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Distributed Noise-resilient Secondary Voltage and Frequency Control for Islanded Microgrids

Nima Mahdian Dehkordi, Hamid Reza Baghaee, *Member, IEEE*, Nasser Sadati, *Member, IEEE*, and Josep M. Guerrero, *Fellow, IEEE*

Abstract—This paper proposes a novel distributed noise-resilient secondary control for voltage and frequency restoration of islanded microgrid inverter-based distributed generations (DGs) with an additive type of noise. The existing distributed methods commonly are designed as secondary control system systems that operate on the assumption of ideal communication networks among DGs. However, the channels are prone to stochastic noise, whereas each DG obtains noisy measurements of the states of its neighbors via environmental noises. The existing distributed noise-resilient methods, ignore a complete model of the system. In contrast, this paper proposes consensus protocols that take into account both the noisy measurements and a complete nonlinear model of the system, examines the mean-square average consensus for voltage and frequency restoration of islanded AC microgrids in an uncertain environment, and provides accurate proportional real power sharing. Our proposed consensus protocol contains two parts: the state feedback of the agent and the relative states of the DG and its neighboring DGs. Finally, simulation studies are carried out in MATLAB/SimPowerSystems to evaluate the performance of the control laws. Simulation results and comparison with previous work reveals the effectiveness of the proposed method in regulating microgrid voltage and frequency and providing accurate proportional real power sharing.

Index Terms—Distributed generation, distributed noise-resilient secondary control, mean-square average consensus, microgrids, multi-agent systems, power sharing, stochastic networks.

I. INTRODUCTION

A. Motivation and Incitement

The concept of a smart microgrid has emerged from the high penetration of renewable and non renewable-based distributed generation (DG) units and energy storage systems (ESS) [1]. A microgrid is a small-scale, low-voltage power grid in the low voltage designed to solve energy issues locally and enhance flexibility. These systems can function in either grid-connected or islanded (autonomous) modes of operation [2], [3]. Despite the inherent benefits of microgrids, they present technical challenges regarding their power management, control, and protection systems [4], [5].

The control strategy of microgrids works on the basis of a hierarchical control scheme, that includes primary/inner

controllers and secondary and tertiary control levels [5]–[7]. Previous secondary control strategies were proposed based on centralized control (with low reliability) [8], [9], decentralized control (with high reliability and reasonable cost) [4]–[7], [10], [11] and distributed control (with high reliability and low cost) [12]–[22]. The idea of distributed control is inspired partly by the idea of cooperative control for multi-agent systems (MASs) and is based on communication among local controllers (LC) that share information with neighboring units via local communication networks [23], [24].

B. Literature Review

Dissipated Control architecture has been used for control and power management of microgrids including DG units and ESSs [14], [15]. In [25], the nonlinear dynamics of the DG units are relaxed using the feedback linearization method into linear dynamics and the conventional into linear secondary control system is altered to initiate the distributed secondary control level on the basis of a first-order tracking synchronization problem, to provide voltage/frequency control and real/reactive power sharing. This idea has been used in [16] as well, although this study does not consider reactive power sharing. This issue is well addressed in [26], which explores independent from voltage measurements and mismatches and line impedance uncertainties, with the result that each DG unit takes the averaged value of reactive power of all units as its own set point to finish the update process. However, there is no clear picture of the relative errors of voltage regulations and reactive power sharing. Some issues, such as communication system uncertainties [27], communication time delay [28], networked variability [29], and measurement noise [17], [30] (which is the subject of this paper), affect the performance and stability of distributed secondary controllers. The effects of the time delay on primary and secondary control levels in a hierarchical structure have been studied in [28], [31], [32], respectively. The existing distributed control paradigms assume the existence of ideal, noise-free communication among inverters. In practice, communication channels are corrupted by additive noise. Environmental events such as rain also can introduce noise into communication channels. As a case in point, in wireless communications, when an additive noise (that can be statistically modeled as Gaussian in nature) is generated in the receiver front end, the surrounding noise can be picked up by the antenna [33]. In a zero-mean white noise model with a nominal threshold of 0.05 for frequency deviation, small deviations can affect sensitive

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electronics loads adversely, whereas larger deviations can lead to circulating currents and potentially can destabilize the microgrid [34]. This issue is discussed for a noise MAS in [35], [36]. Most of the previously reported distributed secondary control methods have been presented based on small-signal modeling and thus do not respond efficiently to large-signal disturbances [19], [20], [26], [37], [38]. Moreover, from a practical perspective the microgrid is parametrically uncertain and structurally unknown. Therefore, unlike [12], [19], [26], [39], the unmodeled dynamics, unknown disturbances, and system uncertainties shall be considered in this study in the design of the microgrid control system.

The reported distributed control techniques have been presented almost based on assuming an ideal, noise-free communication among inverters. The communication channels are practically corrupted by additive noise [33]. In wireless communications, an additive noise will be generated in the receiver front end and surrounding noise picked up by the antenna. Environmental causes such as rain, can also introduce noise in to communication channels. In another category, the additive noise associated with electronic components and amplifiers at the receiver end is classified as thermal noise and statistically modeled as Gaussian in nature [33]. In this paper, without loss of generality, noise is considered to be zero mean white Gaussian. In the presence of noise (that especially disrupt the frequency synchronization), consensus on the desired set point is not warranted [40]. Given the nominal threshold of ± 0.5 Hz on frequency deviation [40], small deviation can adversely affect the sensitive electronics loads, while larger deviations can result in circulating currents and can potentially destabilize the microgrid. The effect of noise and distributed estimators for a noisy multi-agent system have been studied in [35], [36].

C. Contribution and Organization

In this paper, we propose a new distributed noise-resilient secondary control scheme to regulate the voltage and frequency of an autonomous multi-DG AC microgrid while taking into consideration additive communication noise. We assume the communication channels are prone to stochastic noise; thus, the LCs receive noisy measurements from their neighboring units as a result of exterior environmental noises. In contrast to the previously reported distributed noise-resilient control strategies, in this paper we use detailed nonlinear model of the system to propose a consensus protocol that incorporates noisy measurement by exploiting mean square average consensus values of voltage and frequency signals in an uncertain environment and providing proportional accurate real power sharing. The presented consensus protocol comprises a state feedback agent, and moreover, the relative states between a DG unit and its neighbors (which normally are affected by communication noises and thus cannot be measured exactly). The presented consensus protocol consists of state feedback agent and moreover, relative states between a DG unit and its neighbor units (which is normally affected by communication noises and thus, cannot be measured exactly). We can summarize the main features of the proposed method as follows:

- 1) Several presented models suffer from incomplete plant dynamics because they ignore the inner controllers impact on the secondary control, thus affecting both the stability and performance of high-power converters. To the best of the authors knowledge, this paper is the first to propose a new distributed noise-resilient secondary control for both voltage and frequency restoration of an islanded microgrid based on consideration of a complete nonlinear system model, irrespective of parametric uncertainties and noise parameters.
- 2) From a practical perspective, noise parameters and the microgrid parameters, such as line impedances, loads, other parameters of DG unit, and the microgrid configuration are unknown. Unlike existing distributed methods that require a detailed model of the system, the proposed protocols are designed by considering unmodeled dynamics, unknown noises and uncertainties in their models. Therefore, this modeling leads to controllers being independent of the DG parameters and noise type.
- 3) In the case of frequency restoration, the distributed noise-resilient control meets the power sharing accuracy in the presence of any type of noise.
- 4) Compared with the conventional distributed controllers, the proposed method rapidly reaches consensus and shows a more accurate robust performance for controller activation, structure reconfiguration, and load changes. Also, it is fully independent of DG parameters (line impedances, loads, and other DG units parameters) and noise type.
- 5) Easy implementation of the proposed protocols on digital hardware devices under both uncertain and fixed communication networks facilitates fulfillment of the plug-and-play capability of intermittent DG units in the presence of noise.

The theoretical concepts and necessary conditions for stability and robust performance of the proposed distributed noise-resilient secondary control scheme are outlined and effectiveness of the proposed scheme is evaluated by offline time-domain simulations in MATLAB/Simulink environment. The rest of this paper is organized as follows: section II describes the preliminaries of graph theory, DG unit modeling, and microgrid and problem formulation. The proposed distributed noise-resilient secondary scheme for voltage and frequency is presented in sections III and IV, respectively. Verification of the performance of the proposed method based on offline time-domain simulations is presented in section V. Finally, conclusions and discussions are presented in sections VI.

II. PRELIMINARIES AND PROBLEM FORMULATION

A. Preliminary of Graph Theory

The communication topology among DGs can be modeled by a weighted directed graph (digraph) $G = (N_G, E_G, A_G)$, where $N_G = \{1, 2, \dots, N\}$ is the node set, $E_G \subset N_G \times N_G$ is the edge set, and $A_G \in R^{N \times N}$ with non negative elements a_{ij} is a weighted adjacent matrix. Between two DGs, the edge of the communication network $e_{ij} = (i, j) \in E_G$ exists if and only if $a_{ij} > 0$ or there is an information flow from DG_{*i*} to

DG_j; otherwise, $a_{ij} = a_{ji} = 0$. Moreover, there is no self-loop in the graph, that is $a_{ii} = 0$ for all $i \in N_G$. The set of neighbors of node i is represented by $N_{ci} = \{j \in N_G : (i, j) \in E_G, j \notin i\}$.

The graphed Laplacian matrix $L = [L_{ij}] \in R^{N \times N}$ is defined by $L_{ii} = \sum_{j \neq i} a_{ij}$ and $L_{ij} = -a_{ij}$ [41]. A path from node i to node j is a sequence of edges $e_{ik}, e_{il}, \dots, e_{mj}$. The digraph (the corresponding network) contains a directed spanning tree, if there is a root node that has a directed path connecting any two arbitrary nodes in the graph. The communication graph is connected if the graph has a spanning tree. For a digraph, if node i is a neighbor of node j , then node j receives information from node i but not necessarily vice versa [41].

For the leader-following multiagent system with N followers, the adjacency matrix of the leader is described as $g = [g_1, g_2, \dots, g_N]^T \in R^N$. If agent i is a neighbor of the leader, $g_i = 1$; otherwise, $g_i = 0$ [41].

B. Dynamic Modeling of DGs

Fig. 1 illustrates the layout of a typical inverter-based microgrid in islanded-mode operation, which is the main focus of this paper. The microgrid system consists of the physical, communication network, and control layers. The physical layer contains dispatchable sources, including the voltage source converter (VSC), series LCL filter, transmission lines, loads and power, voltage, and current control loops. To facilitate data exchange among DGs, a sparse communication network layer with at least a spanning tree is spanned among the DGs. We selected this communication network so that in the case of a communication link failure, the remaining network would still contain a spanning tree. Several presented models (specially [17]) suffer from incomplete plant dynamics because they ignore the effect of the inner controllers on the secondary control and thus, affecting both the stability and performance of high-power converters. To the best of the authors knowledge, this paper is the first to propose a new distributed noise-resilient secondary control (motivated by [41]) for both voltage and frequency restoration of an islanded microgrid based on consideration of a complete nonlinear system model, irrespective of parametric uncertainties and noise parameters.

We can achieve coordination of the primary controller by considering dynamics of the real and reactive power droop techniques as

$$\begin{aligned} \omega_i &= \omega_{ni} - m_{P_i} P_i \\ v_{odi}^* &= V_{ni} - n_{Q_i} Q_i \\ v_{oqi}^* &= 0, \end{aligned} \quad (1)$$

where V_{ni} and ω_{ni} are, respectively, the reference voltage and frequency provided for the internal control loops. P_i and Q_i are the i^{th} DG's real and reactive powers. m_{P_i} and n_{Q_i} are the static droop gains evaluated based on the inverter ratings.

From [16], the dynamical model of each DG and its internal control loops can be written respectively in the following

forms

$$\begin{aligned} \dot{x}_i &= f_i(x_i) + g_{i1}(x_i)u_{i1} + g_{i2}(x_i)u_{i2} + k_i(x_i)D_i \\ y_{i1} &= v_{odi} = h_{i1}(x_i) \\ y_{i2} &= \omega_i = \omega_{ni} - m_{P_i} P_i = h_{i2}(x_i) + d_i u_{i2}, \end{aligned} \quad (2)$$

where $x_i = [\alpha_i \ P_i \ Q_i \ i_{Ldi} \ i_{Lqi} \ v_{odi} \ v_{oqi} \ i_{odi} \ i_{oqi}]^T$ and α_i is the angle of the DG reference frame with respect to the common reference frame.

Based on the nonlinear model, the control inputs V_{ni} and ω_{ni} will be designed in the next section so that v_{odi} and ω_i are regulated to the desired values.

III. DISTRIBUTED NOISE-RESILIENT SECONDARY VOLTAGE CONTROL

Because of the existence of communication noises among DGs, synchronization of voltage and frequency cannot be achieved appropriately. In this section, we use a fully distributed noise-resilient secondary voltage control to select proper control inputs V_{ni} in (2) to synchronize the DG units' voltage magnitude, $v_{o,magi}$, to the reference value v_{ref} (irrespective of the noise type), where only information from neighboring units is required. In our proposed method, it does not matter whether what kind of noises is considered

Motivated by the dynamical model of the open loop system (2), we employ the partial feedback linearizing method to transform the nonlinear system (2) into a partially linear system as follows:

$$\begin{aligned} \dot{y}_{i1} &= L_{f_i}^2 h_{i1} + L_{g_{i1}} L_{f_{i1}} h_{i1} u_{i1} \\ \dot{\mu}_{i1} &= W_{i1}(y_{i1}, \mu_{i1}), \forall i, \end{aligned} \quad (3)$$

where $L_{f(x)} h(x) = \frac{\partial h(x)}{\partial x} f(x)$ represents the Lie derivative [42] of $h(x)$ along $f(x)$ and $\mu_{i1} \in R^{n_{i1}}$ represents the set of internal dynamics that are asymptotically stable [25]. Therefore, equation (3) is written as follows:

$$\begin{aligned} \dot{y}_{i1} &= y_{i1,2} \\ \dot{y}_{i1,2} &= f_i(x_i) + g_i(x_i)u_{i1}, \forall i. \end{aligned} \quad (4)$$

Let $v_i = f_i(x_i) + g_i(x_i)u_{i1}$. Then we can present (4) as

$$\begin{aligned} \dot{y}_{i1} &= y_{i1,2} \\ \dot{y}_{i1,2} &= v_i, \forall i \end{aligned} \quad (5)$$

or in matrix form

$$\dot{y}_i = A y_i + B v_i, \quad \forall i, \quad (6)$$

where $y_i = [y_{i1} \ y_{i1,2}]^T$, $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, and $B = [0 \ 1]^T$. The reference generator's dynamics (the leader) can be expressed as

$$\dot{y}_0 = A y_0, \quad (7)$$

where $y_0 = [v_{ref} \ \dot{v}_{ref}]^T$.

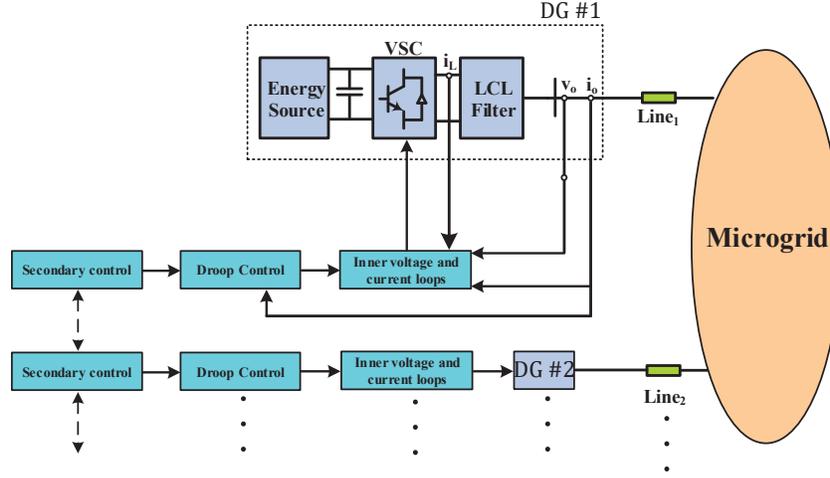


Fig. 1. General layout of an inverter-based microgrid.

A. Control Law

Based on the findings in [41], we suggest the following distributed consensus-based noise-resilient secondary voltage protocol:

$$v_i = k_1(y_i - y_0) + a(t) \sum_{j \in N_{ci}} a_{ij} k_2 Y_{ij}(t), \quad (8)$$

where $Y_{ij} = y_i - y_j + \Lambda_{ij} \sigma_{ij}$; Λ_{ij} is noise intensity; σ_{ij} is independent standard white noise, $k_1 = [-a_1, -a_2 - b_1]$; $k_2 = [b_1, b_2]$, $[b_1, b_2]$ are control parameters to be determined; and $a(t)$ is the consensus gain, which satisfies [41]

$$\int_0^\infty a(s) ds = \infty \quad \text{and} \quad \int_0^\infty a^2(s) ds < \infty. \quad (9)$$

Moreover, the role of the coefficient $a(t)$ is to attenuate the noise effects as $t \rightarrow \infty$. Let $e_v = [e_1^T, \dots, e_n^T]^T$. Therefore, we define the global error vector e_v as

$$e_v = (L \otimes I_n) \begin{bmatrix} y_i - y_0 \\ \vdots \\ y_N - y_0 \end{bmatrix}, \quad (10)$$

where I_n and \otimes represent the unit matrix of size n and Kronecker product, respectively. Substituting for v_i from (8) into (6) and pursuant to the theory of $It\hat{o}$ stochastic differential equation, we have

$$de_v(t) = (I_N \otimes (A + Bk_1) - a(t)L \otimes Bk_2)e_v(t)dt + a(t)\Sigma dW(t), \quad (11)$$

in which $W(t) \in R^{n^2}$ is a standard Winner process; $\Sigma \in R^{n \times n^2}$ is a constant matrix represented by $\Sigma = \text{diag}(\Sigma_1, \dots, \Sigma_n)$ in which $\Sigma_i = [a_{i1}Bk_2\Lambda_{1i}, \dots, a_{in}Bk_2\Lambda_{1n}]$. Using $It\hat{o}$ integral formula [41], the solution of (11) can be obtained as follows:

$$e_v(t) = \phi_{e_v}(t, 0)e_v(0) + \int_0^t a(s)\phi_{e_v}(t, s)\Sigma dW(s), \quad (12)$$

where $\phi_{e_v}(t, s)$ is the state transition matrix of the differential equation (11). $e_v(t)$ converges in the mean square to a random vector $V^* = (v_{11}^*, \dots, v_{1n}^*, \dots, v_{N1}^*, \dots, v_{Nn}^*)$. From [41], it follows that

$$\begin{aligned} E(V^*) &= \lim_{t \rightarrow \infty} E(e_v(t)) = \lim_{t \rightarrow \infty} \phi_{e_v}(t, 0)e_v(0) \\ &+ \lim_{t \rightarrow \infty} E\left(\int_0^t a(s)\phi_{e_v}(t, s)\Sigma dW(s)\right) \\ &= \phi_\infty e_v(0) \end{aligned} \quad (13)$$

Therefore, we obtain

$$E(v_{11}^*) = \dots = E(v_{N1}^*) = \sum_{i=1}^N m_i (e_{i1}(0) + \frac{b_2}{b_1}), \quad (14)$$

and $E(v_{12}^*) = \dots = E(v_{1n}^*) = \dots = E(v_{N2}^*) = \dots = E(v_{Nn}^*) = 0$. Accordingly, $E(V^*)$ is jointly determined by the initial states of the DGs and the communication topology among them. In a similar way, we prove that

$$\begin{aligned} &E((V^* - E(V^*))(V^* - E(V^*))^T) \\ &= \lim_{t \rightarrow \infty} \int_0^t a^2(s)\phi_e(t, s)\Sigma \Sigma^T \phi_e^T(t, s) ds \\ &= \lim_{t \rightarrow \infty} \int_0^\infty a^2(s)\phi_\infty \Sigma \Sigma^T \phi_\infty^T ds. \end{aligned} \quad (15)$$

It follows that

$$\begin{aligned} D(v_{i1}^*) &= \int_0^\infty a^2(s) ds \sum_{i=1}^N m_i^2 \sum_{j \in N_{ci}} \alpha_{ij}^2 (\eta_{ij1}^2 + \frac{b_2^2}{b_1^2} \eta_{ij2}^2) \\ &\equiv \Omega. \end{aligned} \quad (16)$$

$D(v_{ik}^*) = 0$, $\text{Cov}(v_{i1}^*, v_{j1}^*) = \Omega$, and $\text{Cov}(v_{i1}^*, v_{jk}^*) = 0$ ($\forall i, j = 1, \dots, N; k = 2, \dots, N$). Therefore, we can obtain that $\lim_{t \rightarrow \infty} E(e_{ij}(t) - v_{ij}^*)^2 = \lim_{t \rightarrow \infty} E(e_{ij}(t) - v_{1j}^*)^2 = 0$ ($i = 1, \dots, N; j = 1, \dots, N$). Therefore, our proposed method can solve the distributed mean square consensus.

As shown above, our proposed consensus protocol contains two parts: 1) the state feedback of the agent and 2) the relative states between the DG and its neighbor DGs. Because of the

existence of communication noises among DGs, the relative states cannot be obtained exactly. Therefore, the time-varying gain $a(t)$ attenuates the effects of noise. The following mm summarizes the results of this section:

Theorem 3.1: The protocol

$$\begin{aligned} V_{ni} = u_{i1} &= \frac{1}{g_i(x_i)}(v_i - f_i(x_i)) \\ v_i &= k_1(y_i - y_0) + a(t) \sum_{j \in N_{ci}} a_{ij} k_2 Y_{ij}(t) \end{aligned} \quad (17)$$

can guarantee that the DG output voltage, $v_{o,magi}$, tracks the reference value v_{ref} irrespective of stochastic noise in communication channels. Fig. 2 depicts block diagram of the distributed cooperative noise-resilient secondary voltage control.

Proof: Equations (3)-(16) prove the theorem. ■

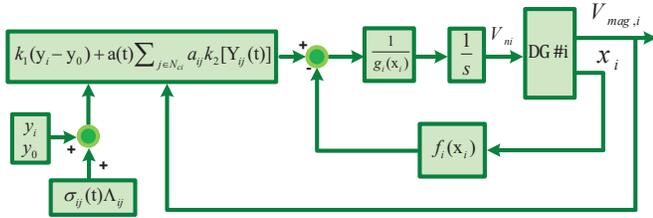


Fig. 2. Block diagram of the distributed noise-resilient secondary voltage control

IV. DISTRIBUTED NOISE-RESILIENT SECONDARY FREQUENCY CONTROL

In this section, we use a fully distributed noise-resilient secondary frequency control to design the proper protocol inputs ω_{ni} in (2) to synchronize the DGs' frequency, ω_i , to the reference value ω_{ref} (irrespective of the noise type), where only information from neighboring units is required. As in the previous section, we employ the consensus algorithm and feedback linearization approach to ensure convergence. We note that the primary control ensures real power sharing among DGs as in (18); thus, after applying the proposed protocols, both frequency restoration and proportional real power sharing should be achieved as follows

$$\frac{P_j}{P_i} = \frac{m_{pi}}{m_{pj}}, \quad \forall i, j \in N. \quad (18)$$

Therefore, the mean square consensus protocol designs u_{i2} in (2) so that $y_{i2} \rightarrow \omega_{ref}$. As in the previous section, we employ the partial feedback linearizing method to transform the nonlinear system (2) into a partially linear system as follows:

$$\begin{aligned} \dot{y}_{i2} &= L_{f_i} h_{i2} + L_{g_i} h_{i2} u_{i2} + d_i \dot{u}_{i2} \\ \dot{\mu}_{i2} &= W_{i2}(y_{i2}, \mu_{i2}), \end{aligned} \quad (19)$$

where $\mu_{i2} \in R^{n_{i2}}$ is the set of internal dynamics that are asymptotically stable [25]. In this case, we obtain the following equation:

$$\dot{y}_{i2} = \dot{\omega}_i = \dot{\omega}_{ni} - m_{P_i} \dot{P}_i. \quad (20)$$

We now define the auxiliary control u_{ω_i} as

$$u_{\omega_i} = \dot{\omega}_{ni} - m_{P_i} \dot{P}_i, \quad (21)$$

which can be substituted into (20) to produce the following linear systems:

$$\dot{\omega}_i = u_{\omega_i}, \quad i = 1, 2, \dots, N. \quad (22)$$

We assumed that DGs communicate with each another through the noisy communication digraph G . Therefore, the proposed protocols design u_{i2} in (2) yields $y_{i2} \rightarrow \omega_{ref}$ and $m_{pj} P_j \rightarrow m_{pi} P_i, \forall i$. As in the previous section, we consider the following distributed consensus-based noise-resilient secondary frequency protocol, u_{ω_i} , based on its own information and the information of its neighbors on the communication graph so that the angular frequency of each DG, ω_i , synchronizes to its nominal value, ω_{ref} , while guaranteeing real power sharing accuracy:

$$u_{\omega_i} = K a_{\omega}(t) \left(\sum_{j \in N_{ci}} a_{ij} Y_{ij}(t) + \sum_{j \in N_{ci}} a_{ij} \gamma_{ji}(t) \right), \quad (23)$$

where $Y_{ij} = \omega_i - \omega_j + \Lambda_{ij} \sigma_{ij}$, $\gamma_{ji} = m_{P_i} P_i - m_{P_j} P_j + \Lambda_{ij} \sigma_{ij}$, Λ_{ij} is the noise intensity, σ_{ij} is independent standard white noise, K is the control parameter to be determined, and $a_{\omega}(t)$ is the consensus gain satisfying

$$\int_0^{\infty} a_{\omega}(t) ds = \infty \quad \text{and} \quad \int_0^{\infty} a_{\omega}(t)^2(s) ds < \infty. \quad (24)$$

We note that the latter term of (23) guarantees that real power sharing will be maintained after applying the secondary control even in the event of communication failure. According to (21) and (22), we can write ω_{ni} as follows:

$$\omega_{ni} = \int u_{\omega_i}, \quad i = 1, 2, \dots, N. \quad (25)$$

The following theorem summarizes the results of this section:

Theorem 4.1: The protocol (25) guarantees that the DG output frequency, ω_{ni} , synchronizes with ω_{ref} irrespective of stochastic noise in communication channels.

Proof: Equations (18)-(25) prove the theorem. ■

In light of the fact that stochastic noise in the communication channels is unavoidable, the proposed method has better noise cancellation compared with the existing distributed control methods because $a_{\omega}(t)$ adds a further degree of freedom to the controller. As shown in (23), the protocol u_{ω_i} comprises two parts. The protocol's first part leads to the steady-state track of the nominal frequency (i.e., $\omega_i \rightarrow \omega_{ref}$) despite stochastic noise in the communication channels, and the second part ensures real power sharing accuracy (i.e., $m_{pj} P_j \rightarrow m_{pi} P_i$). Fig. 3 shows the block diagram of the distributed consensus-based noise-resilient secondary frequency protocol.

Remark 4.2: The parameters of the voltage and frequency protocols are the set $b_1 < 0, b_2 < 0, a(t) < 0, K < 0$, and $a_{\omega} < 0$, and the performance of the microgrid system is specified with the proper selection of these parameters. We use simulations to determine the best combination of these parameters as $a(t) = \frac{-100}{t+1}$, $a_{\omega} = \frac{-20}{t+1}$, and $b_1 = b_2 = K = -100$.

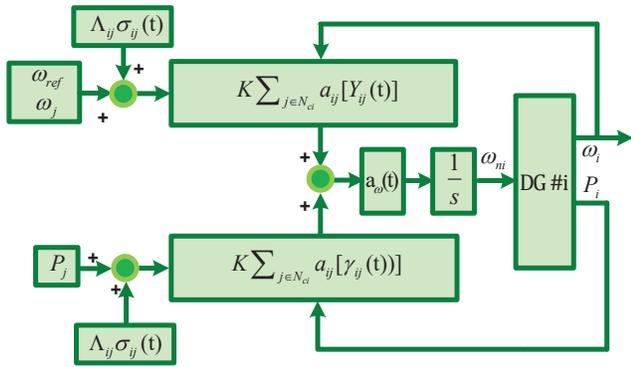


Fig. 3. Block diagram of the distributed noise-resilient secondary frequency control.

V. SIMULATION RESULTS

To evaluate the effectiveness of the proposed distributed noise-resilient secondary control method, we simulate the multi-DG microgrid of [28] (Fig. 4), in the MATLAB/Simulink software environment for different scenarios and verify the results by comparing them with the conventional distributed control method reported in [25]. The parameters of the microgrid system have been obtained from [28]. Although the results have not been experimentally validated, However, the proposed algorithm have been verified by comparing with the previously-reported techniques. In this regard, the following practical issues have been taken into account:

- 1) The intrinsic communication link delays have been taken into account in the simulation scenarios.
- 2) The controllers for each DG unit are digitally implemented (suitable for using in DSP or a micro-controller) in the MATLAB/Simulink software.
- 3) The detailed switching models are used for inverters.
- 4) A time delay has been imposed on the output of PWM controllers before being applied to the switches.
- 5) The signal sampling delay has been taken into account before processing in the inverters control loops. From a computational perspective, the proposed method does not use any particularly problematic operation or heavy computations. Thus, we believe that the computational complexity is not a significant concern for practical implementation in the proposed method.

A. System Performance Evaluation

In this section, we evaluate the performance of the proposed secondary control scheme using a simulation scenario that proceeds as follows:

- 1) $t = 0.0$ s (simulation initialization period). Only the primary control is activated, and Load #6 is out of the circuit.
- 2) $t = 1.5$ s. The proposed distributed noise-resilient secondary control is applied.
- 3) $t = 2$ s. Load #1 is increased by the amount of 19.4 kW + j 13.3 kVar (100% increment of load).
- 4) $t = 2.5$ s. Additive noise with $\sigma^2 = 0.1$ is added to the previous noise.

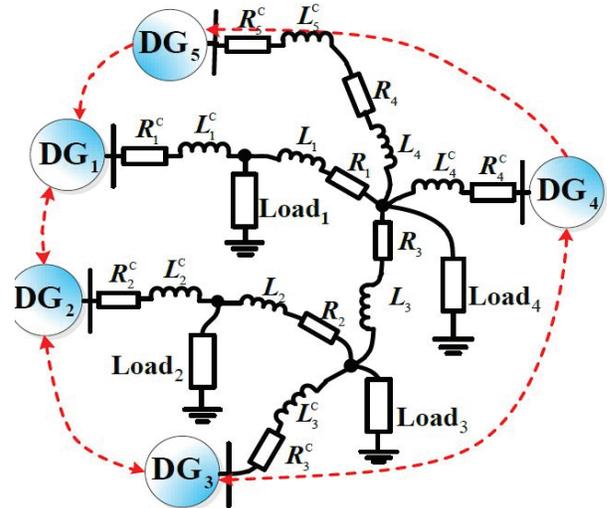


Fig. 4. Topology of the study system (“(c) IEEE from [28]”).

- 5) $t = 3$ s. DG #4 is disconnected (plugged out).
- 6) $t = 3.5$ s. DG #4 is re-connected (plugged in).

The communication links include noise with $\sigma^2 = 0.1$. The simulation results have been shown in Figs. 5 and 6. The proposed distributed noise-resilient controller can regulate the voltage and frequency after step load change, which is known as a small-signal disturbance. After that, when we add the additive noise with the variance of 0.1 to the previous noise at $t = 2.5$ s, the proposed distributed noise-resilient secondary control scheme performs well and the voltage and frequency waveforms are stably regulated without any deterioration. Finally, when the DG unit is plugged out at $t = 3$ s and then plugged in at $t = 3.5$ s, the proposed method responds well to the outage and reconnection of the DG unit, which is known as a large-signal disturbance. After $t = 3$ s, because the DG #4 has been unplugged, and other DG units are still in the communication graph, the remaining DGs will exactly follow the set points. In addition to providing robust stability, this approach realizes the plug and play (P & P) functionality of the microgrid.

The control of voltage and accurate reactive power sharing can only be achieved under a symmetric configuration, due to the line impedance effect, [19]. Therefore, accurate voltage regulation results in large errors in reactive power sharing. Conversely, the precise reactive power sharing leads to the poor voltage regulation. Thus, a trade-off should be made between voltage regulation and reactive power sharing accuracy. In this section, we have just focused on the secondary voltage control; however, we have found that the proposed secondary controller does not worsen the reactive power sharing among the DGs before applying the secondary control.

B. Communication Network Change

The study deals with the change in the communication network. The topology of the communication graph changes from G_1 (Fig. 7(a)) to G_2 (Fig. 7(b)). Then, we repeat the study discussed in Subsection V-A with the same simulation

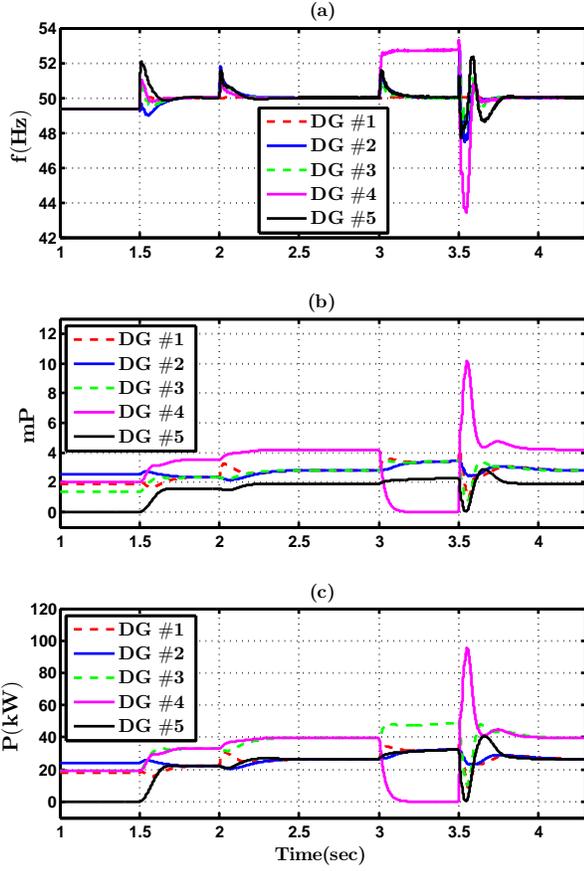


Fig. 5. System performance evaluation: a) frequencies, b) real power ratios, and c) output real powers of DG units.

scenario. In this case, based on the waveforms of frequency, real power ratio, and output real power signals (Fig. 8) and output voltage amplitude of DG units (Fig. 9), We observed that the proposed scheme regulates and stabilizes the fluctuations of the voltage and frequency caused by the primary control level after the small-signal (load step change) and large-signal (outage of DG unit) disturbances in the presence of additive noise.

C. Change of Additive Noise Parameters

In this part of the analysis, to show the robustness and resiliency of the proposed distributed secondary control scheme with respect to the change of the noise parameters, we change the variance of the additive noise from $\sigma^2 = 0.1$ to $\sigma^2 = 0.3$ (thrice). Then, with the same simulation scenario, we repeat the study of subsection V-A. Again, we observe from Figs. 10 and 12 that the microgrid’s voltage and frequency are restored effectively in the case of the small and large-signal events in the presence of additive noise with the higher (tripled) variance value.

D. Comparison with a Previously-Reported Method [25]

Finally, we compare the proposed method with the previously-reported distributed cooperative secondary control method discussed in [25]. The previous simulation scenario in

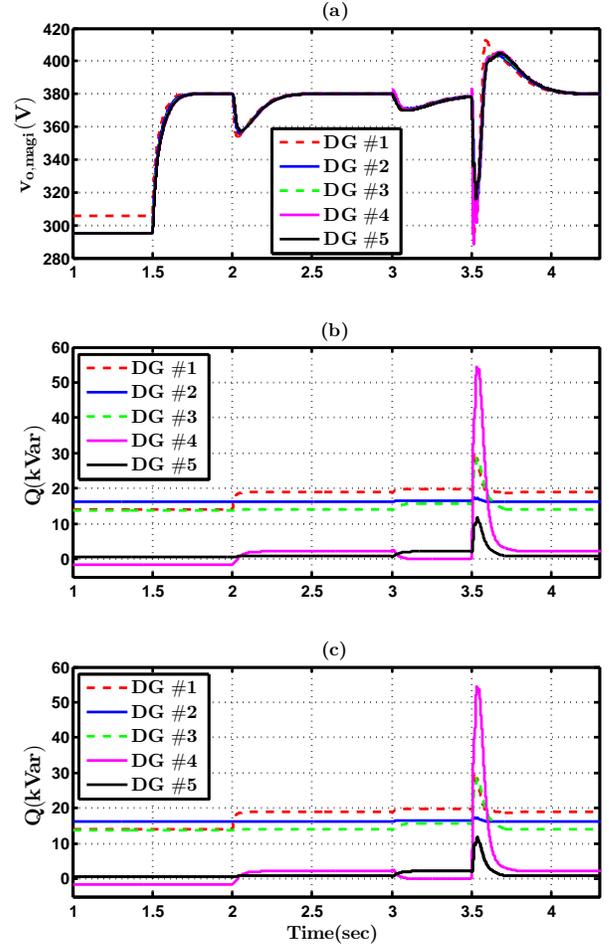


Fig. 6. System performance evaluation: DGs output (a) voltage magnitude, (b) reactive power with secondary control, and (c) reactive power without secondary control.

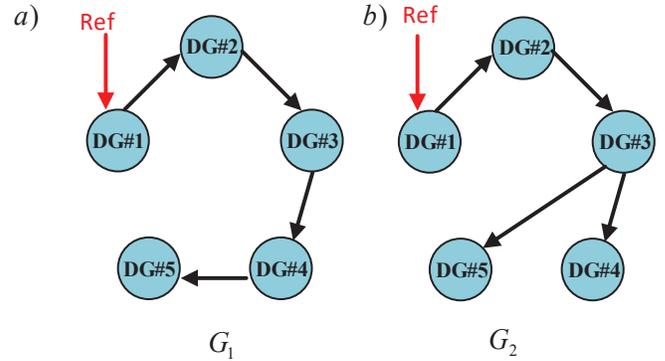


Fig. 7. Topology of communication graphs: a) old topology, b) new topology.

subsection V-A is performed using the secondary controller proposed in [25]. As we will show in Fig. 12 (a)-(b), when additive noise ($\sigma^2 = 0.1$) included, the voltage and frequency waveforms fluctuate greatly with high-frequency distortions using the secondary controller presented in [25]. However, as discussed in subsection V-C, the proposed distributed noise resilient secondary controllers have desirable performance even

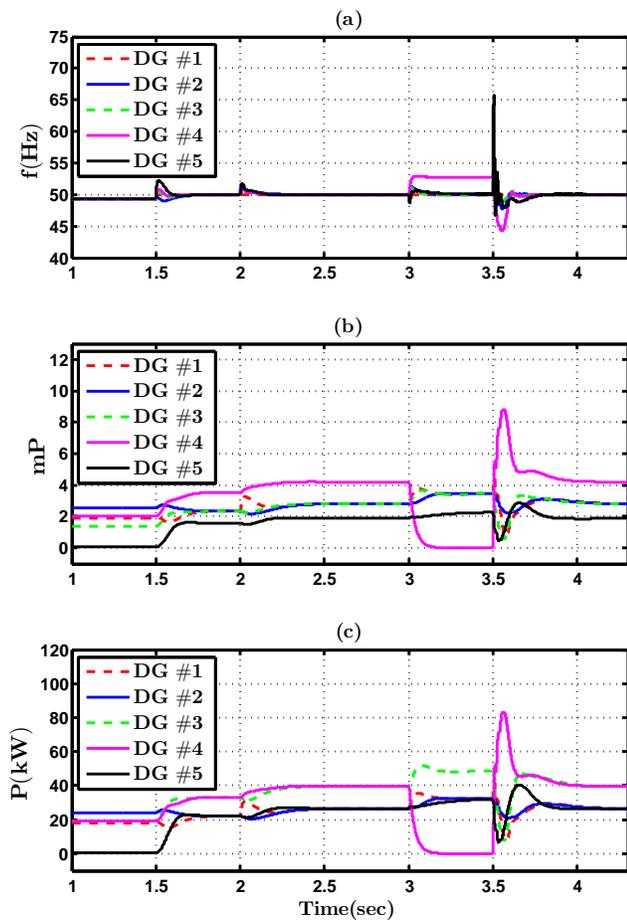


Fig. 8. Communication network change: a) frequencies, b) real power ratios, and c) output real powers of DG units.

when the noise variance is tripled. To show the effectiveness and authenticity of the proposed control strategy and its superiority over the reported techniques, we have compared the voltage and frequency response of the proposed noise-resilient distributed control strategy (when the communication channels are prone to the additive noise) and the previously-published control strategy of [25], as shown in Figs. 12 (c)-(d).

VI. CONCLUSION

In this paper, we have proposed a novel distributed noise-resilient secondary control to restore voltage and frequency of an islanded inverter-interfaced microgrid that includes several DG units. Local controllers receive noisy measurements from neighboring units on account of the existence of stochastic noise in communication channels. In the proposed consensus protocols, we considered not only the noisy measurements, but also the complete nonlinear dynamic large-signal model of the microgrid system. To regulate the microgrid voltage and frequency and provide proportional accurate real power sharing, we present a mean-square average-consensus model in an uncertain environment. We presented theoretical concepts, including mathematical modeling of microgrid, basic theorems, and design procedure of the proposed distributed noise-resilient secondary controller, and evaluated the performance

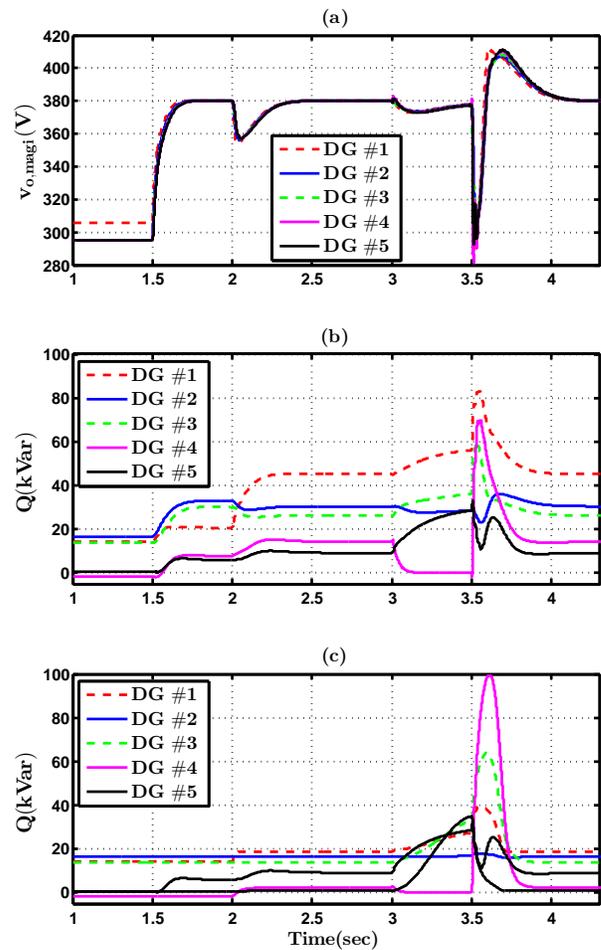


Fig. 9. Communication network change: DGs output (a) voltage magnitude, (b) reactive power with secondary control, and (c) reactive power without secondary control.

of the controller for small and large-signal disturbances, based on offline time-domain simulations in the MATLAB/Simulink environment. We verified our findings by comparing them with a previously-reported distributed secondary control method. The results indicate that using the proposed robust control scheme allows the microgrid to restore the fluctuations of voltage and frequency and maintain its stability when faced with small- and large-signal disturbances. This approach shows robust performance in the face of changes in the communication network topology and communication uncertainties.

Finally, it should be remarked that although the proposed secondary controller does not worsen the reactive power sharing among the DGs before applying the secondary control, however, by adding virtual impedance to complete dynamic of primary control level, the problem of proportional active/reactive power sharing is completely resolved. This issue, along with the generalization of the proposed strategy for hybrid AC/DC and DC microgrids, is the subject of future research of the authors.

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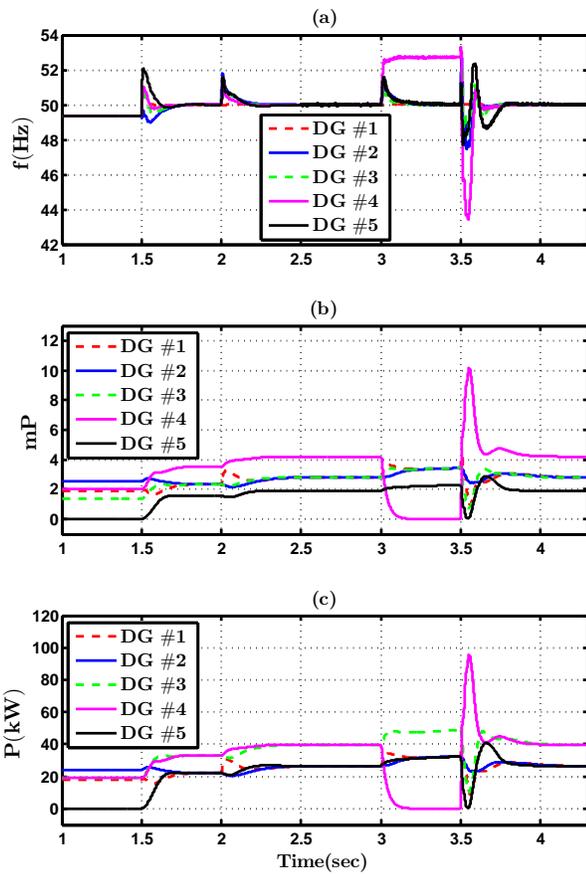


Fig. 10. Change of additive noise parameters: a) frequencies, b) real power ratios, and c) output real powers of DG units.

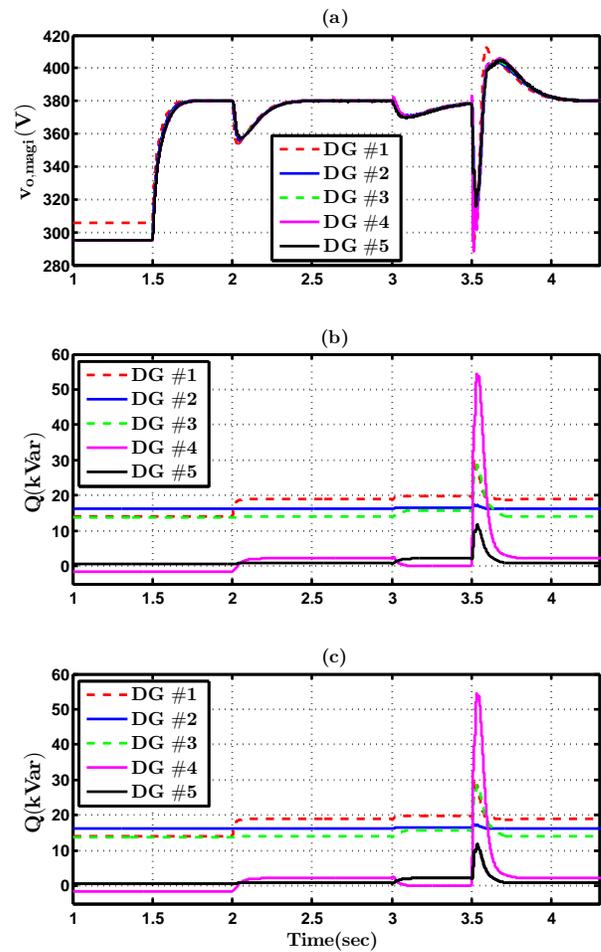


Fig. 11. Change of additive noise parameters: DGs output (a) voltage magnitude, (b) reactive power with secondary control, and (c) reactive power without secondary control.

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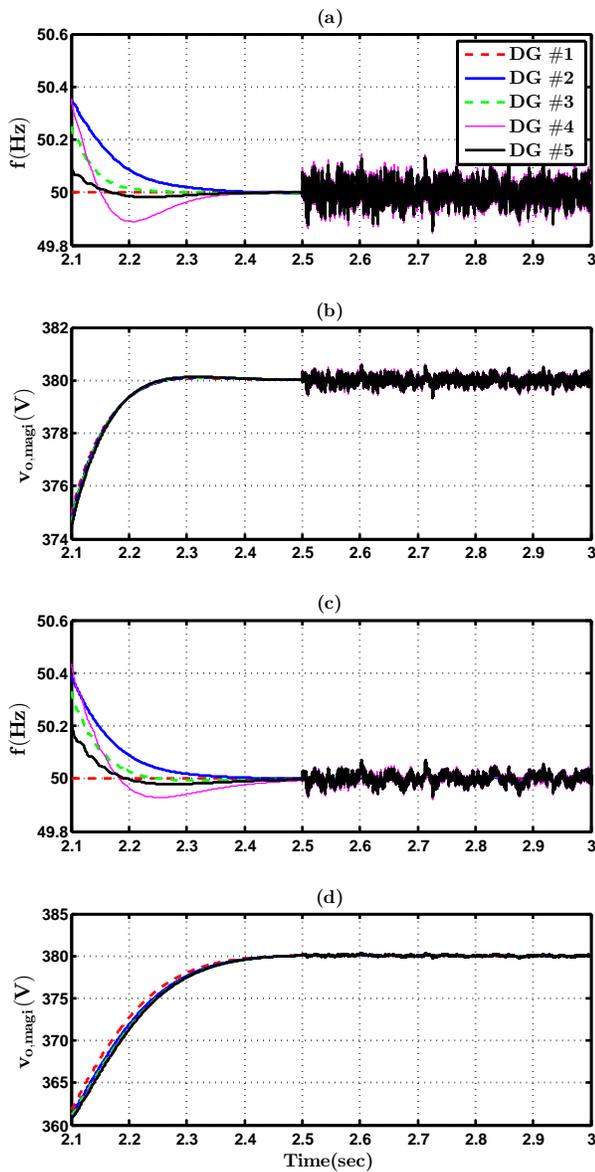


Fig. 12. Comparison with a previously-reported method [25]: a) frequency, b) voltage magnitudes of PCC buses of DG units, using the previously-reported distributed cooperative secondary control method [25], c) frequency, and d) voltage magnitudes of PCC buses of DG units, using the proposed distributed noise-resilient secondary control scheme.

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