Communication-less Optimal Frequency Control of Islanded Microgrids

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Abstract

This paper proposes a decentralized linear quadratic regulator (LQR) for secondary control layer of islanded microgrids. This approach regulates the system frequency while guaranteeing accurate active power sharing among all the sources. Unlike the existing works, a systematic approach is introduced to design a communication-less secondary controller based on an appropriate quadratic cost function via the optimal LQR technique. Its decentralized characteristics, simplicity in implementation, optimality, and straightforwardness of the design procedure are the major features of the presented approach. Design procedure is depended only to the cut-off frequency of the droop layer low-pass filter and renders an optimal performance. Simulation results validate the efficiency of the proposed approach.

1. Introduction

A promising integration of distributed energy resources (DERs) is possible by a thriving concept of microgrids. A simple definition of a microgrid can be descripted as a group of DERs, local and common loads and energy storage units that works in an islanded or grid-connected operation modes to satisfy the whole demands of end-users. Improving the reliability, stability, and the quality of the grid are the special characteristics of microgrids and their significant growth in the last decade [1].

In the islanded mode, a multi-layer strategy is determined to regulate the frequency, set the voltage and to perform an appropriate power sharing. This multi-layer strategy can be layered by primary, secondary, and tertiary controls [2]-[4].

Main control objectives in the primary layer are local voltage amplitude regulation in each distributed generator (DG), system frequency stabilizing, and appropriate power sharing [4]. These goals are realized by designing and implementation of inner current loop, outer voltage loop, and droop mechanism in the primary layer. Steady state errors in the voltage amplitude and the frequency of the system are introduced as main drawbacks in the primary layer. These steady state errors are introduced as droop control challenges [5], which can be eliminated by the secondary layer producing a correction term to droop set points [6].

Secondary control approaches are categorized as centralized secondary control (CESC), distributed secondary control (DISC), and decentralized secondary control (DESC). In the secondary layer, the majority of existing solutions employ communication networks in order to eliminate steady state errors of frequency and voltage.

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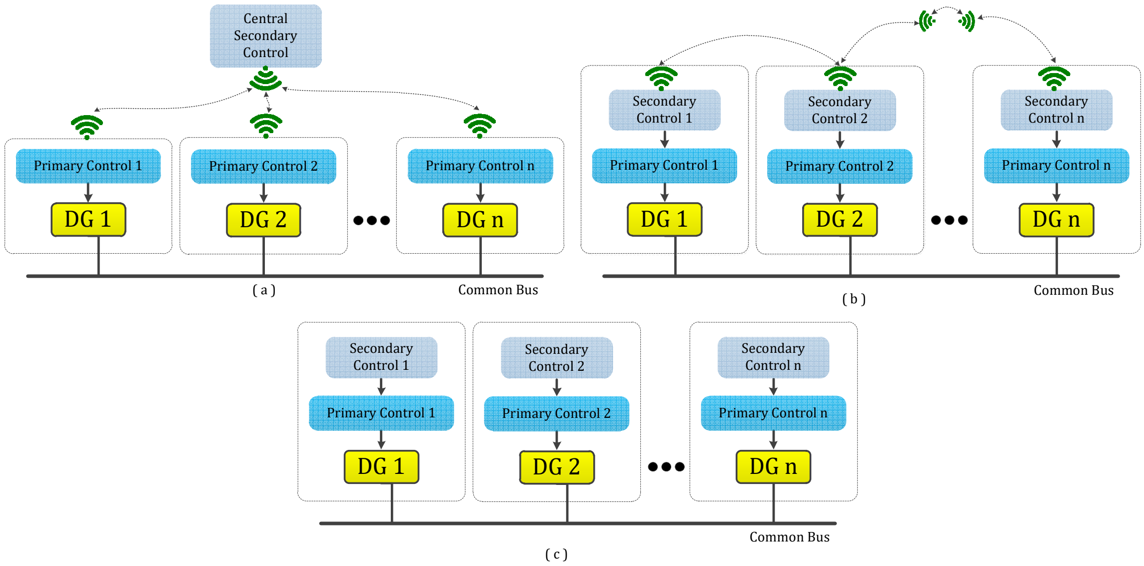

Fig. 1. Secondary control approaches in autonomous microgrids: (a) CESC, (b) DISC, and (c) DESC.

Although the most recent strategies, i.e., DISCs only require spars communication, they still suffer from the failure of communication links [6]. The performance of CESC approaches are highly limited by the point-to-point communication links between all DGs. Scalability of these approaches is not straightforward, and they have single point of failure's drawback, which results in low reliability [7]-[8].

DISC is a promising approach, which requires data exchange among the neighbor DGs using communication links. The control signal provided by a DISC is calculated based on communicated local and global signals of a number of DGs. Averaging and consensus techniques are normally employed for implementation of DISC approaches. Unlike CESC structure, the DISC needs a simple communication network, which provides easily scalability, and improved reliability [9]-[12].

To overcome the barriers of communication-based approaches, such as the failures of communication link, data drop-out, and time delay, the DESC is emerging as an alternative [13], [14]. The DESCs do not require communication links among DGs, however, a general communication infrastructure is needed in the microgrid for coordination of DGs during a black start process, central monitoring, or tertiary control layer's commands. Obviously, by reducing dependency on communication networks, real time data exchange and its impact over control objectives is reduced. The DESC approaches have been recently presented in the literature for frequency [14], and a nonlinear state-estimator based secondary voltage regulation [13] of microgrids.

Authors in [14] introduce a DESC for frequency restoration, which switches between two configurations by a time-dependent protocol. Event-detection and time-dependent protocols increase complexity of the solution, and decrease the system stability and reliability, while the performance is not optimal. Moreover, plug-and-play as an essential capability the proposed method has not taken into account. An overall architecture of the CESC, DISC, and DESC approaches are illustrated in Fig. 1.

This paper proposes an optimal DESC for frequency regulation of droop-controlled microgrids. The proposed approach is based on a linear quadratic regulation (LQR) problem and guarantees precise frequency restoration and active power sharing. This decentralized secondary controller is designed based on the dynamics of the low-pass filter measuring in the droop layer and does not rely on communication.

The reminder of the paper is organized as follows. In Section 2, a general description of multi-layer control of microgrids is presented. In Section 3, design procedure of the proposed controller is studied. Simulation results are presented and discussed in Section 4. Section 5 concludes the paper.

2. Multi-layer Control Framework of Microgrids

Overall configuration of a microgrid including *n* DG units augmented with primary and secondary layers is shown in Fig. 2. Each DG can be connected to AC common bus or to a common load to supply the power. A brief description of primary and secondary layers is presented in the following.

2.1. Primary Layer

The most important aims of this layer are stabilizing the frequency and voltage amplitude, providing accurate power sharing, and improving power quality. This layer follows up the set-points referenced by upper level controllers.

To mimic the synchronous generator's behavior a decentralized power sharing mechanism called droop control is often implemented in this level. This simple mechanism adjusts the amplitude of the voltage and the frequency reference using $\omega_i = \omega^* - m_i P_i$ and $v_i = v^* - n_i Q_i$, where ω^* is the nominal frequency, v^* is the nominal voltage amplitude of the system, P_i is the filtered active power of the i^{th} DG, Q_i is the filtered reactive power of the i^{th} DG, ω_i and v_i are the reference output frequency and voltage amplitude for inner control loops, i.e., voltage controller and current controller.

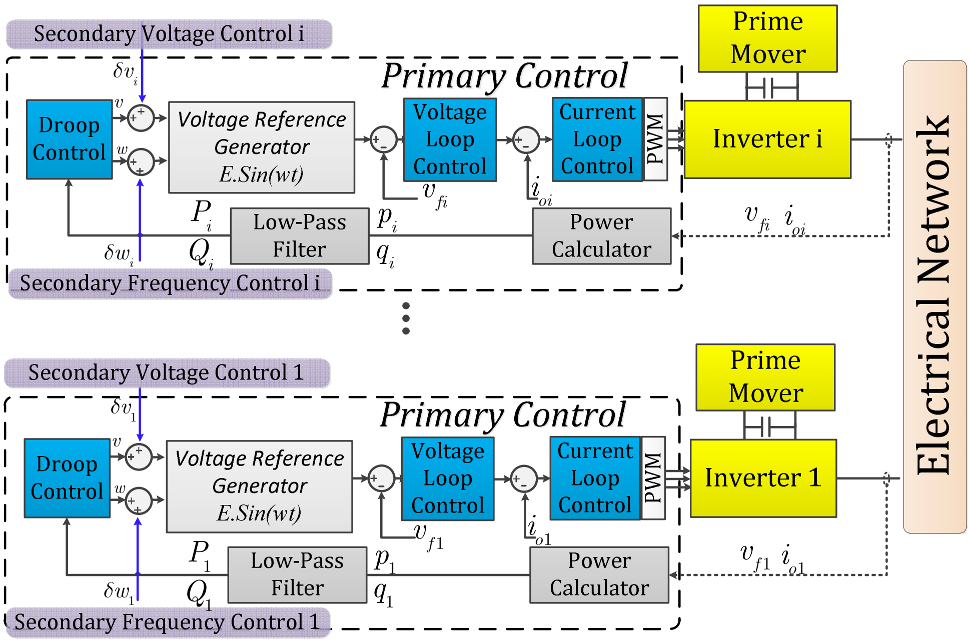

Fig. 2. General scheme of primary and secondary loops for an inverter-based islanded microgrid.

2.2. Secondary Layer

Compensation of the steady state errors of voltage and frequency, created by droop control, is the main goal of this control layer. To achieve this objective, a correction term is aggregated to the primary layers' references to shift up/down the droop slopes as:

$$\begin{aligned} w_i &= w^* - m_i P_i + \delta w_i \\ v_i &= v^* - n_i Q_i + \delta v_i \end{aligned} \quad (1)$$

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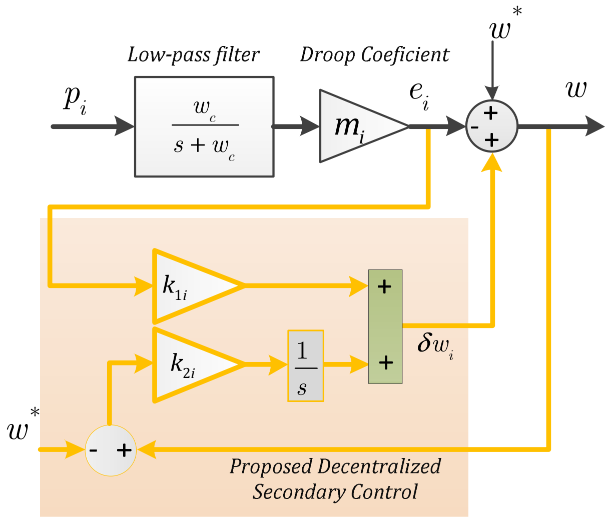

Fig. 3. Proposed DESC implementation.

where δw_i and δv_i are the control signals provided by secondary layer.

The DESC framework is implemented on each DG locally and uses individual local states or estimates neighbor variables. The produced control command is directly sent to the lower level.

3. Proposed Decentralized Secondary Controller

To avoid the drawbacks of communication networks, a decentralized secondary controller is proposed. In order to design the proposed controller, we only use the droop control dynamics and the active power low pass filter (LPF). Fig. 3 illustrates general scheme of the proposed decentralized controller. As this figure shows, all the measurements i.e., ω_i and P_i are obtained locally. Design procedure of the proposed DESC is presented in the following. Active power-frequency droop equation is

$$w_i = w^* - m_i \frac{w_c}{s + w_c} p_i \tag{2}$$

where w^* the reference frequency is p_i is the instantaneous active power, and w_c is the cut-off frequency. Assuming $e_i \triangleq w^* - w_i$, (2) can be written as

$$e_i = m_i \frac{w_c}{s + w_c} p_i. \tag{3}$$

Writing (2) in state space, one can obtain $\dot{e}_i(t) = -\omega_c e_i(t) + m_i \omega_c p_i$, where $e_i(t)$ is the state variable. By choosing $x_{1i}(t) = e_i(t)$ the state space equations can be extended as

$$\begin{cases} \dot{x}_{1i}(\mathrm{t}) = \dot{e}_i(\mathrm{t}) = x_{2i}(\mathrm{t}) \\ \dot{x}_{2i}(\mathrm{t}) = \ddot{e}_i(\mathrm{t}) = -w_c x_{2i}(\mathrm{t}) + m_i w_c p_i \end{cases}. \tag{4}$$

Therefore, state vector, input vector, and state matrix are given as $x_i(t) = \begin{bmatrix} e_i(t) \\ \dot{e}_i(t) \end{bmatrix}, A = \begin{bmatrix} 0 & 1 \\ 0 & -w_c \end{bmatrix}$, and

$$B_i = \begin{bmatrix} 0 \\ m_i . w_c \end{bmatrix}.$$

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To find an optimal solution for the control problem, the following Riccati equation by appropriate selection of R and Q should be solved.

$$A^T P + PA - PB_i R^{-1} B_i^T + Q = 0 \tag{5}$$

Solution of (5), produces the optimal state-feedback coefficients gains, i.e., k_{1i} and k_{2i} which are implemented in Fig. 3. The optimal LQR-based feedback control will be in the form $\delta w_i = -R^{-1} B_i^T P x_i(\mathrm{t})$, and applied to the system as shown in Fig. 3. Controllability and observability of the triple $(A, B_i, Q^{1/2})$ will guarantee a unique positive-definite solution of the Riccati equation (5).

Remark 1. The control law $\delta w_i = -R^{-1} B_i^T P x_i(\mathrm{t})$ can be represented as

$$\delta w_i = -k_{1i} x_{1i}(\mathrm{t}) - k_{2i} x_{2i}(\mathrm{t}) \tag{6}$$

where, $x_i(t) = \begin{bmatrix} e_i(t) \\ \dot{e}_i(t) \end{bmatrix}$. Thus it can be rewritten as

$$\delta w_i = -k_{1i} e_i(t) - k_{2i} \int_0^t e_i(\tau) d\tau \tag{7}$$

which shows a proportional-integral (PI) form. Therefore, one can note that the proposed LQR controller presents an optimal PI controller with tuned parameters by solving the Riccati equation (5).

4. Simulation results

A Microgrid test system, shown in Fig. 4, including four inverter based DGs and two common loads, is considered to assess the performance of the proposed DESC. The configuration of the three-phase AC microgrid and the connection of all sources is in a radial direction to supply two loads, Z_1 and Z_4. LCL filters are considered to reduce the switching harmonics. A series RL circuit is used to model each transmission line. Other control and electrical parameters of the system are tabulated in detail in Table I and II. The performance of the proposed DESC comparing the conventional droop control is demonstrated in Fig. 5 and Fig. 6.

Fig. 5 illustrates the primary control response where the system frequency deviates considerably from its rated value. Fig. 6 presents performance of the proposed DESC. Plug-and-play and load changes scenarios are examined for the comparison studies. In order to study the black start process the simulation results are presented from the beginning. DGs are synched at *t=2, 2.5, 3,* and *7 s*.

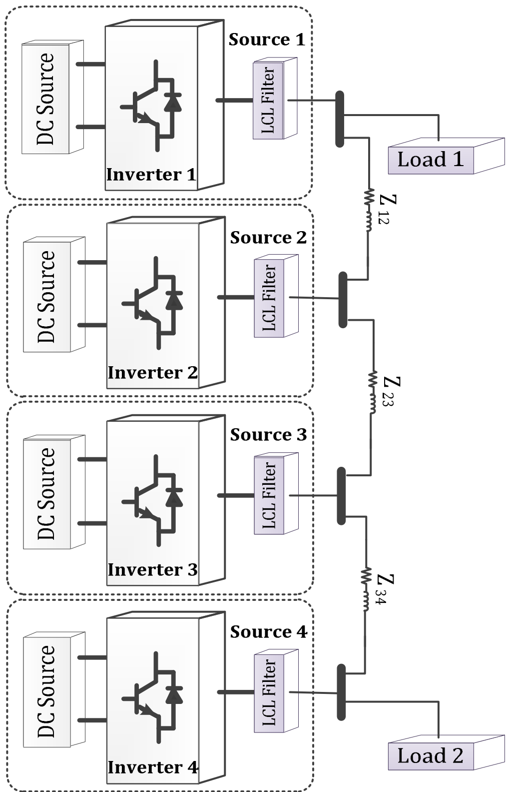

Fig. 4. Overall schematic of the microgrid system.

Table I: MG Electrical Parameters

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
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

Table II: Control Parameters

Parameter	Symbol	Sources1&2	Source 3&4
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 proportional term	k_1	0.25	0.25
Secondary integral term	k_2	1.25	1.25

A. Synchronization and Plug-and-Play Capability

Inverter 1 is intentionally disconnected from and then reconnected to the microgrid in the time interval $17\ s \leq t \leq 24\ s$. When the first source is disconnected at $t = 17\ s$, the excess active power demand is shared among the remaining inverters. The frequency drop in Fig. 5(b) is obvious while it is restored immediately after the disturbance by the secondary control (see Fig. 6(b)).

B. Load Changes

Frequent load changes are applied at $t=30\ s$ and $t=35\ s$ to evaluate the proposed CESC performance. Optimal feedback gains and their effects on active power sharing and frequency restoration are shown in Fig. 6(a) and 6(b). Successful frequency restoration with tight regulation to the nominal value as well as accurate power sharing is demonstrated.

5. Conclusion

This paper proposes a communication-less secondary controller for frequency regulation of islanded microgrids. An LQR solution is presented where only dynamics of the active power's low-pass filter is considered in the design procedure. This solution guarantees stability and optimal performance. Straight-forward design, optimal solution, easy implementing and fully decentralized structure are major features of the introduced controller. Unlike the existing methods, this solution does not need switch control scheme, time-dependent or event-driven protocol. Simulation results have been performed and reported to validate the effectiveness of the proposed approach.

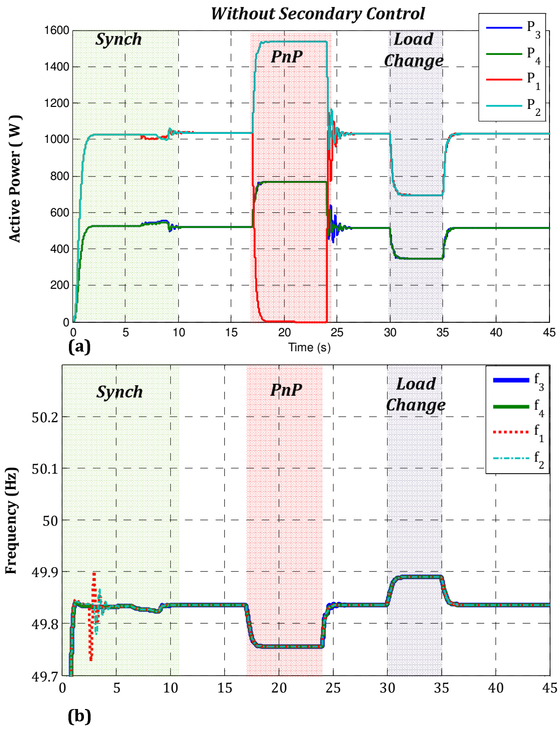

Fig. 5. Microgrid test system response without the proposed DESC: (a) generated active powers, and (b) DGs frequencies.

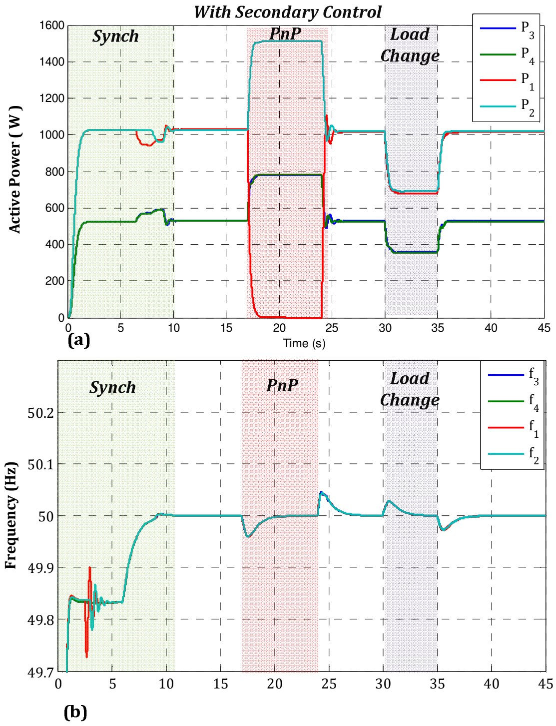

Fig. 6. Microgrid test system response when the proposed DESC is operated: (a) generated active power: (b) DGs frequencies.

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