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Research Paper

A Novel Hybrid Droop-Isochronous Control Strategy for Microgrid Management

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Abstract: The droop control strategy is the most common approach for microgrids control but its application is limited due to frequency deviation following a load change. Complementary control strategy has then been proposed to solve the problem using a communication network. However, under this strategy, regular loads profile produces a continuous change of output power of all distributed generators (DGs) and their generation changes seem to be permanent. This also causes continuous data exchange between DGs through communication links. This paper shows the possibility of adapting the droop/isochronous control methodology used by synchronous generators in conventional power systems to provide frequency control and power balance to inverter-based distributed generation power systems. To this end, this paper presents a centralized complementary control framework for the management of power-sharing and sustaining frequency in its nominal range in microgrids using a hybrid droop-isochronous control system. The proposed method is event-triggered based and communication between DGs is only needed when the output power of the isochronous generator exceeds its power limits. The method provides an efficient and reliable control system and has a simple concept, easy, and cost-effective implementation. Simulations in MATLAB/SimPower are performed on a typical microgrid under various conditions to evaluate the performance of the proposed controller.

Keywords: Microgrid, Central Controller, Isochronous and Droop Schemes, Power-Sharing.

1 Introduction

ELECTRICITY industry is one of the essential infrastructures of each country. So far, large centralized plants and extremely complex interconnected transmission networks have been utilized in electricity infrastructures of most countries [1]. However, the traditional type networks are currently being modified as smart microgrids. Microgrids are small electric networks including distributed generations (DGs) like micro-turbines, photovoltaic cells, wind power plants and, etc. [2], controllable loads, and strong control and power management system [3-5]. Microgrids are mainly grid-connected but they should operate in islanded mode, if necessary [6-10]. They face more challenges in the islanded mode in the absence of the main grid [11, 12]. Indeed, in the grid-connected mode, the main grid controls the microgrid frequency while in islanded mode, all DGs are responsible for sustaining frequency in the permissible range [13-15].

One of the major challenges of smart grids is the design of a proper control system. The control system strategy should preserve microgrid global stability, restore the grid frequency to its nominal value, improve the overall efficiency, and reliability and maximize utilization of existing resources [11-20]. Several control strategies have been introduced in literature so far. The most common has usually a hierarchical structure including primary and secondary control levels which operate in various time scales [16, 17]. The primary

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control includes local voltage and current loops and power droop control. This layer should regulate the voltage and current of DGs while sharing active and reactive powers among them [21-26]. The Secondary control restores the steady-state frequency and voltage deviations caused by the primary control [7-10]. Various secondary control methods have been presented so far among them the distributed consensus approach is more effective and popular [27]. In the distributed approach, each DG only communicates with its neighboring DGs and it thus needs the sparse communication network [28, 29].

In the droop control method, the microgrid frequency deviates from their rated value following a load change [11, 30, 31]. Also, for every load change, all DGs must change their output generations [32]. Due to the frequent change of loads in a microgrid, the generation changes seem to be permanent. To solve this problem, some papers have reported various non-linear droop schemes [33, 34]. Complexity is the major drawback of these methods. Alternatively, some researchers have proposed an isochronous-droop control method inspired by the transmission networks' control system. In this control strategy, one DG (usually the biggest one) works in isochronous mode and maintains the frequency of microgrids while the others operate in droop mode and generate constant power. Slight load changes are consequently compensated by the isochronous (slack) DG. In [1, 27], control of microgrids was performed using an isochronous-droop strategy without requiring communication infrastructures. In both papers, once output power of the isochronous DG being equal or above (below) it's maximum (minimum) generated power limit, the proposed control scheme would not be able to maintain the frequency of the microgrid in a permissible range.

This paper presents a novel droop-isochronous control strategy with a centralized complementary controller to stabilize the frequency of microgrids and to manage the DGs generations in different load conditions. In the proposed method, one DG operates in isochronous mode while the others work in droop mode and generate constant power. Ordinary network load changes are supplied by the isochronous DG. The complementary controller (CC) gets started only while the output power of the isochronous DG exceeds its power limits. The CC shares the surplus power appropriately among other generators such that the microgrid frequency maintains at an acceptable level. The followings are the main novelties of the proposed control strategy:

– The proposed method implementation is simple and provides flexibility for future development;
– Usual network load changes are only provided by one generator (the isochronous one);
– Communication between DGs is only needed when the output power of the isochronous generator exceeds its power limits;
– Power-sharing between DGs is appropriate and frequency regulation is adequate;
– Generation sources have sufficient reserves to handle sudden load changes.

The remainder of this paper is structured as follows: In Section 2, the proposed hybrid droop-isochronous control strategy is introduced. The primary and complementary controllers' algorithms are presented in Sections 3 and 4, respectively. In Section 5, simulation results are discussed. Finally, conclusions are summarized in Sections 6.

2 The Proposed Hybrid Droop-Isochronous Control Strategy

The main purpose of a microgrid is to provide load demand with limited frequency deviations along with proper management of the existing resources. To achieve this goal, engineers try to offer simple and economic control approaches. This paper presents a simple and novel frequency control and Power management method for microgrids using a hybrid droop-isochronous approach along with a centralized complementary controller. In the proposed method, one of the existing DGs is considered as the isochronous (slack) DG and maintains the frequency of microgrid substantially unchanged. The behavior of the slack DG is similar to the slack generator of the traditional transmission systems. The largest DG is usually selected as the isochronous DG so that the grid can allow larger load changes. The other DGs operate in droop control mode. In the droop control mode, the frequency of DG deviates from the rated value following a change in its output power [17]. Under normal operating conditions, the droop-mode DGs generate a pre-specified constant power and the slack DG provides surplus power (the difference between the total load and the total power generated by the droop-mode DGs) in addition to maintaining the grid frequency within the acceptable range. Following a load change, the isochronous DG automatically compensates the load change and stabilizes the microgrid frequency. When the output power of the slack DG exceeds its upper or lower permissible limits, the microgrid frequency will deviate (drop or rise) from its nominal value. Under these circumstances, the complementary controller is started and changes the reference power of the droop mode DGs such that the slack generator output power lies again in the permissible range and the microgrid frequency restores to its nominal value.

3 Primary Controller

Fig. 1 shows the schematic diagram of an islanded microgrid. In the figure, the electrical grid, communication network, and control layers are depicted. DC sources connect to the electrical grid via voltage source converters and LCL filters and feed electrical load through transmission lines. Primary control loops (current, voltage, and power) regulate the output power of DGs. Coordinated control of primary controls is achieved by a hybrid isochronous-droop technique.

In this paper, the d-q framework is employed to formulate the nonlinear dynamics of the system. The nonlinear dynamics of a DG can be written as (1):

$$\dot{X} = f(X) + g(x) \times U \quad (1)$$

where $X = [i_d, i_q, v_{od}, v_{oq}, i_{od}, i_{oq}]^T$ is the state vector and $U = [v_{sd}, v_{sq}]^T$ is the input vector. Details of primary control equations are given in [15].

Fig. 2 shows the block diagram of the active power controller. Droop characteristic of active power-frequency for the i-th DG is as follows:

$$\omega_i = \omega_{ni} - m_{pi} P_i \quad (2)$$

where m_i and P_i are the droop coefficient and measured output active power, respectively, ω_i is the measured frequency and ω_{ni} is the setpoint, all belong to the i-th DG. For the slack DG, $m_{pi} = 0$.

To obtain higher stability, the average value of the measured active power is obtained using (3) in which, ω_c is the low cut-off frequency of the low-pass filters and s is the Laplacian operator.

$$p_i = v_{odi} i_{odi} + v_{oqi} i_{oqi}$$

$$P_i = \frac{\omega_c}{s + \omega_c} p_i \quad (3)$$

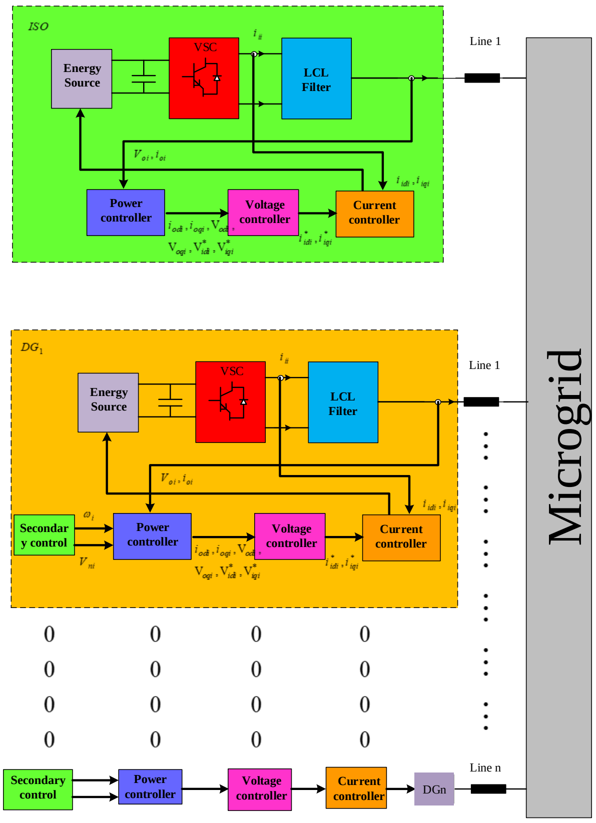

Fig. 1 Schematic diagram of a microgrid system.

4 Complementary Controller

In the proposed control strategy, regular load changes are automatically compensated only by slack DG, and output powers of other DGs are constant. When the output power of slack DG exceeds its power limits (due to large load changes), microgrid frequency deviates from its rated value. In this condition, the centralized complementary control gets started (by sensing the slack DG frequency) and increases (decreases) the output generation of other DGs such that the output power of slack DG returns to its permissible range. The output power and the frequency of each DG should send to the central controller via a communication network. Comparing the frequency of each inverter by reference value and considering its droop coefficient, the central controller decides if more or less active power should be generated by each DG. The algorithm has been shown in Table 1.

5 Simulation Results

To show the efficacy of the proposed controller, a typical microgrid with 6 inverter-based DGs, 5 loads, and several connection lines are considered. DG1 is selected as slack DG. The parameters of DGs, loads, connection lines, and control systems are given in Table 2. All simulations are performed in MATLAB/Sim-Power toolbox.

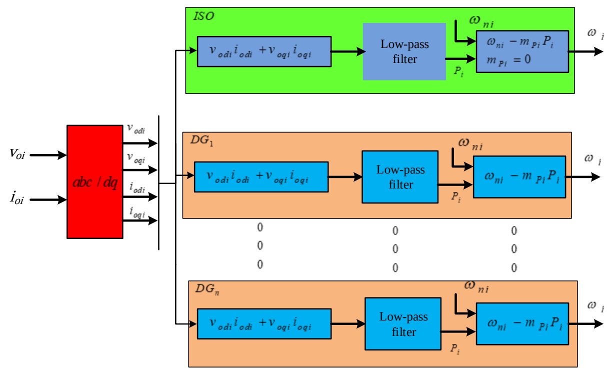

Fig. 2 Block diagram of active power controllers.

Table 1 The proposed control algorithm.

Main input:
ω_{ref}, $\omega_{i\ i=1,\dots,N}$, $P_{ref\ i=1,\dots,N}$, P_{DG1max}, P_{DG1min}

Main output:
$P_{i\ i=1,\dots,N}$

If $P_{DG1} < P_{DG1max}$ and $P_{DG1} > P_{DG1min}$
    $P_{i\ i=2,\dots,N}$, $P_{ref\ i=2,\dots,N}$, $P_{DG1} = P_{DG1}$
Else if $P_{DG1} > P_{DG1max}$
    $\Delta f_i = \omega_{ref} - \omega_i$, $i = 2,\dots,N$
    $\Delta f_i > 0$, $\Delta P_i = \Delta f_i / m_i$, $P_i = P_{ref} + \Delta p_i$, $P_{DG1} = P_{DG1max}$
Else if $P_{DG1} < P_{DG1min}$
    $\Delta f_i = \omega_{ref} - \omega_i$, $i = 2,\dots,N$
    $\Delta f_i < 0$, $\Delta P_i = \Delta f_i / m_i$, $P_i = P_{ref} - \Delta p_i$, $P_{DG1} = P_{DG1min}$
End

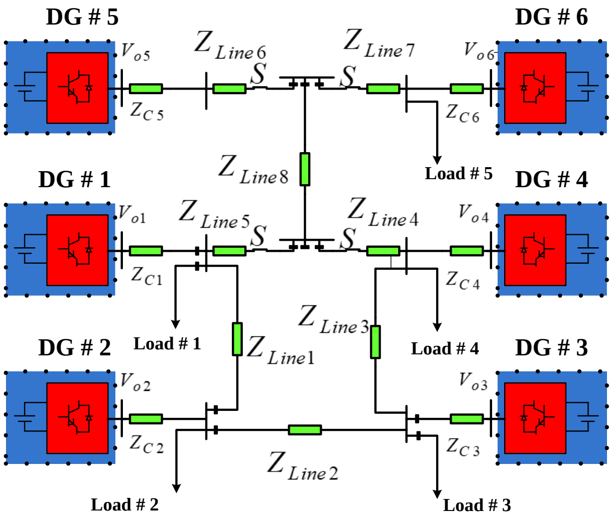

Fig. 3 Single line diagram of a typical MG.

Table 2 Parameters of the Simulated MG System.

	DG#1		DG#2-6	
DGs	m_{Pi}	0	m_{Pi}	0.708×10^{-4}
	n_{Qi}	0	n_{Qi}	5.26×10^{-3}
	Z_c	0.015+j0.65 Ω	Z_c	0.03+j0.65 Ω
	L_{f1}, L_{f2}	1.35, 0.27 mH	L_{f1}, L_{f2}	1.35, 0.27 mH
	R_{f1}, R_{f2}	0.1, 0.05 Ω	R_{f1}, R_{f2}	0.1, 0.05 Ω
	C_f	50 µF	C_f	50 µF
	K_{PC}	0.1	K_{PC}	0.05
	K_{IV}	410	K_{IV}	380
	K_{PC}	14	K_{PC}	11.5
	K_{IC}	12000	K_{IC}	18000
Lines	Z_{Line1}, Z_{Line4}, Z_{Line6}	0.12+j0.1 Ω	Z_{Line3}	0.12+j0.1 Ω
	Z_{Line2}, Z_{Line8}	0.175+j0.58 Ω	Z_{Line5}, Z_{Line7}	0.175+j0.58 Ω
RL Loads	Load#1, Load#2	P = 13 kW, Q = 7.5 kVAr	Load#3	P = 7 kW, Q = 7 kVAr
	Load#5	P = 14 kW, Q = 6 kVAr	Load#4	P = 6 kW, Q = 6 kVAr
P_{ref}	P_s = 70000 kW	$P_{ref\,3}$ = 20000 kW	$P_{ref\,5}$ = 20000 kW	
	$P_{ref\,2}$ = 20000 kW	$P_{ref\,4}$ = 20000 kW	$P_{ref\,6}$ = 20000 kW	

5.1 Study 1: Performance Evaluation Under load Changing

The simulation scenario is as follows:

1) t = 0 sec is the simulation starting time.
2) At t = 3 sec, one load (P = 10 kW and Q = 10 kVar) is added to bus #1.
3) At t = 5 sec, another load (P = 5 kW and Q = 5 kVar) is added to bus #2.
4) At t = 7 sec, another load (P = 15 kW and Q = 15 kVar) is added to bus #4.
5) At t = 9 sec. load #2 is disconnected from the MG.
6) At t = 11 sec. load #5 is disconnected from the MG.
7) At t = 13 sec. load #3 is disconnected from the MG.

Figs. 4 and 5 show the frequency and output power deduced by the proposed method, respectively. As can be seen in the figures, at the beginning of the simulation, the network is in normal operating condition, the droop-mode DGs generate the pre-specified active power, the slack DG provides the surplus power and the microgrid frequency is at its nominal value. At t = 3 sec, one load is added to bus #1. DG1 compensates the surplus power while frequency is kept at nominal value. Note that, the generated power of all droop-mode DGs have not changed. At t = 5 sec, when the second load is added to bus #2, as the output power of slack DG has not been reached to its limit, similar behavior is seen. However, after connecting the third load at t = 7 sec, the output power of DG1 exceeds the permissible range and its frequency drops. Under these conditions, the complementary controller gets started and changes the reference power of the droop-mode DGs such that the slack generator output power and its frequency lies again in the permissible ranges. The similar behavior can be seen in Figs. 4 and 5, whenever the microgrid loads are reduced sequentially, at time 9, 11, and 13 sec.

To validate the method, the results of the proposed controllers are compared to the results of the method presented in [35], which is one of the original activities accomplished in this field. Reference [35] proposes a distributed two-layer control structure for ac microgrids. By doing this, better capabilities of our proposed method are represented in comparison to the conventional two-layer distributed methods. Figs. 6 and 7 represent the results obtained by the method of [35]. As can be seen, the proposed method maintains a better performance than the method of [35]. Furthermore, as the slight load changes are compensated only by the slack DG, the communication burden is reduced and more efficient and reliable operation can be achieved.

5.2 Study 2: Performance Evaluation Under Slack DG Outage

In this case, the performance of the proposed controller under slack DG outage is investigated. For this purpose, at *t* = 1 sec, DG1 is plugged out. The results are shown in Figs. 8 and 9. As can be seen, the proposed controller maintains the microgrid frequency during the event. Actually, after slack DG outage at *t* = 1 sec, the control system forces the other units to generate extra power to compensate active power shortage. However, as a result of slack DG outage, the frequency drops to a value that specifies by droop mode DGs. However, Fig. 9 depicts that correct power-sharing is still maintained.

6 Conclusion

A novel centralized hybrid droop-isochronous control strategy was proposed for inverter-based microgrids. In normal conditions, the slack DG compensates the surplus power and controls the network frequency. When the output power of the slack DG exceeds its power limits, the central complementary controller gets started and changes the reference power of the droop mode DGs. In this way, communication between agents only needed when the complementary controller gets started. The proposed method presents proper power-

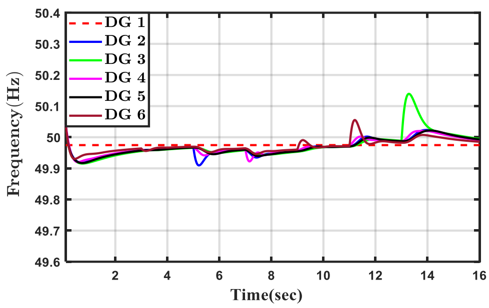

Fig. 4 DGs output frequency.

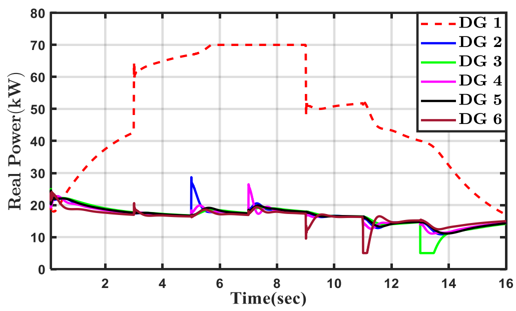

Fig. 5 DGs output real power.

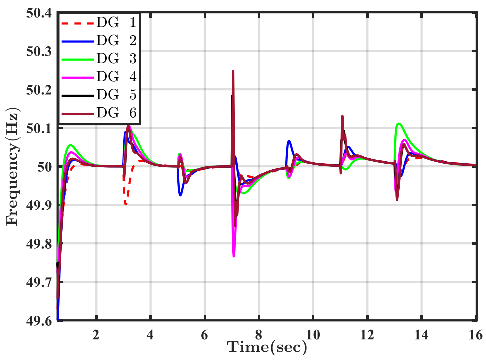

Fig. 6 DGs output frequency obtained by the method of [35].

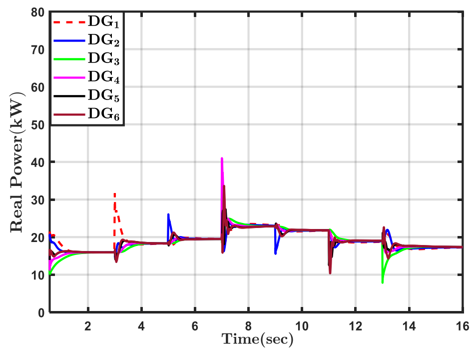

Fig. 7 DGs output real power obtained by the method of [35].

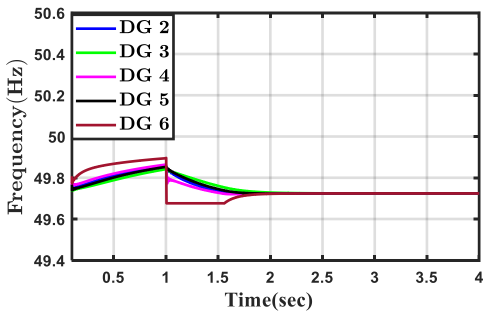

Fig. 8 DGs output frequency obtained by the method of [35].

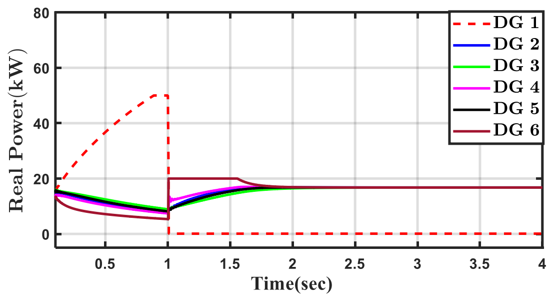

Fig. 9 DGs output real power obtained by the method of [35].

sharing between DGs and regulates the frequency of microgrid under different operating conditions. To validate the method, the results of the proposed controllers are compared to the results of one of the original activities accomplished in this field. Also, simulations show that under the slack DG outage, the microgrid can continue its servicing but the frequency drops to a value that specifies by droop mode DGs. This feature rises the microgrid resiliency.

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