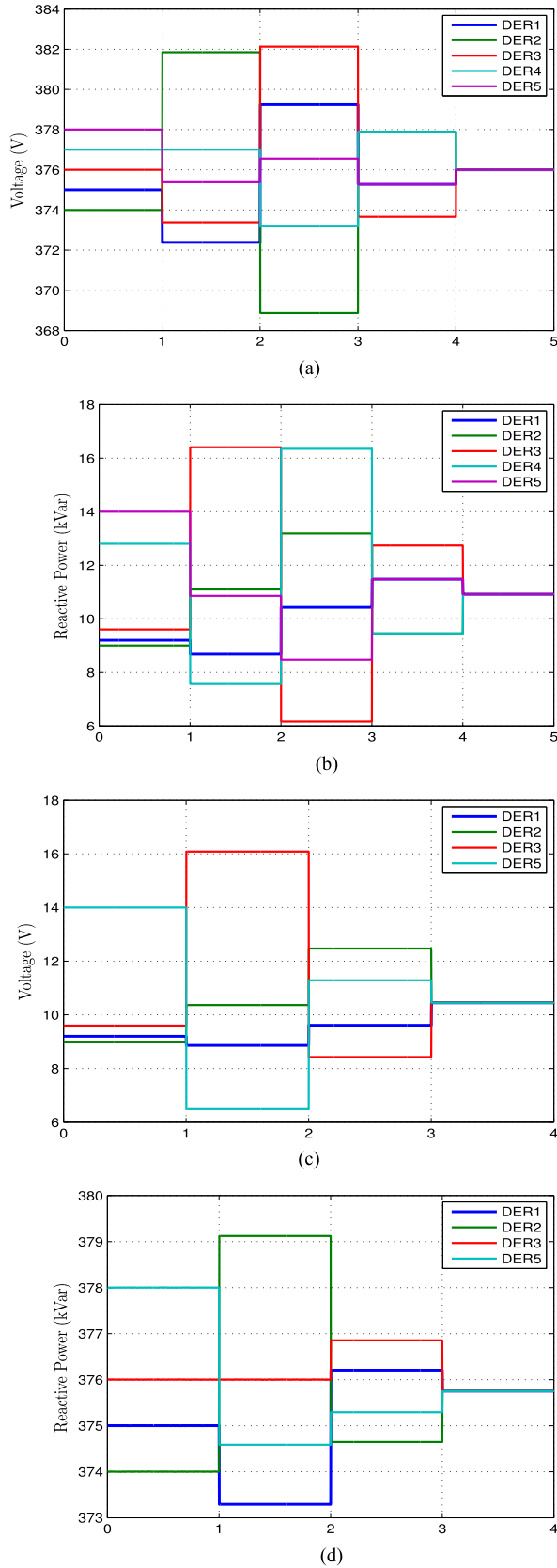


Fig. 5. Broadcast-based gossip information sharing processes. Average voltage discovery process (a) when all DERs are connected to the microgrid and (c) when  $DER_4$  is disconnected from the microgrid. Reactive power discovery process (a) when all DERs are connected to the microgrid and (d) when  $DER_4$  is plugged out from the microgrid.

TABLE II  
GOSSIP-BASED INFORMATION SHARING AMONG DERS

DER <sub>No.</sub>	Neighbors	$a_{ij}$	$Q(0)$ (kVar)	$V(0)$ (V)
DER <sub>1</sub>	2, 5	1	9.2	375
DER <sub>2</sub>	1, 3	1	9	374
DER <sub>3</sub>	2, 4	1	9.6	376
DER <sub>4</sub>	3	1	12.8	377
DER <sub>5</sub>	1	1	14	378

TABLE III  
BROADCAST-BASED GOSSIP INFORMATION SHARING AMONG DERS  
WHEN  $DER_4$  IS PLUGGED-OUT

DER <sub>No.</sub>	Neighbors	$a_{ij}$	$Q(0)$ (kVar)	$V(0)$ (V)
DER <sub>1</sub>	2, 5	1	9.2	375
DER <sub>2</sub>	1, 3	1	9	374
DER <sub>3</sub>	2, 4	1	9.6	376
DER <sub>4</sub>	0	0	0	0
DER <sub>5</sub>	1	1	14	378

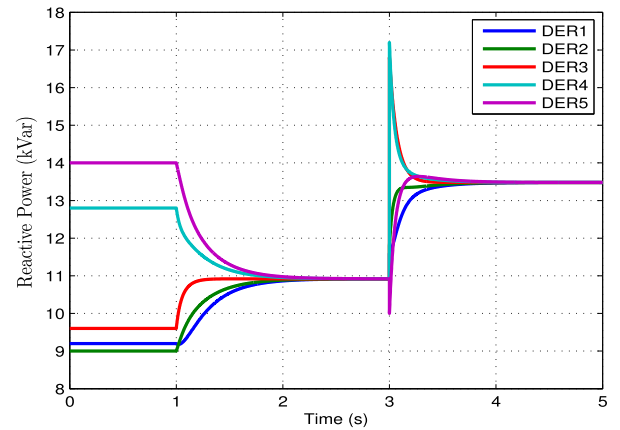


Fig. 6. Performance evaluation of the suggested approach: impact on reactive power under load-change scenarios where the microgrid operates in an autonomous mode.

2) At  $t = 1$  s. The proposed distributed gossip controllers in (13) and in (15) are activated.

3) At  $t = 3$  s. Load<sub>1</sub> and Load<sub>3</sub> are increased in total by the amount of 12.2 kVar.

Figs. 6 and 7 illustrate the state evolution processes of reactive power and PCC's average voltage, respectively. It is assumed that the microgrid works in an autonomous mode at the beginning of the simulation. As seen in Fig. 6, each DER's reactive power  $Q$  is reported at different output values when the microgrid initially operates in an autonomous mode. However, there is a big difference against the reactive power of DERs through the droop control, where the proposed distributed gossip control is able to share properly the reactive power between the DERs even when the load increases from 54.6 to 67.4 kVar. It can also be seen from Fig. 7 that PCC voltage  $V$  reaches a common value of 376 V. However, the PCC voltage is less than the reference value  $V^{DES} = 380$  V owing to the existence of line impedance differences as given in Table I. The proposed distributed gossip control is applied at  $t = 1$  s and  $t = 3$  s, that in turn, restores the PCC operating voltage to its desired reference value, when the load changes frequently as well.



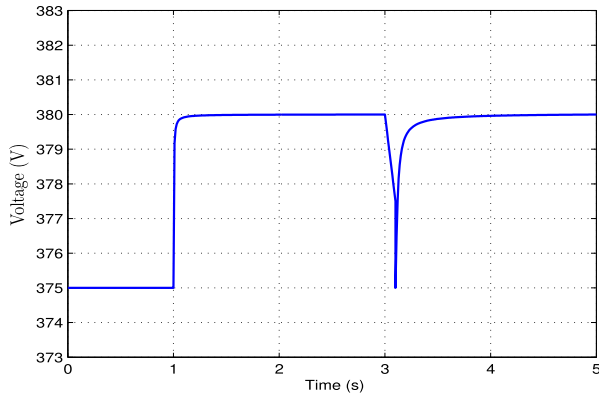


Fig. 7. Performance evaluation of the suggested approach: impact on PCC voltage under load-change scenarios where the microgrid operates in an autonomous mode.

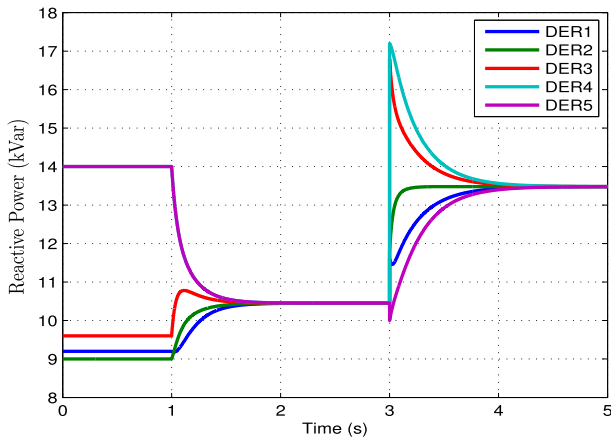


Fig. 8. Performance evaluation of the suggested approach: impact on reactive power under plug-and-play operation of DERs.

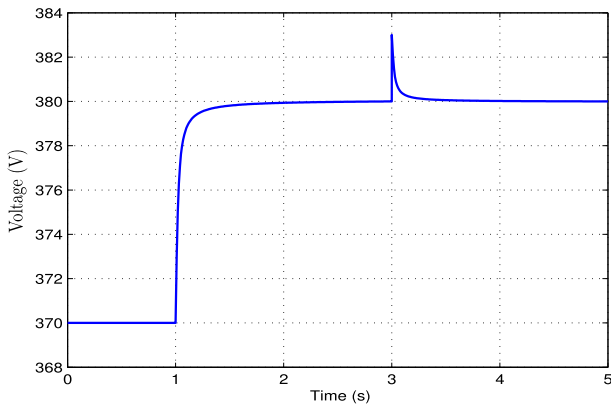


Fig. 9. Performance evaluation of the suggested approach: impact on PCC voltage under plug-and-play operation of DERs.

### C. Plug-and-Play Functionally

In this case study, the broadcast-based gossip information sharing of plug-and-play operation by directed communication network with five DERs (described in Table III) is investigated. In this case, the DER<sub>4</sub> was plugged out and plugged back into the microgrid instantly at  $t = 1$  s and at  $t = 3$  s, respectively.

Figs. 8 and 9 present the dynamic changes in the microgrid and how it can maintain the system transient stability when

TABLE IV  
GOSSIP-BASED INFORMATION SHARING AMONG DERs WITH COMMUNICATION LINK FAILURE BETWEEN DER<sub>3</sub> AND DER<sub>4</sub>

DER <sub>No.</sub>	Neighbors	$a_{ij}$	$Q(0)$ (kVar)	$V(0)$ (V)
DER <sub>1</sub>	2, 5	1	9.2	375
DER <sub>2</sub>	1, 3	1	9	374
DER <sub>3</sub>	2, 4	1	9.6	376
DER <sub>4</sub>	0	0	12.8	377
DER <sub>5</sub>	1	1	14	378

DER<sub>4</sub> experiences a plug-and-play operation. As seen in Fig. 8, when DER<sub>4</sub> fails at  $t = 0$  s, the droop control can capture the corresponding dynamic changes and maintain the microgrid transient stability. The proposed distributed gossip control will operate to respond to such dynamics and restore the output powers of DERs to their average values after 1 s, and then readjusts the load sharing among the remaining DERs. Note that a DER failure can also be realized by failure of all communication links connected to particular DERs. Consequently, while the DER<sub>4</sub> fails, it will automatically drop the link DER<sub>3</sub>–DER<sub>4</sub>, while the remaining links still contain a spanning tree. Then, DER<sub>4</sub> with communication link establishment is plugged back in at  $t = 3$  s. The results in Figs. 8 and 9 show that the proposed distributed gossip-based control method has properly updated the load sharing and global voltage regulation, when DER<sub>4</sub> is plugged back to the steady state. When the communication topology changes, a promising reactive power sharing can also be achieved (see Fig. 8). One can also see in Fig. 9 that the proposed distributed gossip control can restore the PCC output voltage (average) value of all DERs to their prescribed desired values when the communication topology changes.

### D. Communication Link Failure

In order to further confirm the merits of the proposed control strategy from the cyber perspective, we furthermore study the communication link failure in the microgrid. Initially, all DERs exchange their information with their neighbors via a communication network (described in Table IV). Then we repeat the previous analyses discussed in Section V-B with the same simulation scenarios at (1) and (2). In this case, the communication link between DER<sub>3</sub> and DER<sub>4</sub> is no longer connected at  $t = 1$  s. Then it is resumed at  $t = 3$  s.

Figs. 10 and 11 present the dynamical evolutions in case where the communication link between DER<sub>3</sub> and DER<sub>4</sub> is disconnected at  $t = 1$  s, which makes DER<sub>4</sub> unable to exchange information with the rest of the autonomous microgrid. Therefore, as can be seen in Figs. 10 and 11, although the physical link between DER<sub>3</sub> and DER<sub>4</sub> is still effective, the DER<sub>4</sub>'s output voltage is not able to contribute to the average voltage according to (11) and neither be synchronized to their pre-specified reference value. Meanwhile, the reactive power sharing cannot be achieved accurately. On the contrary, the PCC output voltage of the other DERs can still be synchronized to their desired values while a promising reactive power sharing can also be ensured by exchanging shared information from their neighbors. Note that since the DER<sub>4</sub> loses the proposed gossip-based controller, its output voltage is slightly higher than the reference voltage

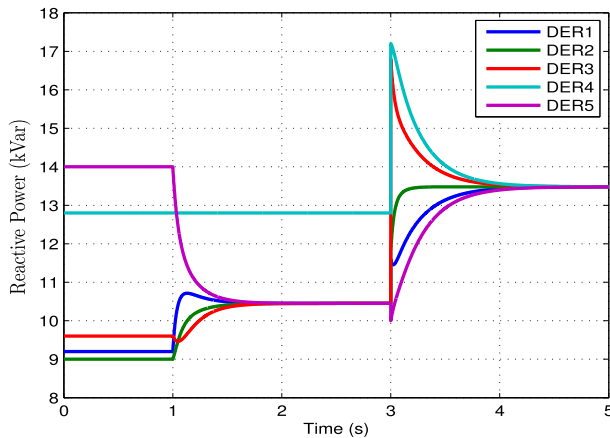


Fig. 10. Performance evaluation of the suggested approach: impact on reactive power under communication link failure scenarios.

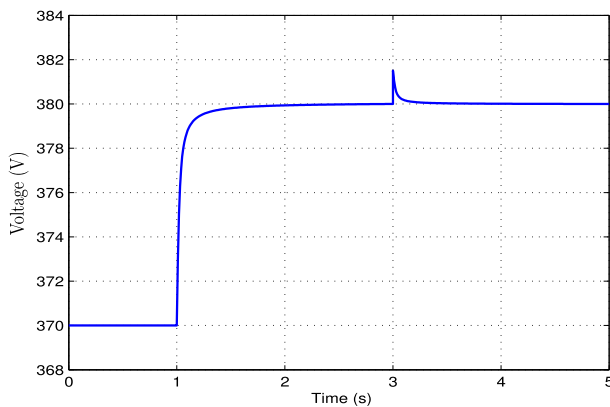


Fig. 11. Performance evaluation of the suggested approach: impact on PCC voltage under communication link failure scenarios.

caused by its own output reactive power reduction. When the communication link between DER<sub>3</sub> and DER<sub>4</sub> is reconnected at  $t = 3$  s, DER<sub>3</sub> could take over the shared information from its neighbors, then the output voltage of DER<sub>4</sub> can be synchronized to their desired value again. Eventually, Figs. 10 and 11 demonstrate the efficiency of the proposed algorithm in the presence of communication link failure. Since DER<sub>4</sub> is in normal operation at the physical level, one can find that the transient behavior of PCC output voltage in Fig. 11 is slightly smaller than that in Fig. 9.

## V. CONCLUSION

In this paper, a fully distributed peer-to-peer gossip control scheme for autonomous microgrids has been proposed, through which all DERs' average voltages can be regulated to the desired values while ensuring an accurate reactive power sharing among them. The broadcast-based gossip information sharing algorithm is locally applied on the DERs for global information discovery indirectly, i.e., the required information of each DER is locally available and only needs to be communicated with its neighboring DERs intermittently. As the main features of the proposed control strategy, the local controllers can satisfy the peer-to-peer requirements of line switches, thereby enabling a plug-and-play operation of DERs as well as a robustness against

the microgrid topology change. As a result, the stability of the microgrid system is preserved in DER plug-in/-out scenarios. Numerical simulations with extensive analysis conducted on a distributed microgrid system demonstrated that the proposed scheme is effective and applicable in real-world scenarios. With the fast increase of DERs and distributed energy storage systems like electric vehicles [28], the researches on the distribution network voltage regulation by distributed energy storage systems [29], [30] and the optimization operation of microgrid like building energy management system associated with demand response [31], [32] should be addressed based on the previous works [33], [34] in the future.

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