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Decentralized Optimal Frequency Control in Autonomous Microgrids

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***Abstract*-- This paper proposes a decentralized optimal secondary controller for frequency regulation and accurate active power sharing in autonomous microgrids. This optimal controller does not require any communication network. Unlike most of the existing works, a systematic approach of secondary controller design is introduced based on a quadratic cost function in the form of a linear quadratic regulator (LQR) solution. The design procedure only depends on the cut-off frequency of the power calculation filter. Decentralized behavior, simplicity, optimality based on a quadratic cost function, and straight forward design procedure are the main advantages of this approach. Using the proposed solution, frequency can be restored immediately following any disturbance in the system, without need of any event-driven and time-dependent protocol. Experimental results validate the effectiveness of the proposed controller.**

***Index Terms*— Autonomous microgrids, active power sharing, decentralized secondary control, frequency control, linear quadratic regulator.**

I. Introduction

In islanded microgrids, control objectives are often determined and implemented by a multi-layer hierarchical structure to set frequency and voltage to their desired values, and to perform accurate active and reactive power sharing [1], [2]. Primary, secondary, central/emergency located in microgrid central control (MGCC), and global control are the main control layers [3]–[6].

Regulation of the system voltage and frequency and power sharing are the main objectives in the primary layer [7], [8]. These control goals are often achieved by current, voltage, and droop control loops. Frequency and voltage deviations are introduced as inherent drawbacks in this layer as a result of the droop mechanism, which will be eliminated by the secondary control [9]. The MGCC coordinates and manages the operation of power transactions at optimal points between DGs, determines the set points of each unit, and finally orders protective commands to accidentally or intentionally plug in/out the DGs. Furthermore, economic concerns, electricity markets, and ancillary services are the main issues in the global layer [10]. The last two layers, *i.e.*, emergency control and global control, are also known as tertiary layer in the literature [3], [5].

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Majority of existing secondary control solutions are based on communication infrastructures to provide a desirable performance. The communication-based solutions are classified in to centralized and distributed secondary controllers. All frameworks based on these two control strategies are vulnerable to the failure of communication links [4]. The performances of centralized secondary control approaches are highly constrained by complex point-to-point communication links between all DGs, no scalability, single point of failure, and low reliability [11].

Unlike the centralized structure, the distributed one provides more scalability, and higher reliability, while using a spare communication network [12], [13]. Voltage and frequency restoration [14]–[19], reactive power sharing [20], voltage unbalance compensation [21], and cooperative control of multi-agent systems [16], [22] are numbers of implemented distributed secondary control approaches.

To mitigate the effect of communication link failures, data drop-out, and time delay issues around communication networks, new solutions are emerging with regard to communication uncertainties [23]–[25]. Although a general communication network is still needed for coordination of units during a black start process or tertiary control layer command exchanges, reducing communication networks on upper control layers can enhance the reliability and flexibility of microgrids. Obviously, by reducing dependency on communication, real time data exchange and its impact over control objectives will be reduced. Even-trigger based secondary control methods are new approaches to reduce the communication band-width [26]–[30]. While these approaches are mainly robust against communication uncertainties, they often have complex design procedure which is a limit in practical implementations.

As an alternative, decentralized secondary control architecture has been recently introduced in the literature [31]–[34]. Authors in [31] present a switched secondary frequency restoration, in which the control scheme switches between two configurations by a time-dependent protocol. The event-detection and time-dependent protocols used in this work, increases complexity of the solution and decreases the system stability and reliability, while its performance is not (proved to be) optimal. Although the presented solution is decentralized, it is not fully communication-less and its plug-and-play capability has not been verified. Moreover, estimation-based decentralized secondary control has been recently introduced in the literature to control voltage and frequency of microgrids [33], [34].

The present paper proposes an optimal secondary frequency

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controller for islanded microgrids using optimal LQR technique. The proposed controller includes one frequency control/power sharing module. It is designed based on the dynamics of power low-pass filter and droop mechanism. Experimental results are conducted to validate the capability of the proposed approach using a laboratory-scale microgrid. The salient features of the proposed control methodology are as follows.

1) The proposed controller is based on a simple, straightforward, and systematic design in the form of an optimal LQR problem. The optimal control solution, used in the secondary layer, guarantees accurate active power sharing and fast frequency restoration.
2) Unlike the distributed secondary control works in the literature, e.g., [15]-[24] , the proposed solution is fully decentralized and it does not require any communication infrastructure.
3) There is no need of small signal-modeling of the system and the controller is designed only based on dynamics of the power filter and the droop control.
4) Unlike the existing decentralized works, e.g., [31], [32], [34], the proposed controller does not require any event detection, time-dependent protocols, and state-estimation calculation.

The rest of this paper is organized as follows. Hierarchical control is reviewed in Section II. In Section III, the design procedure of the proposed approach and stability analysis is presented. Experimental validation of the proposed method is presented in Section IV. Finally, Section V concludes the paper.

II. Multi-Layer Control Framework of Microgrids

A general configuration of a microgrid composed of *n* DG units is shown in Fig. 1. Each unit can be connected to a local load or directly to an AC common bus to supply the power. The inverter based DGs are classified as voltage source inverters (VSI) or current source inverters (CSI). Although in MGs both types can operate in parallel, VSIs are preferred because of their easy control extension in power quality improvements.

In the rest of this section, a brief review of control layers in a typical microgrid is reported.

A. Primary Layer

The first control layer including current loop, voltage loop, virtual impedance loop, and droop mechanism is the primary layer. The most important objectives of this layer are frequency and voltage regulation, accurate power sharing and power quality enhancement. This control layer basically follows up the set-points referenced by upper level controllers.

Various control strategies are designed, investigated, and performed to regulate the output voltage amplitude and to control the current guarantying stability of the system [4], [7].

Droop control strategy is a way to mimic the synchronous generator's behavior by adjusting the amplitude of voltage and the frequency reference conforming to the active and reactive filtered powers as

$$\begin{aligned} \omega_i &= \omega^* - m_i P_i \\ v_i &= v^* - n_i Q_i \end{aligned} \qquad (1)$$

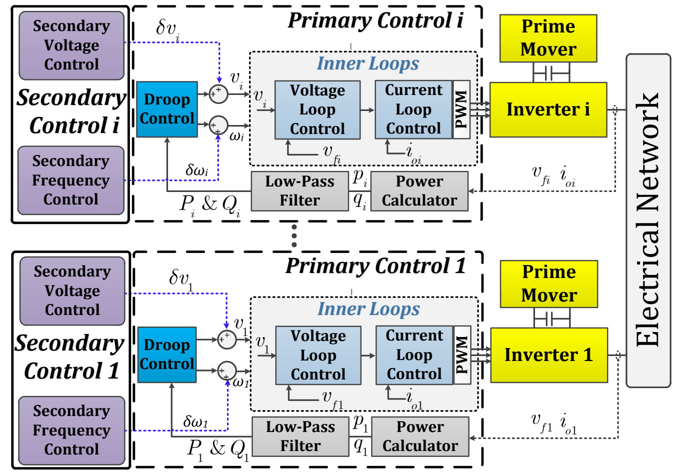

Fig. 1. General schematic of an inverter based microgrid with the primary and secondary loops.

where ω^* is the nominal frequency of the system, v^* is the nominal voltage amplitude of the system, P_i and Q_i are the filtered active and reactive power of unit i, ω_i and v_i are the reference output frequency and voltage amplitude for lower loops, m_i is the $P - \omega$ and n_i is the $Q - v$ droop coefficients of unit i. Furthermore, a virtual impedance loop is often augmented to the voltage amplitude reference to increase the accuracy of power sharing for those microgrids which are not inductive. More details about this control layer can be found in [4].

B. Secondary Layer

This layer located on top of the primary control and deals with compensating deviations of the voltage and frequency. To handle the steady-state errors and deviations, a correction term is aggregated to the primary layer as follows:

$$\begin{aligned} \omega_i &= \omega^* - m_i P_i + \delta\omega_i \\ v_i &= v^* - n_i Q_i + \delta v_i \end{aligned} \qquad (2)$$

where $\delta\omega_i$ and δv_i are correction terms added by the secondary layer to the droop control. These correction terms can be added by three main strategies; centralized, distributed, and decentralized.

1) Centralized control framework

In order to achieve a global controllability of a microgrid, it is required to establish a communication infrastructure among DGs. To this end, a centralized secondary control strategy is implemented in MGCC. Conventionally, in the centralized control strategy, all the command signals are exchanged between MGCC and each one of the units. Each unit is handled by its primary controller, and the gathered information by remote sensing blocks will be transmitted back to the central control unit. Strong controllability and observability of the whole system are the main advantages of the centralized control.

2) Distributed control framework

The distributed control framework, in comparison of the centralized control strategy, uses the recent advances in communication technologies, such as WiFi and Zigbee technologies, and also new algorithms for exchange of

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information (such as gossip, consensus, OpenFMB, and peer to peer). This increases the enthusiasm of practical implementation of the distributed control method. All the control units conversational 'talk' to each other via digital communication such that minimum information is shared among them to enhance coordinated performance of all the units. This coordinated performance is the main challenge of a fully distributed control framework which must satisfy all control objectives.

3) Decentralized control framework

Decentralized secondary control is implemented locally at each DG, either uses individual local states or estimates neighbor variables. In this framework, a secondary control can be designed without remote-based measurement and communication network. In this manner, the required states of the neighbor DGs in the MG are estimated based on local measurements. Using this estimated variables, the secondary controller generates appropriate control command to be forwarded to the primary layer. Although estimation-based decentralized frameworks require no communication infrastructure, they often have complex calculations. An overall architecture of these approaches are illustrated in Fig. 2.

C. MGCC and Global Control

MGCC and global control have the most important role to meet operational constraint, optimization needs, and properly control in grid-connected and autonomous modes of an MG by a reliable and secure manner. Optimal unit commitment, critical and non-critical load servicing, emergency load-shedding, and initialization of protection strategies are categorized as the main objectives of MGCC control. However economic dispatch of multiple networked MGs by considering demand-generation balance refers to global control. More details about MGCC and global control can be found in chapters 5 and 11 of [1].

III. Proposed Decentralized Secondary Controller

Here, we propose a decentralized frequency controller that well regulates the system frequency while maintaining the proportional active power sharing among the DGs. General scheme of the proposed framework is illustrated in Fig. 3. The control scheme is composed of a single module where its required data, i.e. ω^*, ω and P , are obtained from the primary control layer. In order to design this controller, we only use the droop control dynamics and its input low pass filter. Note that the present work is only focused on the frequency control. It is assumed that voltage is regulated by the $Q-v$ droop mechanism.

A. Design Procedure

The droop mechanism for active power path can be formulated as

$$P_i = H_{LPF}(s)\, p_i = \frac{\omega_c}{s+\omega_c}\, p_i \qquad (3)$$

$$p_i = v_{od}^i i_{od}^i + v_{oq}^i i_{oq}^i \qquad (4)$$

where p_i is the instantaneous active power, P_i is the filtered active power, ω_c is the cut-off frequency, and $H_{LPF}(s)$ is the

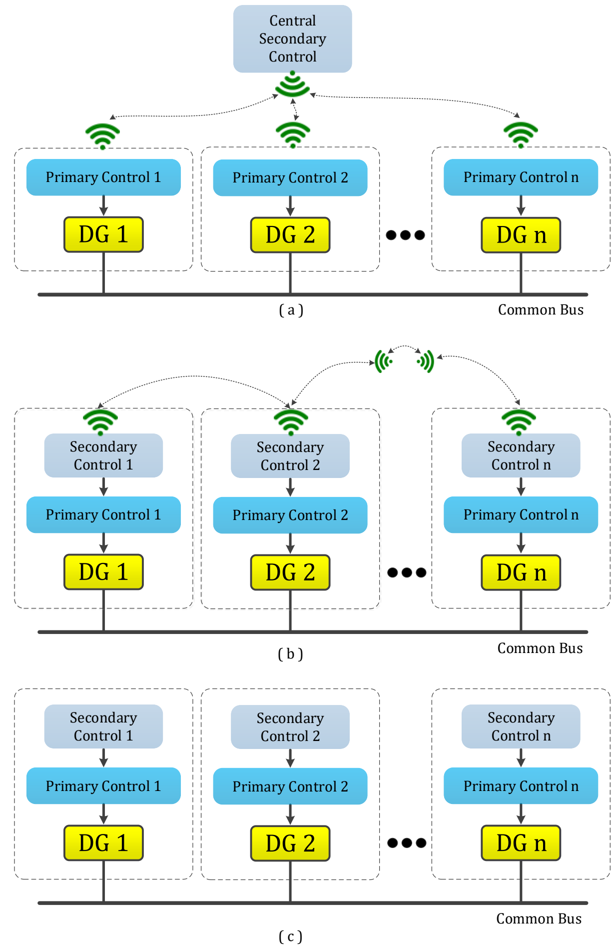

Fig. 2. Various architectures of secondary control frameworks: (a) Centralized, (b) Distributed, and (c) Decentralized.

low pass filter transfer function. The well-known active power-frequency droop equation is expressed as

$$\omega_i = \omega^* - m_i \cdot P_i = \omega^* - m_i \frac{\omega_c}{s+\omega_c} p_i. \qquad (5)$$

Let $e_i \triangleq \omega^* - \omega_i$, then (5) is rewritten as

$$e_i = m_i \frac{\omega_c}{s+\omega_c} p_i. \qquad (6)$$

The time domain equivalent of (6) is

$$\dot{e}_i(t) = -\omega_c e_i(t) + m_i \omega_c p_i. \qquad (7)$$

According to the internal mode control, an integrator should be augmented to (7) to eliminate the steady-state error. Towards this end, let us first define $x_{1i}(t) = \int_0^t e_i(\tau)d\tau$ and $x_{2i}(t) = e_i(t)$ as the state-variables, and $u_i(t) = p_i(t)$ as the control input. Using these definitions, the following state-space representation is obtained as:

$$\dot{x}_i(t) = \begin{bmatrix} 0 & 1 \\ 0 & -\omega_c \end{bmatrix} x_i(t) + \begin{bmatrix} 0 \\ m_i \omega_c \end{bmatrix} u_i(t) \qquad (8)$$
$$\triangleq \boldsymbol{A} x_i(t) + \boldsymbol{B}_i p_i(t)$$

where $x_i(t) = [x_{1i}(t) \quad x_{2i}(t)]^T$. Now, an optimal control problem is defined to optimize the performance of the closed-loop system based on the following quadratic cost function:

$$\mathcal{J} = \frac{1}{2}\int_0^\infty \{x_i^T(t)\boldsymbol{Q}x_i(t) + \mathcal{R}u_i^2(t)\}dt \qquad (9)$$

where $\boldsymbol{Q} = diag(q_1, q_2)$ with $q_1, q_2 \geq 0$ and $\mathcal{R}$ is a positive parameter. The first part of the cost function (9) is related to the

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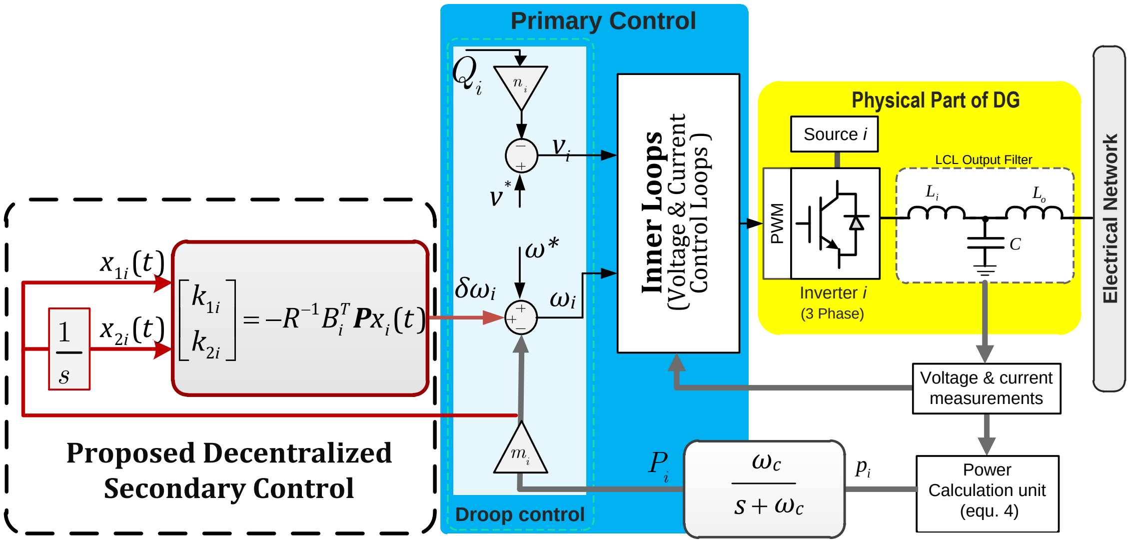

Fig. 3. Proposed control implementation.

quality of the response and the second part is an index for the utilized control effort. The user defined weighing matrices $\mathcal{R}$ and $\boldsymbol{Q}$ are used to make a trade-off the closed-loop system performance and the control effort. For instance, if the error tends to zero slowly, one can increase the weights q_1 and q_2 or decrease the input weight $\mathcal{R}$. A simple and reasonable choice for $\mathcal{R}$, q_1, and q_2 is given by Bryson's rule as follows [35] :

$$\mathcal{R} = \frac{1}{\text{maximum acceptable value of } u_i^2(t)}$$

$$q_1 = \frac{1}{\text{maximum acceptable value of } x_{1i}^2(t)}$$

$$q_2 = \frac{1}{\text{maximum acceptable value of } x_{2i}^2(t)}.$$

To find the solution of the optimal control problem, the following Riccati equation is to be solved:

$$\boldsymbol{A}^T\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A} - \boldsymbol{P}\boldsymbol{B}_i\mathcal{R}^{-1}\boldsymbol{B}_i^T\boldsymbol{P} + \boldsymbol{Q} = 0\,. \tag{10}$$

Once the positive-definite-solution $\boldsymbol{P}$ is obtained from (10), the optimal feed-back control $\delta\omega_i(t) = -R^{-1}\boldsymbol{B}_i^T\,\boldsymbol{P}\,x_i(t)$ is applied to the system. Nevertheless, the Riccati equation (10) has a unique positive-definite-solution if and only if the triple $(\boldsymbol{A}, \boldsymbol{B}_i, \boldsymbol{Q}^{\,1/2})$ is stabilizable and detectable [36]. The pair $(\boldsymbol{A}, \boldsymbol{B}_i)$ is controllable if the state-controllability matrix $\varphi_{ci} = [\boldsymbol{B}_i\ \boldsymbol{A}\boldsymbol{B}_i]$ is full-rank. Using the state space model (8), one can see that the determinant of φ_{ci} is $-m_i\omega_c^2$ which is not zero and therefore the controllability condition is satisfied. In addition, for $q_1 > 0$ and $q_2 > 0$, the observability of the pair $(\boldsymbol{A}, \boldsymbol{Q}^{1/2})$ is also satisfied. It is worth noting that the Riccati equation (10) can be solved using some well-known techniques such as Kleinman iterative algorithm [37] . In this paper, the command "lqr" in MATLAB software is employed to find the solution of this equation in an off-line manner and therefore the time needed for finding the solution is not an important issue.

Remark 1. The control law $\delta\omega_i(t) = -\mathcal{R}^{-1}\boldsymbol{B}_i^T\boldsymbol{P}x_i(t)$ can be rewritten as

$$\delta\omega_i(t) = -\kappa_{1i}x_{1i}(t) - \kappa_{2i}x_{2i}(t). \tag{11}$$

Substituting $x_1(t)$ and $x_2(t)$ with their equivalences, the following control law is obtained:

$$\delta\omega_i(t) = -\,\kappa_{1i}e_i(t) - \kappa_{2i}\int_0^t e_i(\tau)d\tau \tag{12}$$

which has a proportional-integral (PI) structure. Therefore, it can be concluded that the proposed technique leads to an optimal PI controller where its parameters are tuned after solving the Riccati equation (10). Fig. 3 shows the implementation of the decentralized proposed control.

Remark 2. The closed-loop stability is guaranteed by applying the proposed controller since triple $(\boldsymbol{A}, \boldsymbol{B}_i, \boldsymbol{Q}^{\,1/2})$ is fully controllable and observable [36].

B. Closed-loop System Modelling and Stability Analysis

Fig. 4(a) shows an equivalent model of a DG connected to the point of common coupling (PCC) in a microgrid. The injected active power by the DG to the PCC can be obtained as

$$p_i = \frac{x_{eqi}\left(V_iV_b\,Cos(\varphi) - V_b^2\right) + r_{eqi}V_iV_b\,Sin(\varphi)}{x_{eqi}^2 + r_{eqi}^2} \tag{13}$$

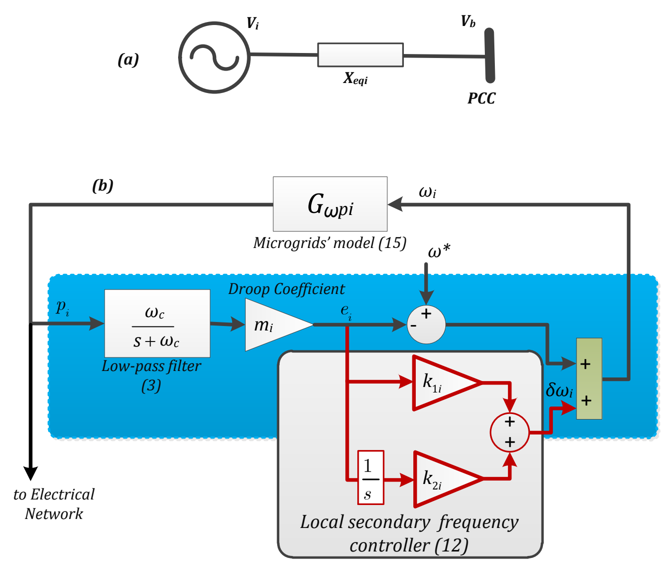

Fig. 4. (a) a general microgrid equivalent model of a DG connected to PCC, (b) model of the proposed secondary control.

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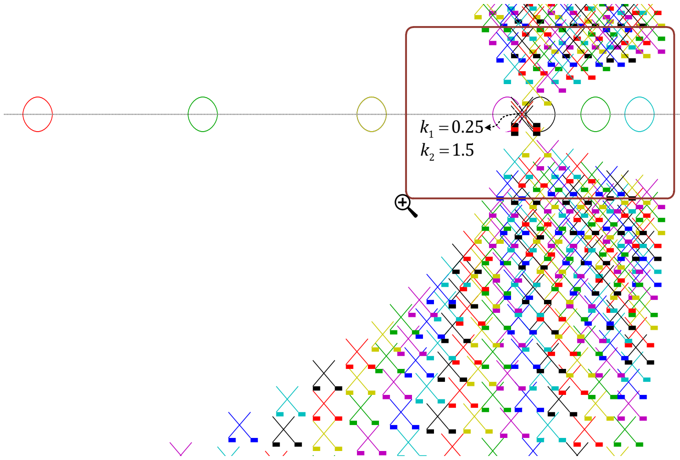


Fig. 5. Dominant closed-loop zp-map for various values of κ_{1i} and κ_{2i}.

where V_i is amplitude of the i^{th} DG output voltage, V_b is amplitude of the PCC, and φ is the phase difference between the DG and the PCC. As illustrated in Fig. 4(a), x_{eqi} and r_{eqi} are the i^{th} coupling inductance and resistance between the DG and the PCC. Once the connecting impedance is mainly inductive, the active power can be assumed as

$$p_i \approx \frac{3\,V_i\,V_b}{2\,x_{eqi}}\,Sin(\varphi). \tag{14}$$

Considering the micro-scale transferred power of each DG to PCC, one can assume $Sin(\varphi) \approx \varphi$. Thus (13) can be rewritten as

$$p_i \approx \frac{3\,V_i\,V_b}{2\,x_{eqi}}\,\varphi = \frac{3\,V_i\,V_b}{2\,x_{eqi}}\,\frac{\omega_i}{s} = G_{\omega pi}.\omega_i \tag{15}$$

Substituting (15) in (4) and (2), the closed-loop system transfer function is obtained as.

$$\omega_i = \omega^* - m_i\frac{\omega_c}{s+\omega_c}\,\frac{3\,V_i\,V_b}{2\,x_{eqi}}\,\frac{\omega_i}{s}$$
$$+\kappa_{1i}(\omega^* - \omega_i) + \frac{\kappa_{2i}}{s}(\omega^* - \omega_i)$$

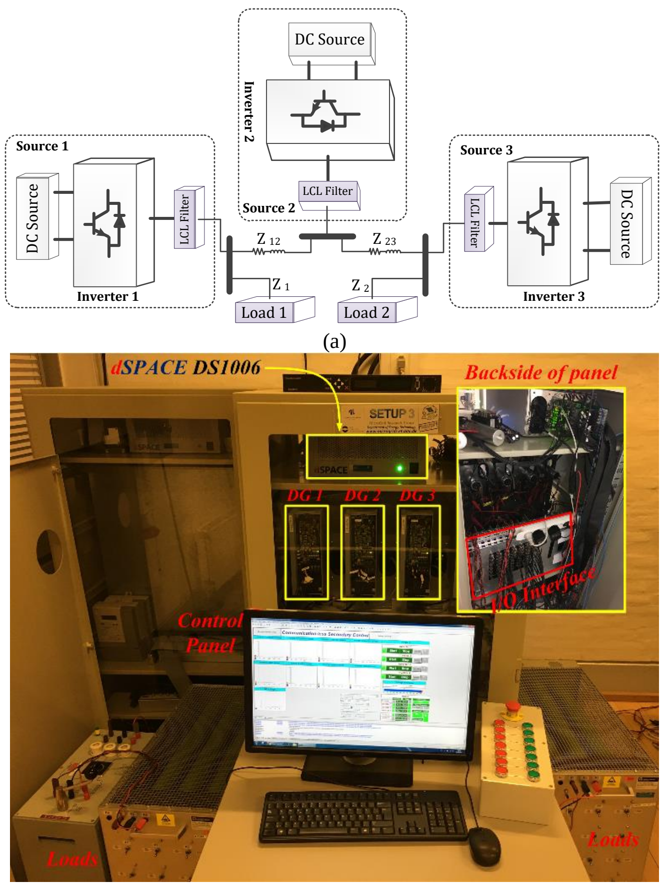
The transfer function can be simplified as

$$\frac{\omega_i}{\omega^*} = \frac{(\kappa_{1i}+1)s^2 + (\omega_c(\kappa_{1i}+1)+\kappa_{2i})s + \kappa_{2i}\omega_c}{(\kappa_{1i}+1)s^2 + (\omega_c(\kappa_{1i}+1)+\kappa_{2i})s + C} \tag{16}$$

where $C = \frac{3\,m_i\,\omega_c\,V_i\,V_b + 2\kappa_{2i}\omega_c}{2\,x_{eqi}}$. Using (16) and a usual assumption for small-scale microgrids $V_b = V_i = V_{MG}$, large-signal stability analysis of the closed-loop system for various values of κ_{1i} and κ_{2i} is depicted in Fig. 5.

IV. Experimental Validation

A three-inverter microgrid setup, illustrated in Fig. 6(a), was prototyped to evaluate the performance of the proposed approach. Nominal voltage and frequency of the system are 230 V and 50 Hz, respectively. The configuration of the prototyped three-phase AC microgrid and the connection of all sources are shown as Fig. 6, in a radial direction to supply two loads Z_1 and Z_2. All inverter based sources have a similar topology with different ratings, i.e., the power rating of the Danfoss inverters at sources 1 and 2 is half of the one at source 3. LCL filters are installed to reduce the switching induced harmonics and



(a)

(b)

Fig. 6. Test bench of experimental microgrid setup: (a) overall schematic of the system configuration, (b) photo of the setup.

TABLE I
ELECTRICAL AND CONTROL PARAMETERS OF THE MG TEST SYSTEM

Electrical Parameters		
Parameter	Symbol	Value
DC Source voltage	V_{DC}	650 V
Nominal voltage magnitude	V_{MG}	325 V
Nominal Frequency	f	50 Hz
Switching Frequency	f_s	10 kHz
Capacitance of LCL filter	C	25 μF
Input inductance of LCL filter	L_i	1.8 mH
Output inductance of LCL filter	L_o	1.8 mH
Virtual impedance	Z_v	3.93 j Ω
Line impedance 1	Z_{12}	0.8 Ω , 3.6 mH
Line impedance 2	Z_{23}	0.4 Ω , 1.8 mH
Load 1	Z_1	43 Ω , 0.3 H
Load 2	Z_2	124 Ω , 0.1 H

Control Parameters			
Parameter	Symbol	Sources 1&2	Source 3
Rated active power	P_n	800 W	1600 W
Rated reactive power	Q_n	300 VAr	600 VAr
P-w droop coefficient	m	0.001 W/rd	0.002 W/rd
Q-v droop coefficient	n	0.01 VAr/V	0.02 VAr/V
Current proportional term	k_{ip}	0.35	0.35
Current integral term	k_{ii}	200	200
Voltage proportional term	k_{vp}	5	5
Voltage integral term	k_{vi}	2000	2000
Secondary parameter	κ_1	0.25	0.25
Secondary parameter	κ_2	2.5	2.5

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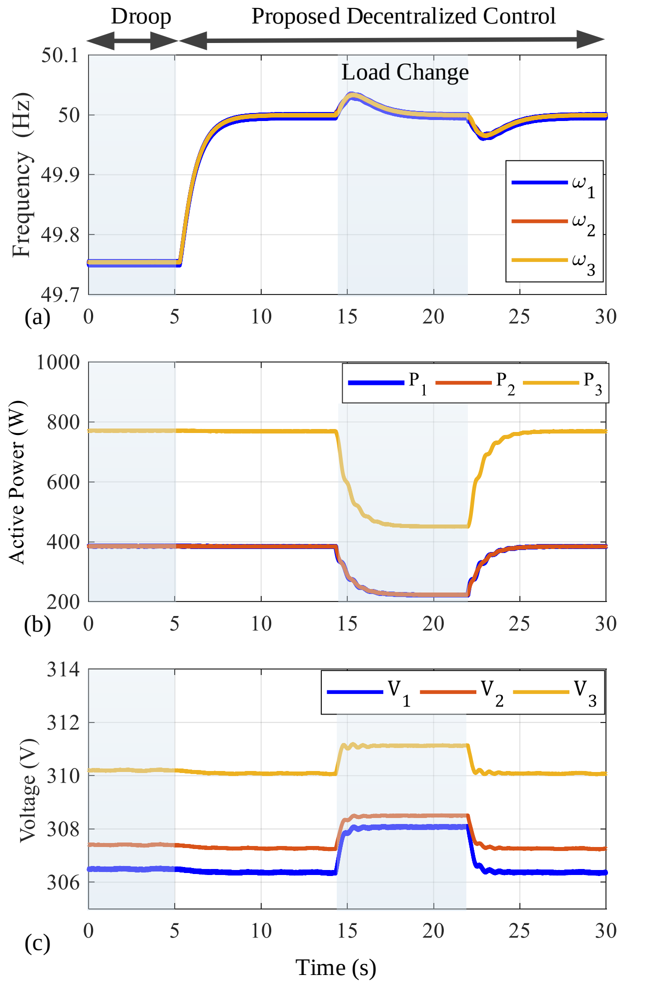

Fig. 7. Performance of the proposed secondary control scheme comparing droop mechanism: a) frequency, b) active powers, and c) output voltage amplitudes.

notches are installed at the outputs of any unit. Low pass filters are used in the output of power calculation unit at droop layer to eliminate undesired switching and harmonics, notches and high frequency distortions. A series RL-circuit is used to model line impedances. DS 1006 dSPACE processor control board acts as an interface between the system and the proposed control and implements the control framework on the prototyped microgrid. Other control and electrical parameters of the system are tabulated in detail in Table I.

In order to validate the control platform in a hardware-in-the-loop manner, the studied microgrids with the presented control are simulated in Simpower system environment of MATLAB software. Then for experimental validation, the control platform are coded by MATLAB into dSPACE.
Performance of the proposed controller is investigated through the following parts.

A. Performance Evaluation

Performance of the proposed control framework is evaluated and compared with the conventional droop control in Fig. 7. As illustrated, for $t < 5\,s$, only the primary and droop control layers are effective, and the frequency term deviates considerably from its rated value. Once the proposed secondary controller is applied for $t \geq 5\,s$, frequency is restored to its nominal value (see Fig. 7(a)). While the active power sharing of droop mechanism is well maintained (see Fig. 7(b)), no voltage change is observed (see Fig. 7(c)) after activation the secondary controller. In the next scenarios, where frequent load changes disconnected and connected at $t = 14\,s$ and $t = 22\,s$, respectively, the proposed control scheme is able to successfully maintain the system frequency within an acceptable range, without any event-detection strategy or time-driven method.

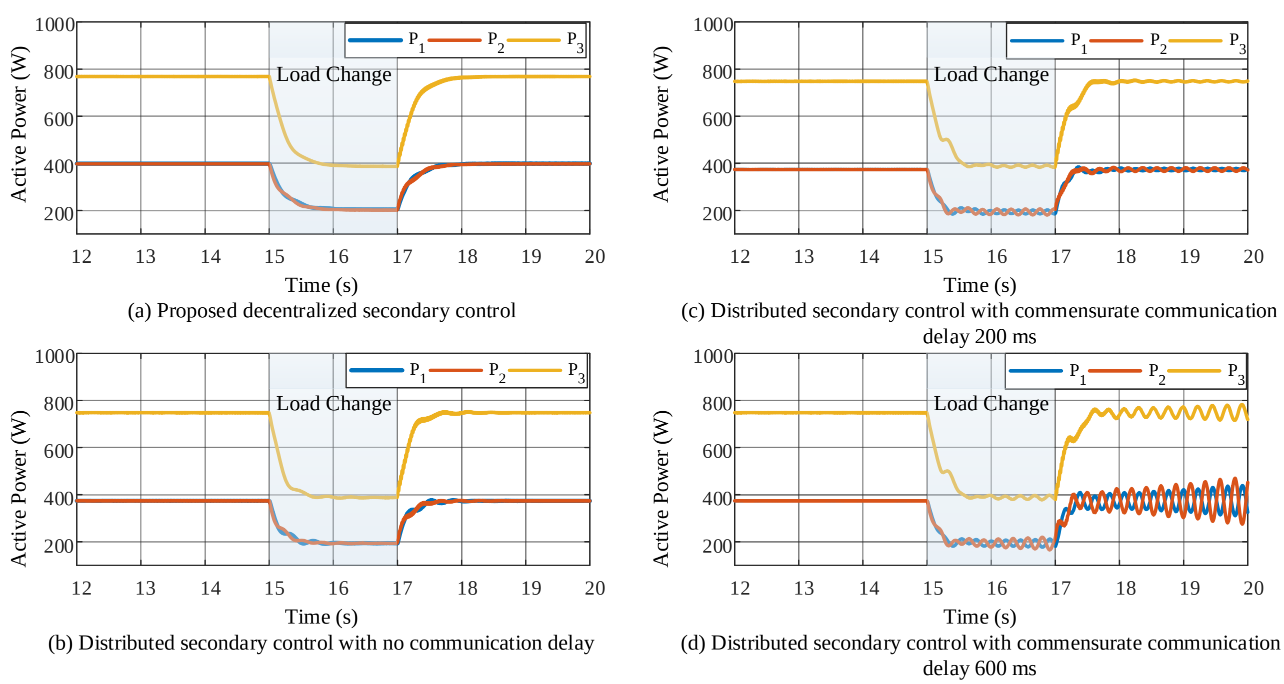

Fig. 8. Performance of the proposed decentralized control scheme versus distributed secondary control introduced at [15] by considering communication delay.

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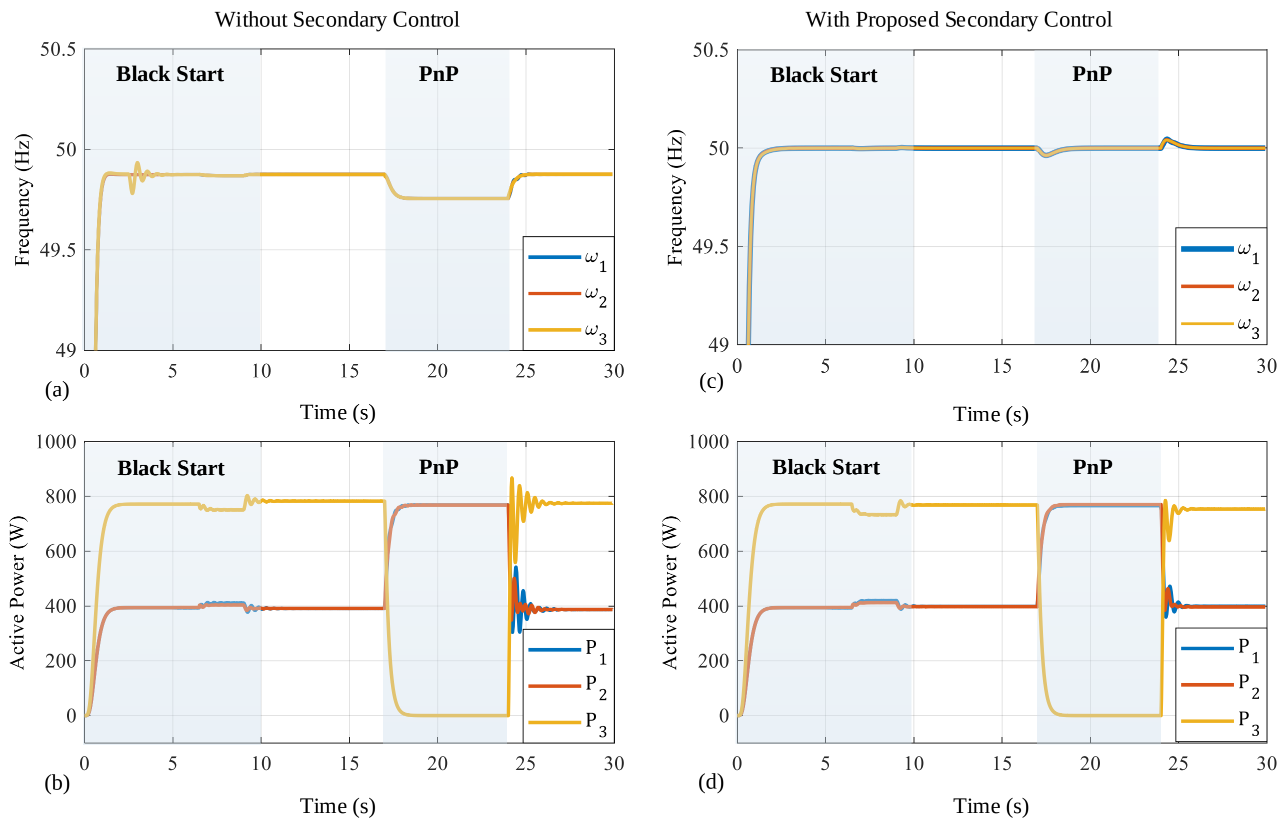

Fig. 9. Comprehensive investigation to assess the performance of the proposed controller under black-start and plug-and-play scenarios: (a) and (b) active power sharing and system frequency without the proposed controller, (c) and (d) active power sharing and system frequency when the proposed controller is applied.

B. Comparison with a Distributed Secondary Control

In this case, we aim to show the communication-less feature of the proposed decentralized control. To this end, the proposed control scheme is compared with a distributed secondary control which suffers from time delays of the communication network in Fig. 8. For an accurate comparison, structure of the studied microgrid is the same for both of the architectures.

Fig. 8 shows a comparison between the proposed secondary control with a distributed secondary control introduced in [15]. Secondary control is activated for both of them and a frequent load change is occurred, disconnection and connection again at $t = 15\ s$ and $t = 17\ s$, respectively.

Fig. 8(a) shows the performance of the proposed control and Fig. 8(b) shows the performance of the distributed secondary control with no any communication disturbance. While we consider a 200 ms time delay as a communication disturbance on the distributed secondary control, fluctuations on active power sharing for the distributed secondary control will be appeared. Results are depicted at Fig. 8(c). By increasing the time delay in the communication network, as shown Fig. 8(d), fluctuations in active power sharing between DG units will be more and wouldn't be damped.

C. Synchronization and Plug-and-Play Capability

Black start process including synchronization of all DGs, and intentionally disconnection and reconnection of DG 3 in the MG are scenarios of this case which are shown in Fig. 9. Performance of the system with and without the proposed controller is demonstrated for all the mentioned scenarios.

Time interval $t \in [0-10]\ s$ shows the black start process where the sources are synchronized with each other, and the connection of the lines occur with the embedded circuit breakers. In the time interval $t \in [17-24]\ s$, the third inverter is intentionally disconnected from the microgrid and connected back again at $t = 24\ s$. In this scenario, the excess active power demand is shared among the remaining inverters (see Figs. 9(b) and 9(d)). The frequency drop in Fig. 9(a) is obvious due to the droop mechanism, while it is immediately restored by the secondary controller, as shown in Fig. 9(c). It should be noted that no any time-dependent and event-driven protocol is used to restore the frequency, neither in the black-start nor in the plug-and-play scenarios.

To plug back the disconnected source to the microgrid, a synchronization procedure must be done to match its frequency, voltage, and phase angle with the microgrid. Source 3 is reconnected to the microgrid after a successful synchronization procedure. It can be seen that the proposed control scheme properly eliminates the deviation caused by the disturbance. When source 3 is reconnected, a better transient response is observed in the active power sharing among the sources.

V. Conclusion

This paper introduces a decentralized secondary frequency control for autonomous microgrids. An LQR optimal solution is utilized which guarantees stability and optimal frequency regulation. In the design procedure, only dynamics of the active power's low-pass filter is taken into account. Straight-forward design, optimal solution, easy implementation, and fully

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decentralized approach without using communication are major features of the presented controller. No switch control scheme, no time-dependent, and no event-driven protocol are used for implementation, and the other state-of-the-art is communication dependency cancellation. The efficacy of the proposed solution was validated by some experimental studies.

Future work will be on extending the main ideas of this proposal in order to achieve a robust voltage control with no communication infrastructure.

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