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Consensus-based Distributed Control for Accurate Reactive, Harmonic and Imbalance Power Sharing in Microgrids

Jianguo Zhou, Sunghyok Kim, Huaguang Zhang, *Fellow, IEEE*, Qiuye Sun, *Member, IEEE* and Renke Han

Abstract—This paper investigates the issue of accurate reactive, harmonic and imbalance power sharing in a microgrid. Harmonic and imbalance droop controllers are developed to proportionally share the harmonic power and the imbalance power among distributed generation (DG) units and improve the voltage quality at the point of common coupling (PCC). Further, a distributed consensus protocol is developed to adaptively regulate the virtual impedance at fundamental frequency and selected harmonic frequencies. Additionally, a dynamic consensus based method is adopted to restore the voltage to their average voltage. With the proposed methods, the microgrid system reliability and flexibility can be enhanced and the knowledge of the line impedance is not required. And the reactive, harmonic and imbalance power can be proportionally shared among the DG units. Moreover, the quality of the voltage at PCC can be greatly improved. Simulation and experimental results are presented to demonstrate the proposed method.

Index Terms—microgrid, adaptive virtual impedance, reactive power sharing, harmonic power sharing, imbalance power sharing, distributed control, consensus protocol.

NOMENCLATURE

ω_{DG}	Reference angular frequency of the DG unit
ω^*	The nominal angular frequency of the DG unit
E_{DG}	The reference voltage magnitude of the DG unit
E^*	The nominal voltage magnitude of the DG unit
m, n	Droop coefficients
P, Q	Measured active and reactive power after low-pass filtering
$X_{DGf,i}$	The reactance of DG equivalent positive sequence impedances
$Q_{Rated,i}$	The rated reactive powers of DG units
$E_{DGh,i}$	Reference harmonic voltage magnitudes of the DG units
$E_{DGI,i}$	Reference imbalance voltage magnitudes of the DG units
$Q_{Har,i}$	Harmonic power of the i^{th} DG unit
$Q_{Imb,i}$	Imbalance power of the i^{th} DG unit
$n_{h,i}$	Coefficient of the harmonic droop controller
$m_{I,i}$	Coefficient of the imbalance droop controller

$X_{DGH,i}$	Reactance of DG equivalent harmonic impedance
$X_{DGI,i}$	Reactance of DG equivalent imbalance impedance
$Q_{HarRated,i}$	Rated harmonic powers of DG units
$Q_{ImbRated,i}$	Rated imbalance powers of DG units
$L_{PhyH,i}$	Physical feeder inductance at h^{th} harmonic frequency of DG units
$L_{PhyI,i}$	Fundamental negative sequence inductance of physical feeders of DG units
$L_{V,H,i}$	h^{th} harmonic virtual inductance
$L_{V,I,i}$	Fundamental negative sequence virtual inductance
$V_{ref,i,\alpha\beta}$	Reference of fundamental positive sequence voltage of the i^{th} DG unit
$V_{refI,i,\alpha\beta}$	Reference of fundamental negative sequence voltage of the i^{th} DG unit
$V_{refH,i,\alpha\beta}$	Reference of harmonic voltage of the i^{th} DG unit
$V_{vf,i,\alpha\beta}$	Voltage drop on the fundamental positive sequence virtual impedance
$V_{vI,i,\alpha\beta}$	Voltage drop on the fundamental negative sequence virtual impedance
$V_{vH,i,\alpha\beta}$	Voltage drop on the harmonic virtual impedance
$L_{V,H,i}^*$	Static virtual inductance at h^{th} harmonic of the i^{th} DG unit
$L_{V,I,i}^*$	Static fundamental negative sequence virtual inductance of the i^{th} DG unit
$\delta_{L_{V,H,i}}^*$	Virtual impedance correction term at h^{th} harmonic of the i^{th} DG unit
$\delta_{L_{V,I,i}}^*$	Virtual fundamental negative sequence impedance of the i^{th} DG unit
$u_{h,i}$	Control input for harmonic power of the i^{th} DG unit
$u_{I,i}$	Control input for imbalance power of the i^{th} DG unit
C_{hQ}, C_{IQ}	Coupling gains
V_{HN}	Lyapunov function
\mathbf{P}	Positive definite matrix
\mathbf{P}^T	Transpose of matrix \mathbf{P}
E_i^*	Voltage set point of DG i after correction
E_{ref}	Voltage set point of DG units before correction
δE_i	Voltage correction term of DG i
\bar{E}_i	Local estimated voltage of DG i
DG	Distributed generation
PCC	Point of common coupling
THD	Total harmonic distortion
VUF	Voltage unbalance factors
τ	Time delay
$\gamma_{i,j}(t)$	Signal of packet loss or communication link failure
$\lambda_{max}(\mathcal{L})$	The maximum eigenvalue of Laplacian matrix \mathcal{L}

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I. INTRODUCTION

MICROGRID, which can operate in both grid-connected and islanding modes, is a small-scale power system, and can provide a promising solution to integrate renewable and distributed energy resources as well as distributed energy storage systems. It has gained significant attention recently. Due to the presently dominant role of ac systems and the advantages of dc microgrids, ac, dc and hybrid ac and dc microgrids have been widely studied and a variety of surveys

have been reported particularly on the subject of architectural [1], modeling [2], stability analysis and enhancement [3], power quality improvement [4], power sharing [5]-[12], and other issues presently.

In the case of islanding operation, a key topic of interest within the microgrid community is that the load power must be properly shared among a bank of DG units operated in parallel, where the goal is to achieve power sharing proportional to DGs' ratings while keeping the desired frequency and voltage values. The real power-frequency and reactive power-voltage magnitude droop control method has been widely developed to realize decentralized power sharing among DG units without any communications [13]-[15]. The sharing of the real and reactive power at fundamental frequency is the major focus of the droop control. Nevertheless, the accuracy of power sharing and the stability of droop-controlled DG units are often affected by DG unit feeder impedances [16]-[19]. Therefore, various modified droop control methods and virtual impedance-based methods have been reported in literature references [7], [20]-[22]. And the main focus is the behavior of virtual impedance at fundamental frequency. Additionally, the accuracy of the power sharing is also affected by the deviation caused by the droop control [1]. Therefore, various types of centralized and distributed secondary control methods based on the hierarchical control framework have been developed to address this issue [8], [23]-[28], where the distributed methods are mainly based on the multi-agent consensus protocol.

On the other hand, the islanding microgrid may have serious power quality issues due to the intensive nonlinear and imbalance loads. These loads can generate harmonic and imbalance currents when a purely sinusoidal voltage supply is provided. The harmonic and imbalance currents then cause harmonic and imbalance components in the voltage because of the feeder impedances. Apart from conventional solutions (passive or active power filters) [29], DG units can be a prefer selection to address this issue [17], [30], [31]. In facts, various types of centralized and distributed control methods have been reported in the literature references [4]-[6], [32]-[42]. In [32], repetitive control method has been developed to maintain low total harmonic distortions (THD). In [42], a stationary-frame control method for voltage imbalance compensation in an islanding microgrid has been proposed by design a imbalance compensator for the DG unit. Voltage-controlled and current-controlled harmonic compensation methods have been proposed in [33] and [35], respectively, and expended in [6] by combining the two methods. It is well known [18], [19], [21] that virtual impedance is often considered to be a promising way to enhance the power sharing and the power quality. In [5], the output impedance of the DG unit has been changed to be capacitive to reduce the THD of the output voltage by properly designing the virtual impedance. Similar to the situation of reactive power sharing, mismatched feeder impedance and impedance phase angle in a weak microgrid also affects imbalance power and harmonic power sharing performance, and causes harmonic circulating currents among DG units. Therefore, virtual impedance at both fundamental and selected harmonic frequencies has been developed to enhance the reactive power, imbalance power, and harmonic

power sharing performance [34], [36]. For the power quality requirements in different areas in the multibus islanding microgrid, a tertiary control approach has been proposed for voltage imbalance compensation recently [39]. However, these method require a microgrid central controller which could reduce the system reliability. Following, decentralized $G - H$ droop [4] and harmonic droop methods [37], and $Q - G$ droop method [38] have been proposed to compensate the harmonic and imbalance components. Unlike the previous literature, consensus protocol-based distributed control methods also have been developed to improve the reactive power sharing [22] and the power quality in [40], [41], respectively. It is interesting that the consensus protocol-based distributed approach was used to adaptively regulate the virtual impedance for accurate reactive power sharing [22]. However, only positive sequence fundamental virtual impedance was considered for power sharing. The negative sequence fundamental virtual impedance and harmonic virtual impedance also should be considered.

With mainly the aforementioned inspirations, this paper focuses on the control of reactive power, harmonic power and imbalance power sharing and the improvement of the voltage quality at PCC for the islanding microgrid, where a harmonic/imbalance droop and a distributed control strategy are proposed to address the issues. Although centralized controller is able to address the harmonic and imbalance power sharing problems. However, it still has some obvious demerits: 1) the centralized controller usually requires a priori knowledge for the physical line impedances and the number of DGs when it is used to solve the harmonic and imbalance problems, which may need extra estimation approach; 2) for the scenarios communication link or physical line failures, the reliability and the control performance can be greatly reduced, resulting in inaccurate harmonic and imbalance power sharing among DG units; 3) when a new DG needs to be connected to the microgrid, a communication link between the new DG and the central controller should be established, this could not be flexible for us to do possible integration and expansions of DG units; 4) centralized control cannot provide a desired plug-and-play framework. On the contrary, the proposed distributed approach in this paper has the advantages of better flexibility, reliability, and plug-and-play. There is a potential benefit that when a new DG system is added into the system, only neighbor agents of this new DG would have to be connected for communication. This function simplifies the system maintenance and possible expansions. Furthermore, the proposed distributed approach can overcome the impacts of mismatched line impedances, achieving accurate harmonic and imbalance power sharing control by dynamically regulating the virtual impedances without the line impedances information. More importantly, a single link or physical failure and even several failures would not affect the control performance of the overall system, thus DG units will maintain accurate harmonic and imbalance power sharing. Additionally, the distributed control method provides desired plug-and-play feature for microgrids. It may be difficult for the central controller to have these abilities to solve the problems. Microgrid is an important component of the Energy Internet, and the better reliability, flexibility and plug-and-play provided by the dis-

tributed method are the key functional characteristics of the Energy Internet. At present, many technical problems need to be solved to realize plug-and-play for DG units, but this is beyond the scope of this paper. Although the topology within a microgrid is not frequently changed, the communication link or power line failures and the connection or disconnection of DG units do bring a change in topology. In order to enhance the performance and reliability, the impacts of the topology change should be considered. There are still many difficulties in the practical application of the distributed control method at the present stage and problems that need to be addressed. However, the distributed fashion is a development trend, especially with the emergence and development of the concept of smart grid and Energy Internet. Therefore, it is worthwhile to try to do something with this method. In fact, several works are reported in the literature [23], [25]-[28], [40], [41] about the application in power systems.

This paper considers the application of the distributed consensus protocol which are also applied to address various issues in microgrids [23], [25]-[28], [40], [41]. Compared with these literatures in which consensus methods are applied, the main novelty of this paper is that the consensus protocol is applied to dynamically regulate the virtual impedances, overcoming the impacts of mismatched line impedances and the disadvantages of the static virtual impedance. The proposed scheme will result in enhanced reactive power, harmonic power, and imbalance power sharing performance, voltage quality at PCC, system reliability and utilization of distributed energy resources. The main contribution and salient features of this paper can be summarized as follows:

1) A harmonic and imbalance droop control method is proposed to primarily reduce the harmonic and imbalance voltage components, respectively. With this effort, the PCC voltage quality can be enhanced.

2) A consensus-based distributed control strategy is developed to adaptively regulate the positive and negative sequence virtual impedance at fundamental frequency, and virtual impedance at selected harmonic frequencies. Thus, the performance of the reactive power, harmonic power and imbalance power sharing can be improved.

The remainder of this paper is structured as follows. The structure of the microgrid system and the preliminary of graph theory are briefly introduced in Section II. Section III presents the proposed distributed control strategy. Some simulation results are given to validate our method in Section IV. Conclusions are finally drawn in Section V.

II. SYSTEM STRUCTURE AND PRELIMINARY

A. System Structure

An simplified diagram of an islanding microgrid is shown in Fig. 1, where N parallel inverter-based DG units are integrated into the microgrid with different feeders. The microgrid also consists of linear, harmonic, and imbalanced loads placed at PCC. To simplify the discussion, an infinite dc link with fixed dc voltage is assumed in this paper. As well known, all DG units are supposed to provide electric power for the loads in the microgrid when it is operating in islanded mode.

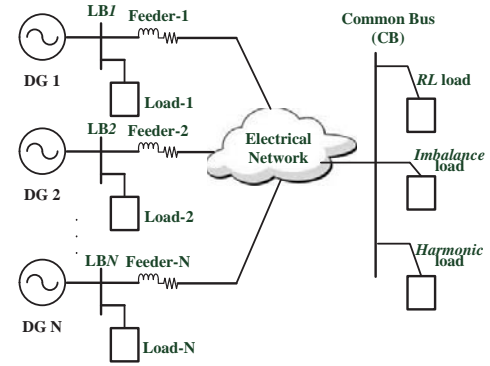


Fig. 1. Single line representation of a three-phase islanding microgrid with harmonic and imbalance loads.

Also, it should be noted that harmonic and imbalance loads commonly exist in a real microgrid, which can cause poor PCC voltage quality. Therefore, DG units should not only provide fundamental frequency power but also provide harmonic power for the loads. In order to improve the quality of PCC voltage, imbalance/harmonic droop controllers are proposed in the paper. When multiple DG units are connected into the microgrid, the feeder impedances are generally mismatched. Thus the harmonic load cannot be supplied by DG units properly. And the quality of voltage at PCC could be still poor. As a result, we need to find a proper method to control DGs to accurately share the load harmonic and imbalance power. This topic is also discussed in several literatures with different control schemes. Of course, if the harmonic magnitudes of DGs are too large, we may need to consider installing extra harmonic compensation equipment in the microgrid. But this is not considered in this paper, and we assume that the DG units could generate enough load harmonic power in the islanding microgrid. And usually, many DG units exist in microgrids, thus the harmonic magnitudes may be not too large if properly shared. Due to the harmonic and imbalance loads, the voltage at PCC will be distorted and imbalanced. To provide enhanced voltage quality and power sharing performance of all the linear, harmonic and imbalance loads, harmonic and imbalance droop method, and consensus-based virtual impedance regulation method are proposed in this paper. The details of the proposed methods will be explained in the next section.

B. Power Sharing with Harmonic and Imbalance Loads

Generally, the conventional real power-frequency droop control and reactive power-voltage magnitude droop control at a DG unit local controller are adopted as

$$\omega_{DG} = \omega^* - mP \quad (1)$$

$$E_{DG} = E^* - nQ \quad (2)$$

where ω^* and ω_{DG} respectively are the nominal and reference angular frequencies of the DG unit; E^* and E_{DG} are the nominal and reference DG voltage magnitude; P and Q are the measured power after low-pass filtering; and m and n are the droop coefficients of the controllers.

Unlike the real power sharing, the stability and the accuracy of the reactive power sharing is affected by mismatched

DG unit feeder impedances. To share the reactive power in proportion to DG rated power and enhance the power sharing performance, the DG unit equivalent impedance shall be designed to be in inverse proportion to DG rating. Accordingly, the following equation should be satisfied:

$$X_{DGf,1}Q_{Rated,1} = X_{DGf,2}Q_{Rated,2} \\ = \cdots = X_{DGf,N}Q_{Rated,N} \quad (3)$$

where $X_{DGf,1}$ to $X_{DGf,N}$ are the reactance of DG equivalent fundamental positive sequence impedances, and $Q_{Rated,i}$, ($i = 1, \dots, N$) are the rated DG reactive powers. The equivalent fundamental positive sequence impedance includes physical feeder impedance and virtual impedance. Conventionally, this equation is correct only when the line is mainly inductive. However, the virtual impedances can be used to design the controllers such that this equation can be correct.

To design and apply the virtual impedance, the physical feeder impedance should be known. Considering the unknown mismatched DG unit feeder impedances, adaptive virtual impedance using the multiagent consensus has been adopted [22], where only the linear loads were considered. In facts, intensive nonlinear and imbalance loads may exist in an islanding microgrid. Thus, DG units should share the nonlinear and imbalance loads, resulting in distorted and imbalanced voltage. This is an important issue. Similarly, fundamental negative sequence and harmonic virtual impedances can be used to ensure better harmonic and imbalance current sharing and improve the quality of voltage at PCC. The online virtual impedance adjustment using PCC voltage has been introduced [34], where a microgrid central controller shall be required. Ideally, according to Kirchhoff Voltage Laws and superposition theorem, if the harmonic and imbalance components of voltage at PCC are expected to be zero, then the voltage drops of the harmonic current and imbalance current on the output impedance should be the same as the harmonic component and the imbalance component of the voltage reference of DG unit. Therefore, a harmonic and imbalance droop control method is proposed in this paper to make the harmonic and imbalance voltages of DG units output voltages match with the voltage drops of the harmonic current and imbalance current on the output impedance thereby obtaining satisfied PCC voltage. Considering the impact of mismatched line impedances which may cause harmonic and imbalance circulating currents and poor power sharing performance, we further develop a consensus-based distributed control strategy to adaptively regulate the positive and negative sequence virtual impedance at fundamental frequency, and virtual impedance at selected harmonic frequencies. With this effort, the PCC voltage quality can be enhanced, and the performance of the reactive power, harmonic power and imbalance power sharing can be improved.

C. Preliminary of Graph Theory

Before introducing the proposed method, some preliminary knowledge of graph theory [43] is briefly presented first for completeness.

A graph is defined as $\mathcal{G} = (\mathcal{V}, \xi)$, where $\mathcal{V} = \{1, \dots, N\}$ denotes the set of vertices and $\xi \subseteq \mathcal{V} \times \mathcal{V}$ is the set of edges between two distinct vertices. if, for all $(i, j) \subseteq \xi$, $(j, i) \subseteq \xi$, then we call \mathcal{G} undirected. Otherwise, it is called a directed graph. In this paper, both the physical and the communication graph are modeled as a undirected connected graph. The set of neighbors of the i^{th} vertex is denoted as $\mathcal{N}_i \triangleq \{j \subseteq \mathcal{V} : (i, j) \subseteq \xi\}$. The elements of the adjacency matrix \mathbf{A} are defined as $a_{ij} = a_{ji} = 1$ if $j \in \mathcal{N}_i$; otherwise, $a_{ij} = a_{ji} = 0$. The Laplacian matrix of \mathcal{G} is defined as $\mathcal{L} = \mathbf{\Delta} - \mathbf{A}$, where $\mathbf{\Delta}$ is called an in-degree matrix and is defined as $\mathbf{\Delta} = \text{diag}(\Delta_i) \subseteq \mathbb{R}^{N \times N}$ with $\Delta_i = \sum_{j \in \mathcal{N}_i} a_{ij}$. The incidence matrix \mathbf{B} of the graph with M distinct edges is defined as $\mathbf{B} = [b_1 \cdots b_M]$, where $(b_l)_i = 1$ and $(b_l)_j = -1$, with other entries being 0 if edge l connects vertices i and j . Then, the weighted Laplacian matrix is defined as $\mathcal{L}_w = \mathbf{B}\mathbf{W}\mathbf{B}^T$, where $\mathbf{W} = \text{diag}(w_1, \dots, w_M)$ is the edge weight matrix and w_i , ($i = 1, \dots, M$) are the edge weights.

III. PROPOSED CONTROL SCHEME

A. Harmonic and Imbalance Droop Controllers

The intensive harmonic and imbalance loads in the microgrid will generate harmonic and imbalance currents. The DG units should properly share the harmonic and imbalance loads in the islanding mode. Additionally, the harmonic and imbalance currents will cause harmonic and imbalance components in the voltages. DGs should be controlled to improve the voltage quality. If the voltage drop of the harmonic current on the output impedance is properly designed and regulated, the harmonic voltage can be reduced [37]. Similarly, if the voltage drop of the imbalance current on output impedance is properly designed and regulated, the imbalance voltage component can be attenuated obviously. Therefore, in order to share the harmonic and imbalance loads in proportion to DG power ratings similar to the fundamental positive sequence real and reactive power loads and enhance the voltage quality, the following h th harmonic droop controller and imbalance droop controller are proposed:

$$E_{DGh,i} = -n_{h,i}Q_{Har,i} \quad (4)$$

$$E_{DGI,i} = -m_{I,i}Q_{Imb,i} \quad (5)$$

where $Q_{Har,i}$ and $Q_{Imb,i}$ are defined as the i th DG unit harmonic power and imbalance power, respectively; $E_{DGh,i}$ and $E_{DGI,i}$ are the reference DG h th harmonic and imbalance voltage magnitude, respectively; and $n_{h,i}$ and $m_{I,i}$ are the corresponding droop coefficients. The imbalance power is calculated by the multiplication of positive-sequence voltage and negative-sequence current, i.e., $Q_{Imb,i} = 3/2 \cdot E_{f,i} \cdot \sqrt{I_{line,I,i,\alpha}^2 + I_{line,I,i,\beta}^2}$ [36], where $E_{f,i}$ is fundamental positive-sequence voltage and $I_{line,I,i,\alpha}$ and $I_{line,I,i,\beta}$ are the fundamental negative-sequence current components on $\alpha - \beta$ coordinate, respectively. It should be noted that in this paper, the phase angle of this voltage can be generated from the integration of ω_{DG} from equation (1) with the addition of $\delta_{I,i}$ which is integrated form $-m_i P_i$. At the same time, the phase angle of the reference harmonic voltage can be obtained in a similar way [37].

With this effort, the harmonic and imbalance load power could be properly shared and the voltage quality could be improved. For proportional harmonic and imbalance power sharing, the DG unit equivalent harmonic impedance and fundamental negative sequence impedance shall be designed to be in inverse proportion to the DG rating. Therefore, the following equations shall be satisfied:

$$X_{DGH,1}Q_{HarRated,1} = X_{DGH,2}Q_{HarRated,2} = \dots = X_{DGH,N}Q_{HarRated,N} \quad (6)$$

$$X_{DGI,1}Q_{ImbRated,1} = X_{DGI,2}Q_{ImbRated,2} = \dots = X_{DGI,N}Q_{ImbRated,N} \quad (7)$$

where $X_{DGH,1}$ to $X_{DGH,N}$ are the reactance of DG equivalent harmonic impedances; $X_{DGI,1}$ to $X_{DGI,N}$ are the reactance of DG equivalent fundamental negative sequence impedances; $Q_{HarRated,1}$ to $Q_{HarRated,N}$ are the rated DG harmonic powers; and $Q_{ImbRated,1}$ to $Q_{ImbRated,N}$ are the rated DG imbalance powers.

For satisfying equation (6) and (7), virtual impedances at fundamental negative sequence and harmonics are adopted due to the mismatched DG unit feeder impedances. Accordingly, the reactance of the DG equivalent impedances at fundamental negative sequence and harmonics in (6) and (7) are composed of two parts:

$$X_{DGH,i} = X_{PhyH,i} + X_{VH,i} = h\omega^*L_{phy,H,i} + h\omega^*L_{V,H,i} \quad (8)$$

$$X_{DGI,i} = X_{PhyI,i} + X_{VI,i} = -(\omega^*L_{phy,I,i} + \omega^*L_{V,I,i}) \quad (9)$$

where $L_{phy,H,i}$ and $L_{phy,I,i}$ are the i th DG unit physical feeder inductance at the h th harmonic and the fundamental negative sequence; and $L_{V,H,i}$ and $L_{V,I,i}$ are the h th harmonic virtual inductance and the fundamental negative sequence inductance controlled by the i th DG unit. Note that only the fifth and seventh harmonic frequencies are considered in this paper, and higher harmonic frequencies can be considered to get a better PCC voltage if it is needed.

Therefore, the reference voltage of the i th DG unit can be given by

$$\begin{aligned} E_{DG,i,\alpha\beta} &= V_{ref,i,\alpha\beta} + V_{refI,i,\alpha\beta} + V_{refH,i,\alpha\beta} \\ &= (E_{DGf,i,\alpha\beta} - V_{vf,i,\alpha\beta}) + (E_{DGI,i,\alpha\beta} - V_{VI,i,\alpha\beta}) + (E_{DGH,i,\alpha\beta} - V_{VH,i,\alpha\beta}) \end{aligned} \quad (10)$$

where $V_{vf,i,\alpha\beta}$, $V_{VI,i,\alpha\beta}$, and $V_{VH,i,\alpha\beta}$ are voltage drops on the virtual impedances.

According to equation (10), by properly designing the droop controllers (4) and (5) and regulating the virtual impedance (9) and (9) at selected harmonics and the fundamental negative sequence, the harmonic and imbalance powers could be better shared by DG units and the PCC voltage quality could be improved. The concept of the method is shown in Fig. 2. The distributed adaptive virtual impedance regulation approach based on the multiagent consensus is also developed in this paper. This will be discussed in detail in the following subsection.

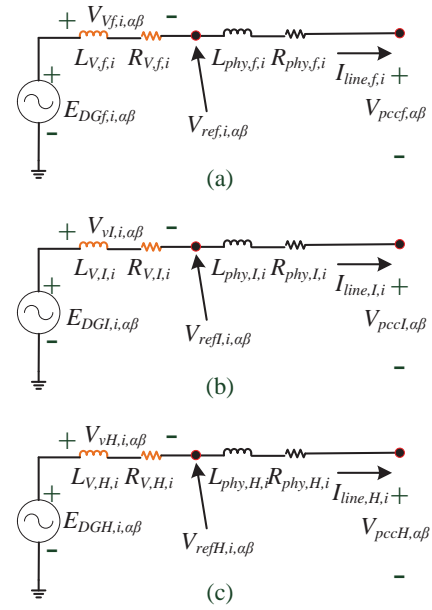


Fig. 2. Illustration of the proposed methods. (a) Equivalent circuit at fundamental positive sequence. (b) Equivalent circuit at fundamental negative sequence. (c) Equivalent circuit at harmonic frequencies.

B. Distributed Adaptive Virtual Impedance Control

As discussed earlier, to design and apply the virtual impedance, it requires the knowledge of DG unit physical feeder impedance which could be difficult to be obtained in reality. Therefore, consensus-based distributed control method is developed in this subsection to regulate the virtual impedance. It should be noted that the regulation of the fundamental positive sequence virtual impedance has been discussed in [22]. It will not be discussed here again. The harmonic and fundamental negative sequence virtual impedance can be expressed as:

$$X_{VH,i} = X_{VH,i}^* + \Delta x_{VH,i} = h\omega^*(L_{V,H,i}^* - k_{LV,H,i}\delta_{LV,H,i}) \quad (11)$$

$$X_{VI,i} = X_{VI,i}^* + \Delta x_{VI,i} = \omega^*(L_{V,I,i}^* - k_{LV,I,i}\delta_{LV,I,i}) \quad (12)$$

where $L_{V,H,i}^*$ and $L_{V,I,i}^*$ are the i th DG unit static virtual inductance at the h th harmonic and the fundamental negative sequence; $\delta_{LV,H,i}$ and $\delta_{LV,I,i}$ are the virtual impedance correction terms at the h th harmonic and the fundamental negative sequence, respectively; and $k_{LV,H,i}$ and $k_{LV,I,i}$ are the corresponding proportional gains.

The distributed consensus protocols are designed to generate the virtual impedance correction terms $\delta_{LV,H,i}$ and $\delta_{LV,I,i}$ through PI controllers to drive $n_{h,i}Q_{Har,i}$ and $m_{I,i}Q_{Imb,i}$ to be equal, respectively. In this paper, the harmonic and imbalance power sharing based on distributed control is realized by constructing multi-agent systems. Also, this control problem in our paper can be considered as a regulator synchronization problem of the first-order linear integral multi-agent system. Therefore, we, in the paper, construct the first-order linear multi-agent system (13) and (14) by using the local DG harmonic and imbalance power information, respectively.

$n_{h,i}Q_{Har,i}$ and $m_{I,i}Q_{Imb,i}$ can be considered as the state x_i from the perspective of control theory, and $u_{h,i}$ and $u_{I,i}$ can be considered as the control input u_i .

$$n_{h,i}\dot{Q}_{Har,i} = u_{h,i} \quad (13)$$

$$m_{I,i}\dot{Q}_{Imb,i} = u_{I,i} \quad (14)$$

where $u_{h,i}$ and $u_{I,i}$ are the auxiliary control inputs for harmonic power and imbalance power, respectively, and $\dot{Q}_{Har,i}$ and $\dot{Q}_{Imb,i}$ are the variations of the harmonic power and imbalance power, respectively. To achieve the consensus of the system (13) and (14), respectively, the harmonic power and the imbalance power information from the local DG unit and the neighboring DG units are utilized to construct the auxiliary control inputs:

$$\begin{aligned} u_{h,i} &= -C_{hQ}e_{h,i} \\ &= -C_{hQ} \sum_{j \in \mathcal{N}_i} a_{ij} (n_{h,i}Q_{Har,i} - n_{h,j}Q_{Har,j}) \end{aligned} \quad (15)$$

$$\begin{aligned} u_{I,i} &= -C_{IQ}e_{I,i} \\ &= -C_{IQ} \sum_{j \in \mathcal{N}_i} a_{ij} (m_{I,i}Q_{Imb,i} - m_{I,j}Q_{Imb,j}) \end{aligned} \quad (16)$$

where C_{hQ} and C_{IQ} are the coupling gains. Further, the entire system can be derived as

$$\dot{\mathbf{X}} = \mathbf{u} \quad (17)$$

$$\mathbf{u} = -\mathbf{C}\mathbf{e} \quad (18)$$

$$\mathbf{e} = \mathbf{L}\mathbf{X} \quad (19)$$

where $\mathbf{X} = [(n_h \mathbf{Q}_{Har})^T, (m_I \mathbf{Q}_{Imb})^T]^T$, $\mathbf{u} = [u_h^T, u_I^T]^T$, $\mathbf{e} = [e_h^T, e_I^T]^T$, $n_h \mathbf{Q}_{Har} = [n_{h,1}Q_{Har,1}, \dots, n_{h,N}Q_{Har,N}]^T$, $m_I \mathbf{Q}_{Imb} = [m_{I,1}Q_{Imb,1}, \dots, m_{I,N}Q_{Imb,N}]^T$, $u_h = [u_{h,1}, \dots, u_{h,N}]^T$, $u_I = [u_{I,1}, \dots, u_{I,N}]^T$, $e_h = [e_{h,1}, \dots, e_{h,N}]^T$, $e_I = [e_{I,1}, \dots, e_{I,N}]^T$, $\mathbf{L} = \text{diag}(\mathcal{L}, \mathcal{L})$. $e_{h,i}$ is the sum of the harmonic power sharing errors from the local i th DG unit and its neighbor DG units, $e_{I,i}$ is the sum of the imbalance power sharing errors from the local i th DG unit and its neighbor DG units, and \mathcal{L} is the Laplacian matrix of the graph.

The auxiliary control inputs $u_{h,i}$ and $u_{I,i}$ are fed to the PI controllers to generate the corresponding virtual impedance correction terms $\delta_{LV,H,i}$ and $\delta_{LV,I,i}$ to adaptively regulate the virtual impedances. Following, the proof of the stability of the method is presented.

Consider the Lyapunov function as

$$V_{HI} = \frac{1}{2} \mathbf{e}_h^T \mathbf{P} \mathbf{e}_h + \frac{1}{2} \mathbf{e}_I^T \mathbf{P} \mathbf{e}_I \quad (20)$$

where the matrix $\mathbf{P} = \mathbf{P}^T$ is positive definite. Then the deviation of (21) could be obtained.

$$\begin{aligned} \dot{V}_{HI} &= \mathbf{e}_h^T \dot{\mathbf{P}} \mathbf{e}_h + \mathbf{e}_I^T \dot{\mathbf{P}} \mathbf{e}_I \\ &= -C_{hQ} \mathbf{e}_h^T \mathbf{P} \mathbf{L} \mathbf{e}_h - C_{IQ} \mathbf{e}_I^T \mathbf{P} \mathbf{L} \mathbf{e}_I \\ &= -\frac{1}{2} C_{hQ} \mathbf{e}_h^T (\mathbf{P} \mathbf{L} + \mathcal{L}^T \mathbf{P}) \mathbf{e}_h - \frac{1}{2} C_{IQ} \mathbf{e}_I^T (\mathbf{P} \mathbf{L} + \mathcal{L}^T \mathbf{P}) \mathbf{e}_I \end{aligned}$$

According to the literature [44], the matrix $\mathbf{P} \mathbf{L} + \mathcal{L}^T \mathbf{P}$ is positive definite. Therefore, $\dot{V}_{HI} < 0$ is satisfied, demonstrating that the proposed control system is asymptotically stable.

The proof is completed. Thus, when the system steady state is achieved, $n_{h,i}Q_{Har,i} = n_{h,j}Q_{Har,j}$ and $m_{I,i}Q_{Imb,i} = m_{I,j}Q_{Imb,j}$, where $i \neq j$. This means that the imbalance power and harmonic power can be properly and proportionally shared by DG units, respectively.

It is worthy to remark here that the proposed adaptive regulation approach of the virtual impedance at the fundamental negative sequence and the selected harmonics is fully distributed. Each local distributed controller needs only the information from the local DG units and its neighbor DG units, resulting in better reliability for the whole system. Furthermore, with the proposed harmonic/imbalance droop method and the distributed adaptive virtual impedance regulation approach, the harmonic and imbalance load power could be properly shared by DG units and the voltage quality could be improved as well.

On the other hand, communication delay, loss of packet, and failures of communication links may also affect the performance of the system. Considering the communication time-delay $\tau > 0$, the consensus protocol-based control inputs (15) and (16) could be expressed as:

$$u_{h,i}(t) = -C_{hQ} \sum_{j \in \mathcal{N}_i} a_{ij} (x_{h,i}(t - \tau) - x_{h,j}(t - \tau)) \quad (21)$$

$$u_{I,i}(t) = -C_{IQ} \sum_{j \in \mathcal{N}_i} a_{ij} (x_{I,i}(t - \tau) - x_{I,j}(t - \tau)) \quad (22)$$

where $x_{h,i}(t - \tau) = n_{h,i}Q_{Har,i}(t - \tau)$, $x_{I,i}(t - \tau) = m_{I,i}Q_{Imb,i}(t - \tau)$. Then, by taking the Laplace transform, the following equations in a compact form can be obtained:

$$n_h Q_{Har}(s) = (sI + L)^{-1} n_h Q_{Har}(0)$$

$$m_I Q_{Imb}(s) = (sI + L)^{-1} m_I Q_{Imb}(0)$$

where \mathcal{L} is the Laplacian matrix of a graph with adjacency matrix $\mathbf{A} = [C_{hQ}a_{ij}e^{-\tau s}]$ or $[C_{IQ}a_{ij}e^{-\tau s}]$. According to the literature [46], the consensus control with time-delay can be globally asymptotically stable by solving the average-consensus problem if and only if $0 < \tau < \pi/(2\lambda_{\max}(\mathcal{L}))$. Because the upper bound of the time-delay is inversely proportional to the maximum eigenvalue of Laplacian matrix $\lambda_{\max}(\mathcal{L})$, there is a tradeoff between robustness margin to the time-delays and convergence speed. Therefore, the adjacency matrix \mathbf{A} should be suitable chosen with considering a tradeoff between them. More details about the proof can be found in [46].

Further, if the loss of packet and communication link failures are considered, the consensus protocol-based control inputs can be expressed as:

$$u_{h,i}(t) = -C_{hQ} \sum_{j \in \mathcal{N}_i} \gamma_{i,j}(t) a_{ij} (x_{h,i}(t - \tau) - x_{h,j}(t - \tau))$$

$$u_{I,i}(t) = -C_{IQ} \sum_{j \in \mathcal{N}_i} \gamma_{i,j}(t) a_{ij} (x_{I,i}(t - \tau) - x_{I,j}(t - \tau))$$

where $\gamma_{i,j}(t) = 1$ if there is no packet loss or communication link failure from agent j to agent i , and $\gamma_{i,j}(t) = 0$ otherwise. According to the published literature [47]-[49], for the first-order integrator dynamics (13) and (14), the agents can converge to a common steady state if the undirected topology

has a spanning tree or is jointly connected. This condition is usually satisfied in microgrids. The parameters can be properly designed by using the theory of linear matrix inequality (LMI). More details about the theory and design method can be found in literature [47]–[49].

C. Voltage Restoration Control

Voltage regulation is another objective of the microgrid control. In this subsection, the voltage restoration issue will be considered. To compensate the voltage deviation caused by the droop control and the virtual impedance, the dynamic consensus-based distributed controllers are developed to regulate the output voltages of all the DG units. The voltage regulation requirement is redefined to incorporate the line impedance effect. The average voltage across the microgrid (and only not a specific bus voltage) should be regulated at the global voltage set point. In this paper, a so called dynamic consensus-based observer [22], [45] that processes neighbors data to estimate the average voltage across the microgrid is adopted. This estimation is further used to generate a voltage correction term through a PI controller to adjust the local voltage set point. The voltage set point for an individual DG can be expressed as

$$E_i^* = E_{ref} + \delta E_i \quad (23)$$

where δE_i is the voltage correction term which can be obtained from equation (24):

$$\delta E_i = G_i(s)(E_{ref} - \bar{E}_i) \quad (24)$$

where $G_i(s)$ is the PI controller for generating the correction term of voltage restoration, and \bar{E}_i is the local estimation obtained from the observer given by

$$\bar{E}_i = E_i + C_E \int_0^t \sum_{j \in \mathcal{N}_i} a_{ij} (\bar{E}_j - \bar{E}_i) d\tau \quad (25)$$

where \bar{E}_j is the estimation from the neighbor j , and C_E is the coupling gain. With this method, the estimated voltage will converge to the global average voltage and can be restored to the rated voltage of the microgrid. The proof can be found in detail in [22].

D. Overall Control Diagram

The overall control block diagram showing the realization of the proposed control scheme can be found in Fig. 3 in detail. The controller consists of separate modules: imbalance and harmonic droop controllers, distributed adaptive virtual impedance controllers, and voltage restoration controller. The imbalance and harmonic droop controllers are developed to enable the DG units proportionally share the imbalance and harmonic loads and enhance the voltage quality at PCC. The adaptive virtual impedance control is based on the consensus protocol, which can enhance the accuracy of power sharing among DG units. The voltage restoration controller collectively adjust the average voltage of the microgrid on the rated value, yet individual bus voltages may slightly deviate from the

rated value (typically, less than 5%). The controller at inverter i receives information of its neighbors (\bar{E}_j , $n_{f,j}Q_{Fund,j}$, $m_{I,j}Q_{Imb,j}$, $n_{h,j}Q_{Har,j}$), and processes the neighbors' and local data (E_i , $n_{f,i}Q_{Fund,i}$, $m_{I,i}Q_{Imb,i}$, $n_{h,i}Q_{Har,i}$) to generate the correction terms (δE_i , $\delta_{LV,F,i}$, $\delta_{LV,I,i}$, $\delta_{LV,H,i}$) of the voltage and the virtual impedance through PI controllers ($G_i(s)$, $H_{f,i}(s)$, $H_{I,i}(s)$, $H_{H,i}(s)$). It can be seen that the controller at each inverter is totally distributed and that each controller only use the information of its local and neighbors units, which can be more flexible and reliable.

IV. SIMULATION RESULTS

To validate the performance of the proposed control scheme, the microgrid system has been simulated in MATLAB/Simulink environment. The microgrid has its own four DGs and loads. The test system and the parameters are presented in Fig. 4 and Table I to Table III in Appendix, respectively. The communication topology is also shown in Fig. 4, which is a ring-shape topology with four channels.

Several alternative communication connections are shown in Fig. 5. Communication links are assumed bidirectional to feature a balanced Laplacian matrix and help with the sparsity of the resulting communication graph. Although all alternative graphs include spanning trees, some are prone to lose connectivity in the case of a single link failure. For example, if any of the links highlighted in black in Fig. 5(a) or (b) is lost, the corresponding graph losses its connectivity, which hinders the functionality of the control mechanism. Fig. 5(c) is a fully connected graph, but it lacks sparsity. However, for the set of four agents, the ring-shape communication topology in Fig. 5(d) is the sparsest network where the failure of a single link does not compromise the graphical connectivity. Therefore, the communication topology in Fig. 5(d) is chosen for data exchange in the cyber layer. The communication network in Fig. 5(e) is utilized to test the performance in case of communication link failures (link between DG1 and DG2, links between DG1 and DG2, and between DG1 and DG4).

Some results are presented and discussed in detail in the following.

A. Case-1: Imbalanced Load

Firstly, only a linear imbalanced load is connected to PCC. All DG units have the same power ratings. From the time range $t=0s$ to $t=0.5s$, only the conventional method is adopted. After $t=0.5s$, the proposed method which combines the proposed imbalance droop controller (4), (5) and the consensus-based virtual negative sequence impedance controller (15), (16) is adopted. The simulation results are presented in Fig. 6. From Fig. 6(a) to Fig. 6(c), it is obvious that the active power sharing is always accurate, but the sharing of the reactive power and the imbalance load power has obvious errors with the conventional method. Although DG units have the same power ratings, DG units share different amount of reactive power and imbalance power. This is mainly caused by the mismatched feeders. From $t=0.5s$, the reactive power and the imbalance power are accurately shared among DG units with the proposed method activated. As shown in Fig. 6(b) and

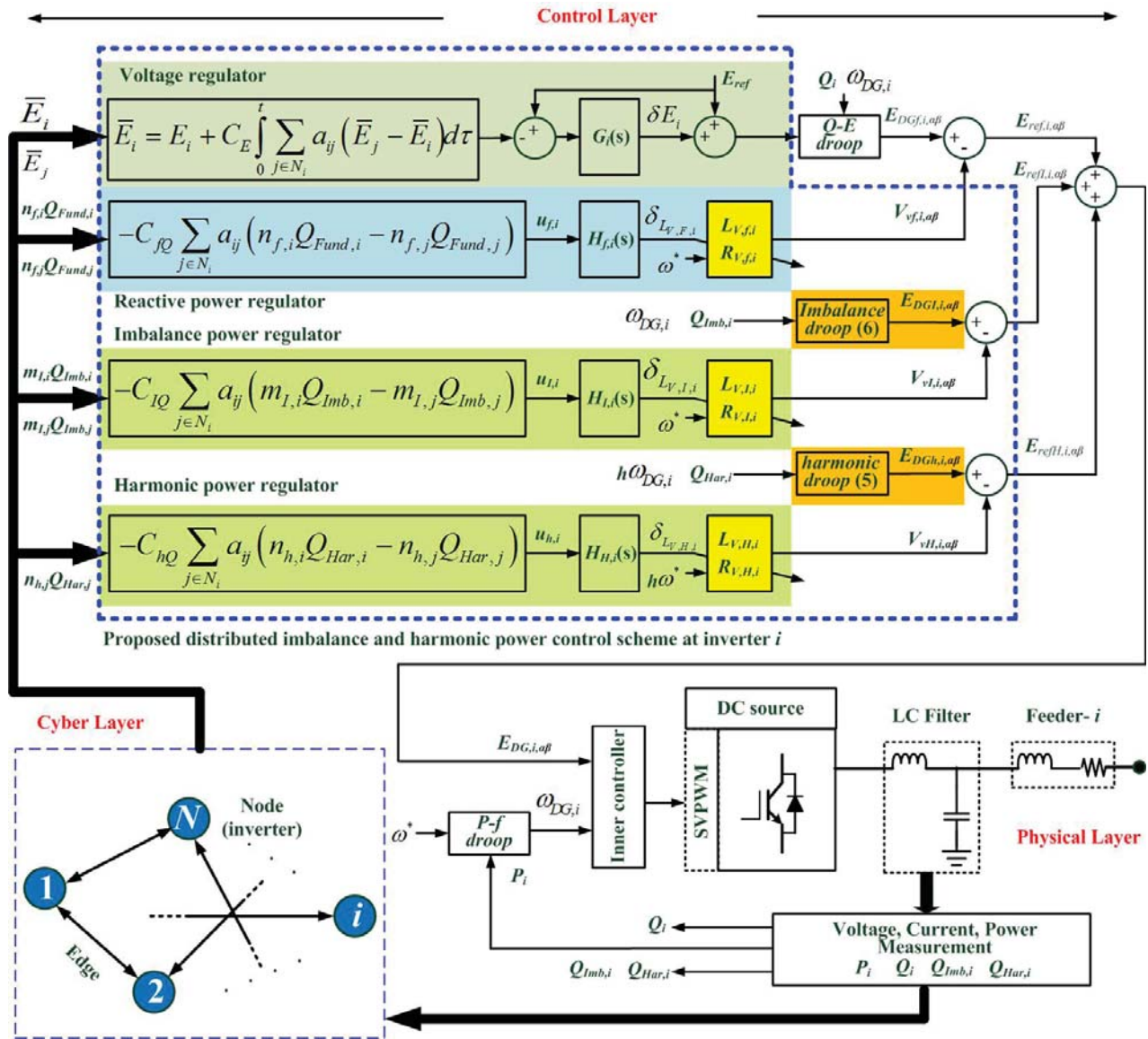


Fig. 3. The overall control block diagram of the proposed distributed control scheme.

Fig. 6(c), all DG units share the same amount of reactive and imbalance powers, which mainly benefits from the consensus-based adaptive regulation of virtual impedances. Also, as shown in Fig. 6(a), the proposed strategy has hardly effects on the active power sharing performance. Form Fig. 6(d), (e) and (f), the DG units properly share the load current with the proposed method. Fig. 6(g), (h) and (i) show the PCC voltage performance. Fig. 6(j), (k) and (l) show the components of the fundamental negative sequence PCC voltage without and with the proposed method, respectively. It should be noted that the voltage quality at PCC is also obviously improved using the proposed method. Seen from Fig. 6(k) and (l), the magnitudes of the fundamental negative sequence voltage magnitude at PCC on $\alpha\beta$ coordinates are reduced from about 7.5 V to 1 V.

B. Case-2: Harmonic Load

Following, to investigate the performance of harmonic load sharing, a three-phase diode rectifier load is considered at the

PCC to replace the three-phase linear imbalance load. Fig. 7 shows the performance of the microgrid. As illustrated in Fig. 7(a) and (b), the harmonic power could not be accurately shared by DG units proportional to their power ratings with the conventional method (before $t=0.5s$). They share different amount of harmonic power. Fig. 7(d) shows the phase-A currents of all the DG units, which also demonstrates the inaccurate harmonic power sharing. At the same time, the voltage at PCC is seriously distorted (THD=10.39%) shown in Fig. 7(g) and Fig. 7(i). After $t=0.5s$, the proposed control scheme is implemented in DG units. The harmonic power is accurately shared by DG units (shown in Fig. 7(a) and Fig. 7(b)), and DG units output the same amount of currents shown in Fig. 7(e). Moreover, the quality of the voltage at PCC is improved seen from Fig. 7(h) and Fig. 7(j) (THD=7.67%). Note that only the fifth and seventh harmonic frequencies are controlled in this paper, and higher harmonic frequencies can be considered if it is needed.

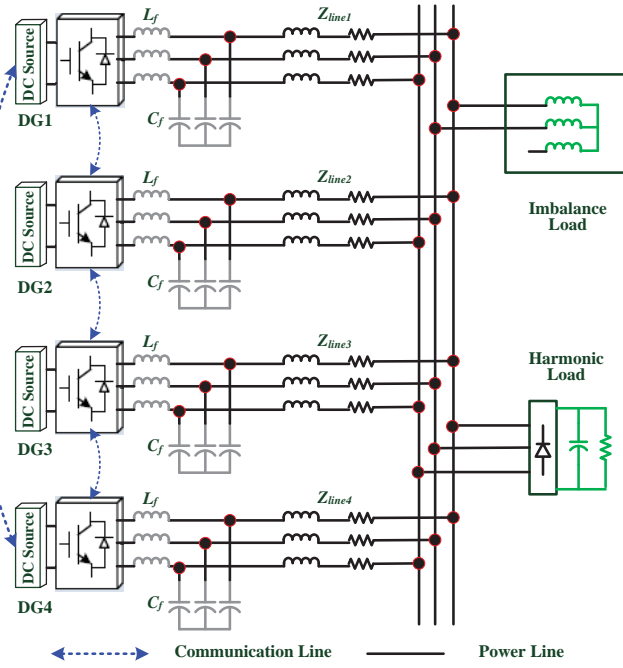


Fig. 4. The simulation test microgrid system.

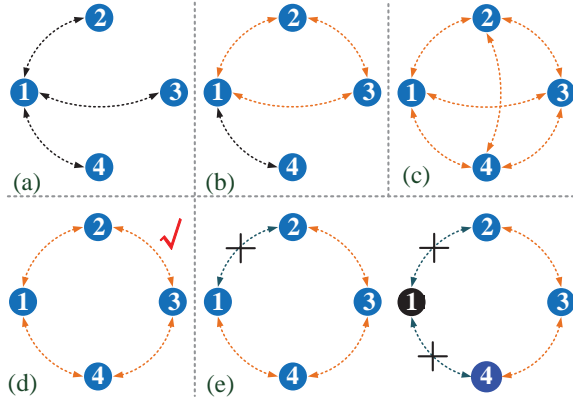


Fig. 5. Connections of communication topology: (a) No redundant link. (b) Suboptimal link redundancy. (c) Full connection. (d) Optimal ring-shape connection adopted in this paper. (e) Link failures: link 1-2; link 1-2 and link 1-4.

C. Case-3: Generalized Loads

Finally, generalized PCC loads, an imbalanced load and a three-phase diode rectifier, are connected to PCC at the same time to test the effectiveness of the proposed method. The results are presented in Fig. 8. As illustrated in Fig. 8(a) to Fig. 8(e), without the proposed method, the DG units cannot accurately share the imbalanced and nonlinear loads, the output reactive, imbalance and harmonic powers are greatly different with each other before $t=0.5s$. And seen from Fig. 8(g), the output currents (phase-A) of DG units are also not the same, their magnitudes are different. From Fig. 8(i), (k) and (m), we could find that the PCC voltage is imbalanced ($VUF=6\%$) and distorted ($THD=9.72\%$). The PCC voltage quality is fairly poor. However, after $t=0.5s$, the situation is greatly improved with the proposed method activated. Seen

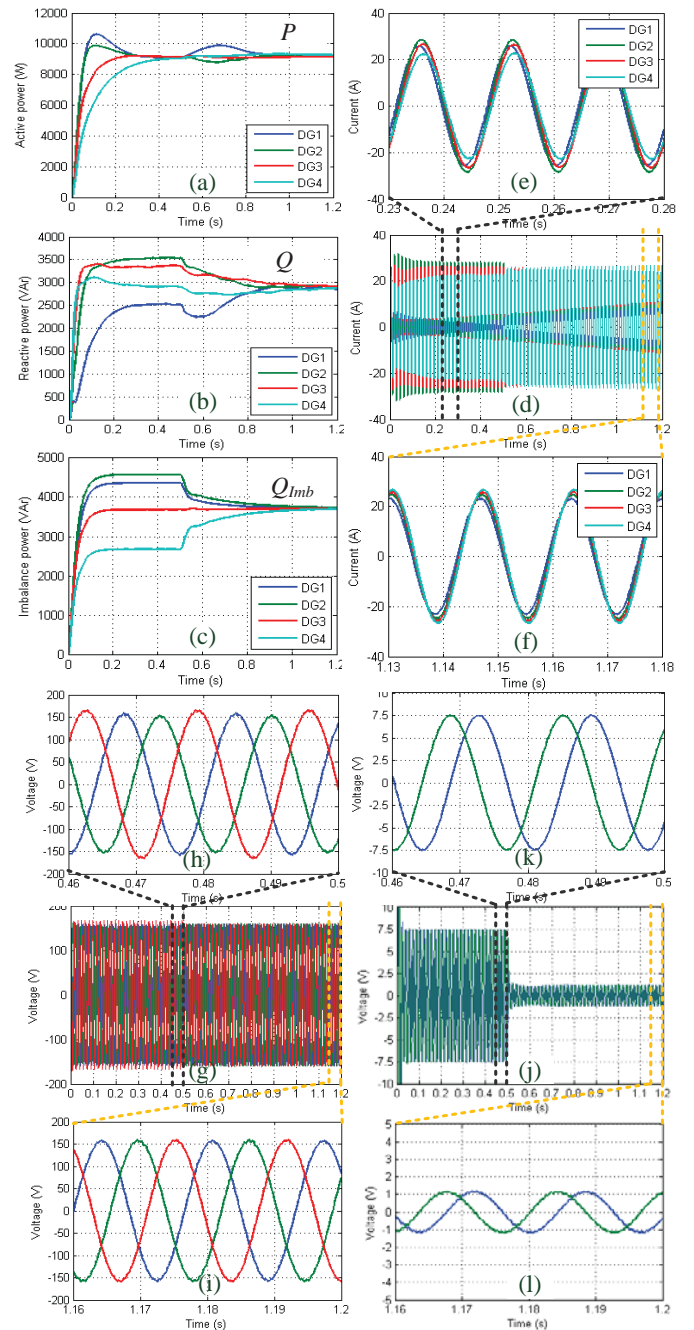


Fig. 6. The simulation results with imbalance loads. (a) Active power. (b) Reactive power. (c) Imbalance power. (d) Phase-A currents of DG units. (e) Phase-A currents of DG units with conventional method. (f) Phase-A currents of DG units with proposed method. (g) PCC voltage. (h) PCC voltage before with the conventional method. (i) PCC voltage with the proposed method. (j) $\alpha\beta$ components of the negative sequence PCC voltage. (k) $\alpha\beta$ components of the negative sequence PCC voltage with the conventional method. (l) $\alpha\beta$ components of the fundamental negative sequence PCC voltage with the proposed method.

from Fig. 8(a) to Fig. 8(e), the reactive, imbalanced and harmonic loads are accurately shared among DG units, and the output currents shown in Fig. 8(h) are changed to be equal as well. From Fig. 8(i), (l) and (n), the voltage quality at PCC are better now. The THD and VUF of the voltage at PCC are changed to 6.28% and less than 2%, respectively. It

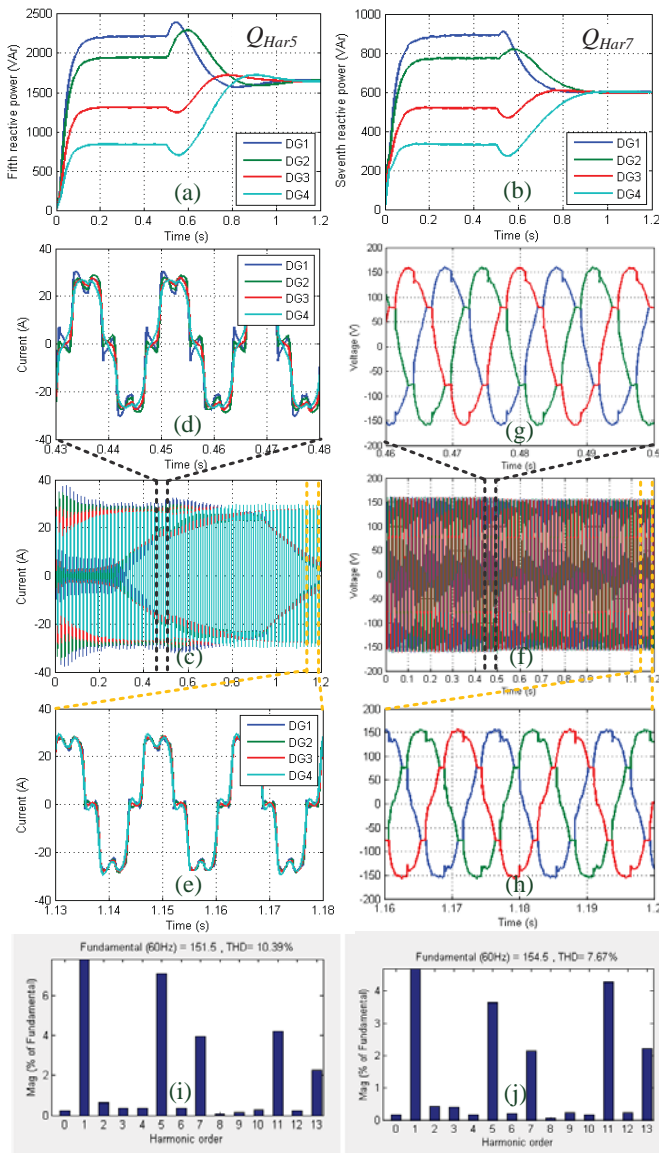


Fig. 7. The simulation results with harmonic loads. (a) and (b) Harmonic power performance. (c) Phase-A currents of DG units. (d) Phase-A currents of DG units without the proposed method. (e) Phase-A currents of DG units with the proposed method. (f) PCC voltage. (g) PCC voltage without the proposed method. (h) PCC voltage with the proposed method. (i) THD of PCC voltage without the proposed method. (j) THD of PCC voltage with the proposed method.

should be noted that the harmonic voltages at PCC are not totally eliminated since only the fifth and seventh harmonic frequencies are considered. If other harmonic frequencies are considered in the control loops, the quality of the PCC voltage about harmonic compensation would be better.

D. Case-4: Impact of Time Delay

In reality, communication time-delays may affect the performance of the system and even result in instability. Therefore, the effects of the communication time-delays are considered in this case. According to the system settings, the maximum time-delay is $\tau_{max} = 31.4\text{ms}$ with the maximum eigenvalue of Laplacian matrix $\lambda_{max}(\mathcal{L})=4$ and the coupling gains $C_{hQ} =$

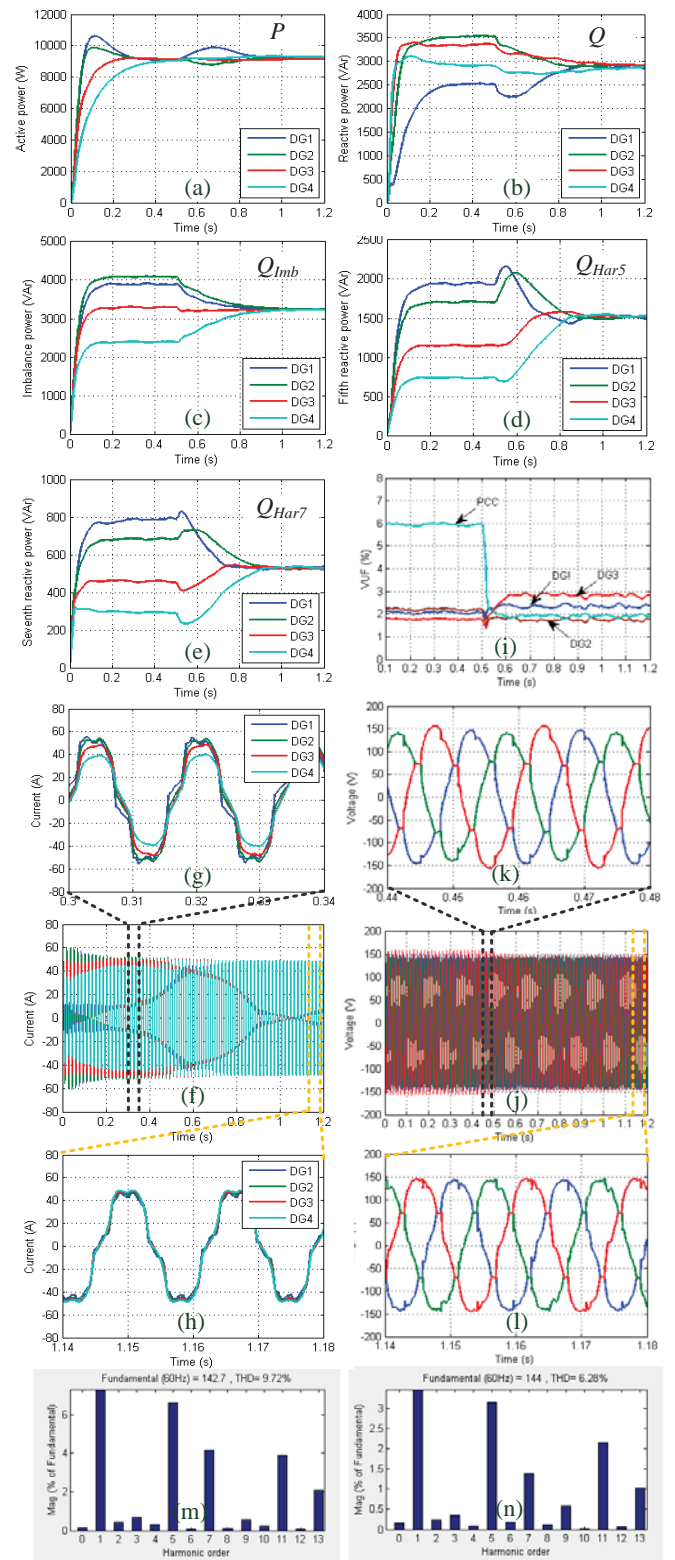


Fig. 8. The simulation results with generalized loads. (a) Active power. (b) Reactive power. (c) Imbalance power. (d) and (e) Harmonic power. (f) Phase-A currents of DG units. (g) and (h) Phase-A currents of DG units without and with the proposed method. (i) Voltage unbalance factors (VUF) at PCC and DG output terminals. (j) PCC voltage. (k) and (l) PCC voltage without and with the proposed method. (m) and (n) THD of PCC voltage without and with the proposed method.

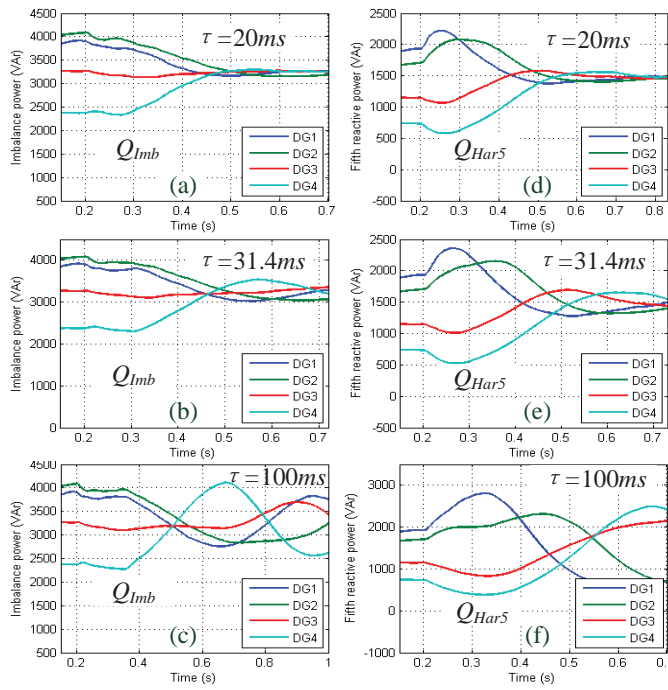


Fig. 9. Power sharing performance with different communication time delays: (a), (b) and (c) Imbalance power sharing performance with $\tau = 30\text{ms}$, 100ms , 150ms , respectively. (d), (e) and (f) Harmonic power sharing performance with $\tau = 30\text{ms}$, 100ms , 150ms , respectively.

$C_{IQ}=12.5$. In this case, the time-delay τ is set to be 20ms , 31.4ms , and 100ms , respectively. Fig. 9 shows the corresponding responses of the imbalance power ($Q_{I\text{mb}}$) and harmonic power ($Q_{\text{Har}5}$) of the DG units when the consensus controllers (21) and (22) are applied at $t=0.2\text{s}$. It can be seen that the imbalance power ($Q_{I\text{mb}}$) and harmonic power ($Q_{\text{Har}5}$) consensus is achieved for the case of $\tau = 20\text{ms}$ (Fig. 9(a) and (d)). The DG output imbalance and harmonic power can also converge to the consensus for the case of $\tau = 31.4\text{ms}$, but they begin to oscillate before the consensus is achieved (Fig. 9(b) and (e)). For the case of $\tau = 100\text{ms} > \tau_{\text{max}} = 31.4\text{ms}$, the system cannot be maintained stable, and the power sharing consensus is not achieved in Fig. 9(c) and (f). The simulation results are consistent with theoretical analysis in Section III. It should be noted that the response of the harmonic power at the seventh harmonic frequency is similar to that of the fifth harmonic frequency, thus it is not presented in the paper.

E. Case-5: Communication Link Failures

In this case, scenarios of failures of communication links are also considered. The original communication graph in Fig. 5(d) is designed to carry a minimal redundancy, so no single link failure can cause loss of connectivity in the graph. Firstly, the single link failure is carried out. As shown in Fig. 10(a), the link between DG1 and DG2 has failed at $t = 0.8\text{s}$, but it does not have any impact on the accurate sharing of the reactive power. The power sharing errors (Fig. 10(b)) can converge to zero even though the link 1-2 failed since the single link failure does not cause loss of connectivity. Following, the scenario of two-link failure is illustrated in Fig. 10(c) to (f).

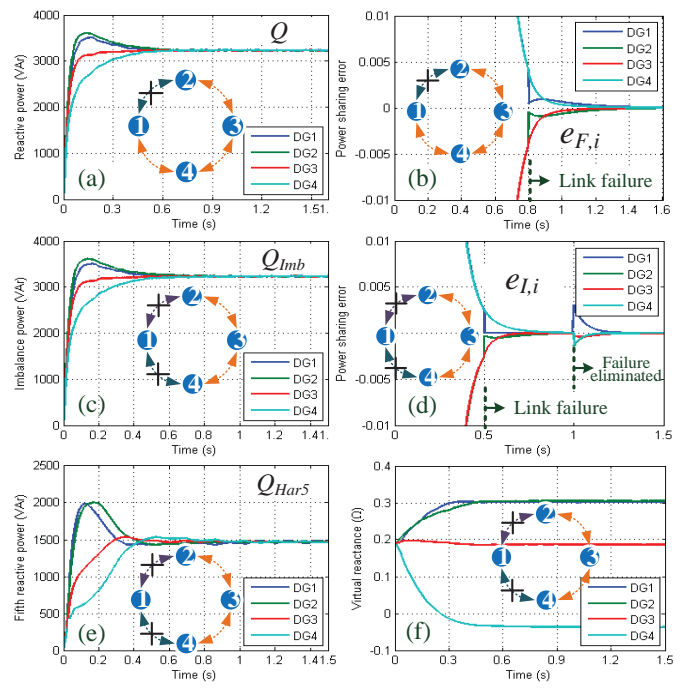


Fig. 10. Power sharing performance with different communication link failures: (a) and (b) Reactive power and power sharing error responses when the communication link between DG1 and DG2 failed. (c), (d), (e) and (f) Responses of imbalance power sharing, power sharing errors, harmonic power sharing, and virtual impedances, respectively, when both the link between DG1 and DG2 and the link between DG1 and DG4 failed.

The communication links (link 1-2 and link 1-4) failed at $t = 0.5\text{s}$ and restored at $t = 1.0\text{s}$. As shown in Fig. 10(c) and (e), although the communication link failures have caused loss of connectivity in the graph, the imbalance power sharing is hardly affected, which is maintained accurately and the power sharing error (Fig. 10(d)) could be negligible. This is mainly because that the system steady state has been almost achieved when the failure occurred. Thus the virtual impedances (Fig. 10(f)) are held at the quasi steady state values due to the integral action of the PI controllers, resulting in the equation (6) and (7) almost satisfied. We can further conclude that the power sharing can be still accurate enough when more links fails or load changes during the steady state.

F. Case-6: Dynamic Performance of Distributed Controllers

In this case, the effects of the coupling gains (C_{hQ}, C_{IQ}) on the power sharing dynamics are carried out. Fig. 11 shows the measured dynamic response of the microgrid for three different values of C_{hQ} and C_{IQ} . As shown in the figure, small coupling gain can slow down the system response while a large coupling gain can lead to resonance or even make the system unstable. A medium value is adopted here, i.e., $C_{hQ} = C_{IQ} = 12.5$. Satisfactory system performance is verified empirically. It is noted that the dynamic performance of the distributed controllers is acceptable with proper parameter selection and that the response time could be enough close to that of the centralized controller [50]. What's more, the distributed fashion could provide higher reliability seen from the above section.

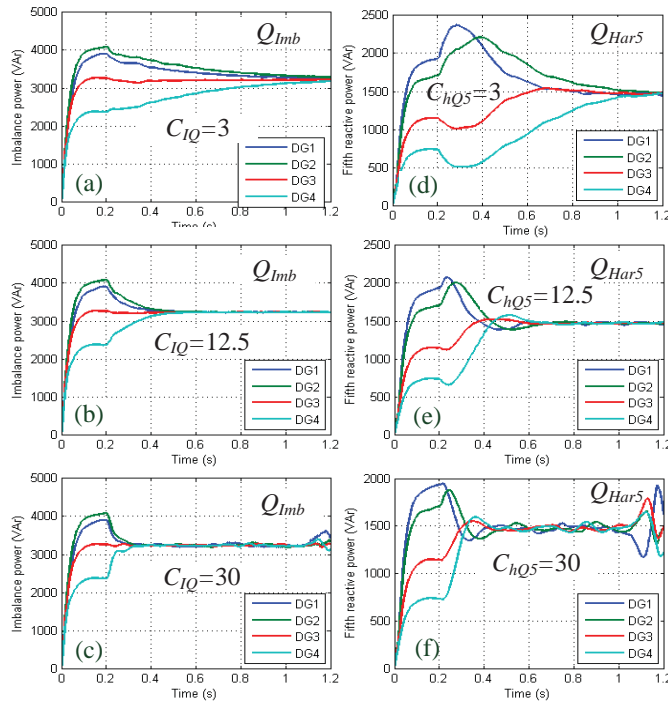


Fig. 11. The dynamic responses for different coupling values: (a), (b) and (c) Imbalance power response. (d), (e) and (f) Harmonic power response.

G. Case-7: Voltage Restoration

Finally, in the last case, the voltage restoration is considered. Fig. 12(a), (b) and (c) show, respectively, the restoration of the droop output voltages, the DG output voltages and the estimated average voltages of the DG units by using the voltage consensus control. At the beginning, the output voltages of the DG units are less than the reference voltages. Once the voltage consensus control is applied at $t=0.5s$, the droop output voltages in Fig. 12(a) and the DG output voltages in Fig. 12(b) are boosted until the average voltage is regulated at the rated voltage of the microgrid. Especially, the droop output voltage of each DG becomes exactly the same after the consensus-based adaptive virtual impedance control is enabled at $t=0.5s$, as expected. Although the DG output voltage cannot be regulated at identical value due to the mismatched line impedances, they are kept within a proper margin of the rated voltage since the average of the DG output voltages is regulated at the rated voltage, i.e., 120V, by using the voltage consensus control. Fig. 12(c) shows that the estimated average voltages of the DG units keep finely consensus (the rated voltage).

V. EXPERIMENTAL RESULTS

In this section, a test microgrid system shown in Fig. 13 was built in the laboratory, comprising three DG units, a three-phase Y-connected linear load with phase-c disconnected and a three-phase diode rectifier with shunt capacitor and resistor in the dc side. The DG units have the same power ratings. Detailed power stage and control system parameters can be found in Table I, II and III in Appendix.

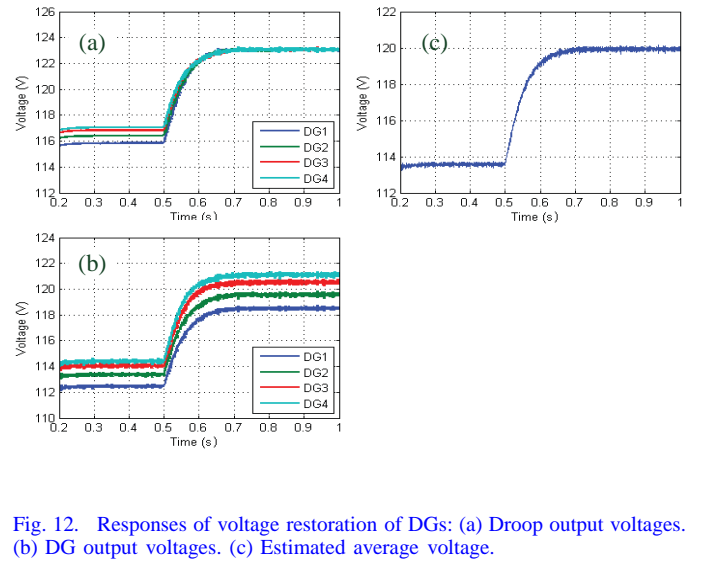


Fig. 12. Responses of voltage restoration of DGs: (a) Droop output voltages. (b) DG output voltages. (c) Estimated average voltage.

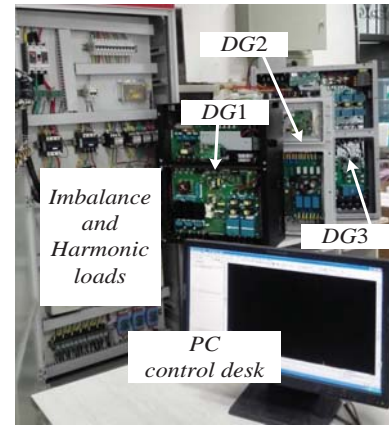


Fig. 13. The tested microgrid system setup.

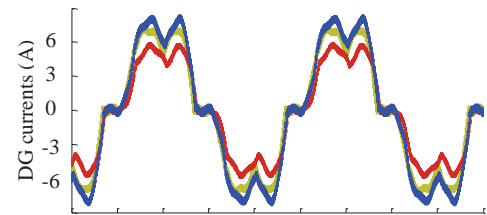


Fig. 14. Phase-A currents of DG units with conventional method.

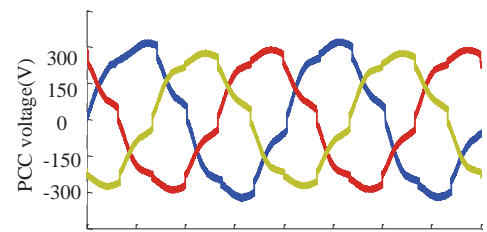


Fig. 15. PCC voltage with conventional method.

The load sharing performance using only conventional control method is presented in Fig. 14, which shows that the DG units share different amount of imbalance and harmonic

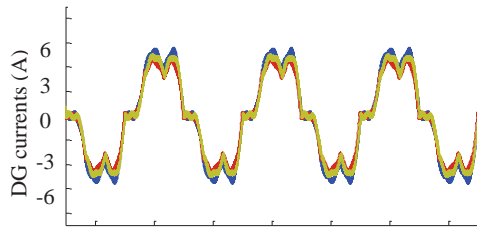


Fig. 16. Phase-A currents of DG units with proposed method.

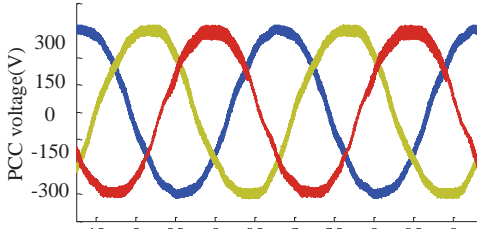


Fig. 17. PCC voltage with proposed method.

load currents due to the mismatched feeder impedances. It is obvious that DG1 shares the most load current as its feeder impedance is the smallest and that DG3 shares the least load current because of its largest feeder impedance. Also, we can find that the voltage at PCC shown in Fig. 15 mirrors relatively poor quality. The VUF and the THD are 6.5% and 14.3%, respectively. To enhance the microgrid power sharing performance and the voltage quality at PCC, the proposed imbalance/harmonic droop controllers and the consensus-based distributed adaptive virtual impedance regulation scheme are activated in each local DG unit. After the implementation of the imbalance/harmonic droop controllers and the adjustment of DG virtual impedance at the corresponding fundamental positive sequence, fundamental negative sequence, and harmonic frequencies, the PCC voltage and the current sharing performance are illustrated in Fig. 16 and Fig. 17, respectively. Compared to the performance in Fig. 13 and Fig. 15, it can be seen that the proposed method is effective to address the power sharing errors in a microgrid with generalized loads and the quality improvement of voltage at PCC as well. It can be easily found that all DG units share the load currents accurately thereby the reactive, imbalance and harmonic power are proportionally shared. At the same time, the proposed method allows the quality of voltage at PCC to be much better seen from Fig. 16. The VUF and the THD are reduced to about 1.98% and 6.3%, respectively.

VI. CONCLUSION

This paper discusses the control of reactive, imbalance and harmonic powers in microgrids and the voltage quality improvement at PCC as well. The imbalance and harmonic droop controllers and the consensus-based virtual impedance regulators at fundamental negative sequence frequency and harmonic frequencies have been developed to accurately control the power sharing and improve the PCC voltage quality. The proposed method is fully distributed, which can overcome several drawbacks of the centralized control method. The

feasibility and effectiveness of the proposed method has been demonstrated by several simulation and experimental results. In future research, the voltage quality improvement in hybrid ac and dc microgrids will be further discussed.

APPENDIX

TABLE I
POWER STAGE PARAMETERS

DG power rating	DG output filter		Harmonic load
P	L_f	C_f	C_{HL}/R_{HL}
20kW	1.8mH	50μF	5μF/2.5Ω
Line impedances			
Z_{line1}	Z_{line2}	Z_{line3}	Z_{line4}
0.3Ω+0.5mH	0.2Ω+0.6mH	0.175Ω+0.95mH	0.175Ω+1.55mH
Imbalanced load		Voltage and frequency rating	
P_{IL}	Q_{IL}	E	f
30kW	15kVar	120V	60Hz
2.8kW	1.5kVar	220V	50Hz
(experiment)	(experiment)	(experiment)	(experiment)

TABLE II
LOCAL CONTROLLER PARAMETERS

Droop controllers			
$m(\text{Hz/W})$	$V(\text{V/vAr})$	$m_{L,i}(\text{V/vAr})$	$n_{h,i}(\text{V/vAr})$
2×10^{-5}	1×10^{-3}	1×10^{-3}	3×10^{-3}
Voltage/Current PR Controllers			
k_{pV}/k_{pI}	k_{rV1}/k_{rI1}	k_{rV5}/k_{rI5}	k_{rV7}/k_{rI7}
1/5	100/500	50/300	50/300
0.6/3.2	50/300	30/200	25/200
(experiment)	(experiment)	(experiment)	(experiment)
ω_{bV}	2	ω_{bI}	2
Static virtual impedance			
L_V/R_V	L_{VImb}	L_{VHar5}	L_{VHar7}
0.5mH/0.05Ω	0.5mH	0.1mH	0.1mH

TABLE III
CONSENSUS-BASED CONTROLLER PARAMETERS

Reactive/Imbalance/Harmonic Power sharing PI controllers	
k_{pQ}/k_{IQ}	k_{pIQ}/k_{IIQ}
0.008/0.5	0.05/1.5
0.1/0.4	0.07/1.4
(experiment)	(experiment)
k_{pH5Q}/k_{IH5Q}	k_{pH7Q}/k_{IH7Q}
0.01/0.5	0.01/1.4
0.014/0.05	0.014/1.2
(experiment)	(experiment)
Gains of virtual impedances	
k_L/k_R	k_{LImb}/k_{RImb}
$1.5 \times 10^{-4}/0.02$	$1.5 \times 10^{-4}/0.02$
$1.1 \times 10^{-4}/0.01$	
(experiment)	
k_{LHar5}/k_{RHar5}	k_{LHar7}/k_{RHar7}
$1.5 \times 10^{-4}/0.02$	$1.5 \times 10^{-4}/0.02$

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