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Published (to be published) in: ***IEEE Journal of Emerging and Selected Topics in Power Electronics***

(Expected) publication date: **2019**

Estimation-based Consensus Approach for Decentralized Frequency Control of AC Microgrids

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Keywords

≪Microgrids≫, ≪Secondary frequency control≫, ≪Decentralized control≫, ≪Communication-free secondary control≫, ≪Consensus protocol≫

Abstract

In this paper, a decentralized frequency control of ac microgrid (MG) governed by $P-\omega$ droop characteristics is presented. This approach is realized by applying an active power estimation to eliminate the required communication infrastructure in the secondary control layer. The proposed decentralized frequency control is achieved by employing the unique feature of the frequency as a global variable in autonomous ac MGs. By utilizing a consensus protocol, the proposed method restores the MG frequency to the nominal value while maintaining accurate power sharing of the droop mechanism. The consensus protocol is an estimation-based approach and does not require communication infrastructure. Experimental results verified accurate power-sharing and the frequency restoration to the nominal value without any communication requirement.

Introduction

Microgrids (MGs) comprises a combination of distributed energy resources (DERs) as well as energy storage and loads which can be operated in grid connected or islanding mode. In order to control the MG voltage and frequency, a multi-layer hierarchical control strategy is introduced [1]. Primary layer locally controls the voltage and frequency of each DGUs, while droop control loop shares power in this layer. Secondary control (SC) layer compensates for voltage and frequency deviations and finally tertiary layer guarantees the economical operation of the MG [1]. In the most literature related to the hierarchical control structure, the primary controllers are implemented based on the decentralized control scheme, while the tertiary layer is based on the centralized communication system [2]. However, there is no standard architecture for SC layer. Therefore, it can be categorized to centralized [3], distributed [4, 5, 6] and communication free decentralized approaches [7, 8]. Fig. 1 demonstrates the centralized, distributed and decentralized SC architectures.

Communication network uncertainties and cyber-attacks degrade the SC architecture [9, 10]. Distributed SC and event-triggered SC scheme is presented in the literature to reduce malicious effect of communication network delay and data drop out [11, 12, 13].

However, all the aforementioned approaches rely on communication links among DGUs. Therefore, decentralized SC architectures have been presented. In [14, 15] an estimation based decentralized control

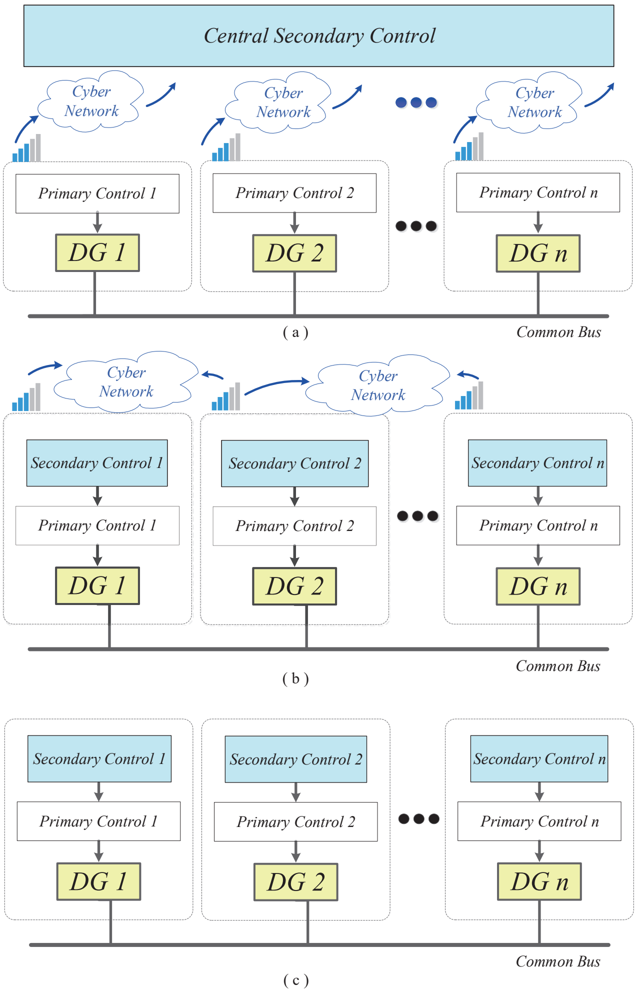

Fig. 1: Secondary control architectures; (a) Centralized secondary control. (b) Distributed secondary control (c) Decentralized secondary control.

structure based on the nonlinear and Luenberger-like observers has been introduced to compensate for the voltage and frequency deviations of the MG. however, high burden calculation and the control model complexity degrades the efficiency of the SC structure. In [16] a communication free SC is presented. However, only frequency restoration without accurate power sharing is presented.

State estimation and observer-based methods as the promising approaches to eliminate the dependency of the SC of MGs to the communication network (CN), can increase the overall reliability and reduce cyber-security concerns. In this digest, an active power estimation is proposed to restore the MG frequency and share active power among DGUs. Compared to the estimation based approaches presented in the state of the art which need a complete knowledge of the MG topology [14, 15], the proposed approach takes advantage of the unique feature of the frequency as a global variable to estimate active power of neighbour DGU. Furthermore, a consensus-based approach is presented with no need for a communication network between DGUs.

Reminder of the paper is prepared as follows. Section II proposes the function of SC in hierarchical control structure. In Section III, active power estimation with its remarks are presented. The proposed SC is addressed in Section IV. Experimental verification to show the effectiveness of the proposed SC is demonstrated in Section V. Finally, we conclude the remarks of the study in Section VI.

Secondary Control Function

The droop control loop in primary layer tunes the frequency and the voltage amplitude of the MG. Furthermore, it could be employed to relate frequency with the active power, and the voltage amplitude with reactive power based on their droop gains, m_i, and m_i respectively, as follows:

$$\omega_i^d = \omega^* - m_i.P_i\,, \tag{1a}$$
$$v_i^d = v^* - n_i.Q_i\,, \tag{1b}$$

where m_i and n_i represents droop characteristic coefficients for the MG frequency and voltage amplitude, respectively. ω^* and v^* stand for the reference frequency and voltage respectively, and P_i and Q_i are active and reactive output powers, respectively. In (1), ω_i^d and v_i^d are the references for inner voltage and current control loops. In worth to note that any changes in P_i and Q_i at (1) will change the value of ω_i^d and v_i^d, which leads to steady-state errors.

To compensate for the steady-state errors caused by primary control and droop, the SC layer send an appropriate signals to droop in order to compensate for the ω_i^d and v_i^d deviations. Mathematically, the SC signals satisfy the following expressions:

$$\lim_{t\to t_f} \omega_i^d(t) = \omega^*\,, \tag{2a}$$
$$\lim_{t\to t_f} v_i^d(t) \approx v^*\,, \tag{2b}$$

where (2b) and (2a) refer to the voltage and frequency restoration in a finite time t_f, respectively. Practically, since the voltage is a local variable of the MG, accurate voltage regulation as well as reactive power sharing cannot be archived together employing only the droop mechanism in (1b). In this digest we only focus on (2a) and assume that the $Q-v$ droop mechanism regulates the v_i for the DGUs. Therefore, to share active power accurately and (2a) satisfactory, the SC layer send a correction term to (1a) as follows:

$$\omega_i = \omega^* - m_p.P_i + \delta u_{\omega i}\,, \tag{3}$$

where, $\delta u_{\omega i}$ is the control signal send from the SC to the droop and ω_i is the regulated frequency of DGU$_i$.

Active Power Estimation

In this section the proposed approach for active power estimation of neighbour DGU$_j$ in the location of DGU$_i$ will be presented, where, $\{i, j \in N\}$ and N is the number of DGUs. The proposed estimation is completely based on $P-\omega$ droop coefficients. As the frequency is a global variable in the autonomous MGs, in normal operation of the MG under steady state demand/generation operation, the APE of the neighbour DGUs can be acheved as follows:

$$\hat{P}_j = \frac{\omega^* - \omega_i^d}{m_j}\,, \tag{4}$$

where $\hat{P}_j$ is the active power estimation of DGU$_j$ in DGU$_i$.Worthing to note that plug-and-play (PnP) operation of DGUs are controlled by MGCC and tertiary controller.

Proposed Secondary Control

The proposed SC structure is fully communication-free and decentralized. However, in emergency condition determined by MGCC, tertiary controller send PnP signal to each DGUs. The concept of adjacency

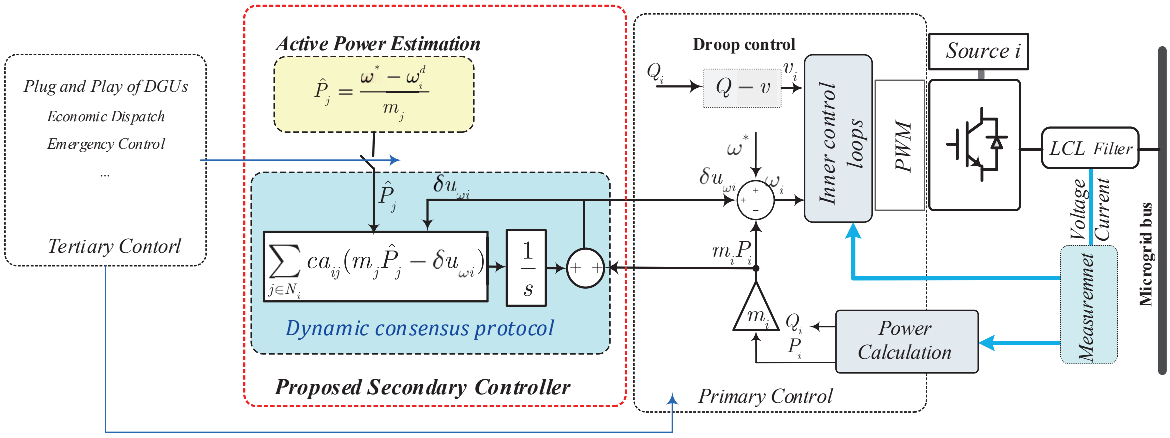

Fig. 2: Proposed communication-free secondary control.

matrix on graph theory has been applied to the proposed SC, which explained briefly in the following subsection.

Adjacency Matrix Expression

An adjacency matrix $\mathbf{A} = [a_{ij}] \in R^{N\times N}$ presents the status of neighbourhood DGUs. Although the networked control systems a_{ij} show the communication weights and directions, here it shows just the neighborhood status. For instance if DGU$_i$ is a neighbour of DGU$_j$ then $a_{ij} = a_{ji} = 1$, otherwise $a_{ij} = a_{ji} = 0$ [17]. Complete adjacency matrix expression, direction and weighting values, and corresponding implementation details will be given in the full version of the paper.

Control Protocol

In order to implementing a consensus protocol in the secondary layer, situation of neighbour DGUs should be considered. To this end, the estimated value of the active power (4) is employed. Accordingly, the frequency SC part at DGU$_i$ updates the correction term $\delta u_{\omega i}$ continuously based on the following consensus protocol

$$\delta u_{\omega i} = m_i P_i(t) + \int_0^t \sum_{j\in N_i} c a_{ij}(m_j \hat{P}_j(\tau) - \delta u_{\omega i}(\tau))d\tau, \tag{5}$$

where the consensus control gain c is a design parameter. A comprehensive expression on the optimal design of control gains c for the consensus protocols is addressed in [18]. An implementation diagram of the proposed controller is illustrated in Fig. 2.

Experimental Verification

In order to assess the performance of the proposed decentralized SC, it is experimented on a laboratory-scaled MG including four DGUs with the electrical and control parameters given in Table I. The configuration and of the experimental case study is shown in Fig. 3 (a). To show the merits of the communication-free SC, an experimental test is carried on in the following scenarios.

Scenario 1 (A comparison between the droop control and the proposed SC):

In this scenario, to assess the frequency restoration and accurate active power sharing, a comparison between the proposed communication-free SC and the $P-\omega$ droop mechanism is done, the results are shown in Fig. 3 (b) and (c). As it has been pointed out from Fig. 3 (a) and (b), framed as scenario 1, the MG system runs while Z_1 and Z_2 are supplied and the $P-\omega$ droop mechanism tunes the frequency magnitude, till $t < 4$ s when the proposed communication-less SC is activated and consequntly the frequency restores to 50 Hz (Fig. 3 (a)), while the active power among DGUs is accurately shared (see $t > 6$ in scenario 1 of 3 (b)).

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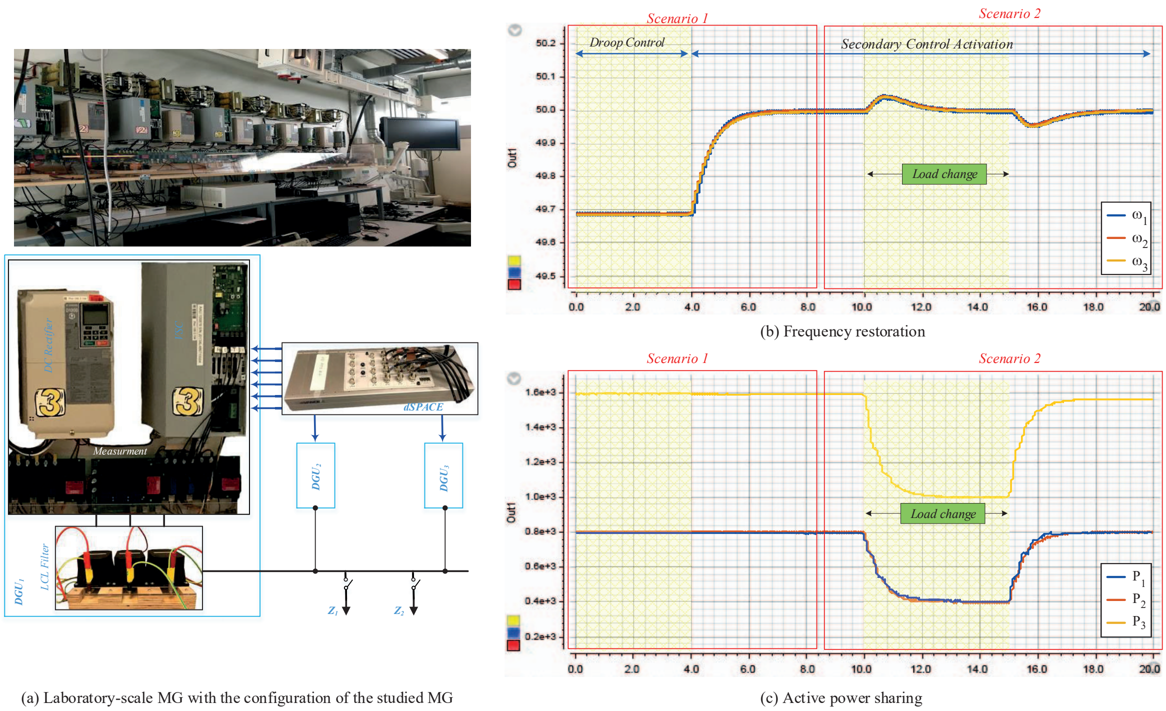

Fig. 3: Experimental set-up and results.

Scenario 2 (Load disturbance):

To accurate assess the performance of the communication-less SC, a load change as a common disturbance in the MG system is applied. As depicted in the scenario 2 at $t = 10$ s, Z_2 is switched off. After a transient time which the frequency meets an overshoot and the active power is decreased (see Fig.3 (b) and (c), scenario 2 frame), the frequency restored to its nominal value again. Consequently, Z_2 at $t = 15$ s returns to the MG circuit and the proposed SC restores the frequency to the nominal value.

Conclusion Remarks

In this study, a communication-free decentralized secondary control (SC) for frequency restoration in autonomous MGs is introduced. The proposed decentralized SC utilizes a consensus solution based on the active power estimation, which guarantees the stability of the system. The main feature of the MG frequency as a global variable is taken into account to active power estimation of the neighboring DGUs. Compared to the previous SC architectures, the main contribution of this paper was its communication-free control structure. Furthermore, straight-forward design, easy implementation, and consensus-based design to enhance the reliability of the system are the key features of the proposed SC. The proposed approach is verified on a test MG setup with four DGUs. The experimental results validate the performance and efficiency of the proposed method.

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Table I: ELECTRICAL AND CONTROL PARAMETERS OF THE TEST SYSTEM

Electrical Parameters		
Parameters	Symbol	Value
Output voltage of rectifier	V_{DC}	650 V
Nominal voltage magnitude	V_i	325 V
Nominal Frequency	f	50 Hz
Switching Frequency	f_s	10 kHz
Capacitance of LCL filter	C_f	25 μF
Input / output inductance of LCL filter	L_i / L_o	1.8 mH
Load 1	Z_1	43 Ω , 0.3 H
Load 2	Z_2	124 Ω , 0.1 H
Inner loop coefficients and other control Parameters		
Control Parameters	DGU: 2 and 4	DGU: 1 and 3
$P-\omega$ droop coefficient	0.001 rad/W.s	0.002 rad/W.s
$Q-v$ droop coefficient	0.005 V/VAr	0.01 V/VAr
Current integral / proportional terms	1000 / 0.5	1000 / 0.5
Voltage integral / proportional terms	120 / 0.05	120 / 0.05
Control design gain c	200	200

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