Distributed Generation Control Method for Active Power Sharing and Self-Frequency Recovery in an Islanded Microgrid

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***Abstract*—This paper describes a control method for distributed generation (DG) units to implement active power sharing and frequency recovery simultaneously in an islanded microgrid. Conventional active power–frequency (*P–f*) droop control is used for the DG controller, and the frequency deviation is recovered by the DG itself via self-frequency recovery control, without requiring secondary frequency control. Because the electrical distance (impedance) from each DG unit to a point where the load demand changes differs among DG units, the instantaneous frequency deviations may differ between DG units. These differences are fed into the integrators of the self-frequency recovery control and may result in errors in active power sharing. To solve this problem and share active power more accurately, a compensation control method is developed for active power sharing, which considers the droop coefficients of each of the DG units. Simulation results show that the proposed control method is effective.**

***Index Terms*—Active power sharing, distributed generation (DG), islanded microgrid, self-frequency recovery.**

I. Introduction

DUE to growth in the global population, as well as the increase in the use of devices that consume electricity, demand for electrical power has grown to unprecedented levels [1]. However, the electricity supply has become saturated due to environmental, social, and geographical factors. To address these problems, attempts have been made to meet the electrical energy demand locally via microgrids and distributed generations (DGs).

The microgrid concept was first introduced in [2], [3]. Microgrids consist of a low- or medium-voltage distribution network containing loads and distributed energy resources. Microgrids contain a central controller (CC), local controllers (LCs) [4], a static switch, loads, and various types of energy sources. Microgrids can operate in two different modes: grid-connected mode and islanded mode, depending on the connection state with the main grid. In grid-connected mode, a microgrid is connected to the main grid, which usually has large system inertia; hence, the microgrid frequency is almost identical to the nominal value [5]. Thus, DG units in a microgrid typically inject the desired output power, and the electrical power mismatch between supply and demand is balanced by the main grid. However, in islanded mode, the microgrid must supply its own demand and maintain its frequency solely using DG units.

There have been several studies aimed at developing active power and frequency control strategies for islanded microgrids. In [6], active power–frequency (*P–f*) droop control (the most commonly used method) was developed for active power sharing by emulating conventional power systems composed of synchronous generators. In [7], in contrast to conventional droop control, a tunable droop controller with two degrees of freedom was proposed, considering an adaptive transient droop function. In [8], single-master and multiple-master operating modes were introduced for islanded microgrids, considering secondary load–frequency control for frequency recovery. In [9]–[11], a virtual impedance control scheme was used for decoupling the active and reactive power to enhance the control stability and power sharing ability. A method for determining the droop coefficient based on the generation cost of each DG unit was proposed in [12]. In [13], a constant frequency control method was used rather than frequency droop, and the state of charge of a battery energy storage system was used to monitor changes in the system load.

Most reports have considered frequency deviation in sharing active power [5]–[12]; however, the frequency must be restored to its nominal value according to the requirements of the grid code, and secondary control is required to achieve this [8]. Problems may arise if the frequency deviation is too great. Under these circumstances, this will impose too much burden on the frequency control units. Hence, it is desirable that the active power should be "re-shared" among DG units after the secondary control action, so that proper load sharing may occur. It has been suggested that constant frequency control could be used [13], making frequency restoration unnecessary; however, active power sharing was not considered.

In this paper, we propose a DG control method that simultaneously implements accurate active power sharing and self-frequency recovery. Using this control method, DG units share the changes in load with a predetermined ratio and are able to restore their output frequency to the nominal value autonomously (hence the term "self-frequency recovery") immediately following a change in load. However, the self-frequency recovery

Manuscript received October 1, 2015; revised January 17, 2016; accepted March 5, 2016. Date of publication April 6, 2016; date of current version December 20, 2016. This work was supported by the Power Generation & Electricity Delivery Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20143010011830). Paper no. TPWRS-01385-2015.

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Digital Object Identifier 10.1109/TPWRS.2016.2543231

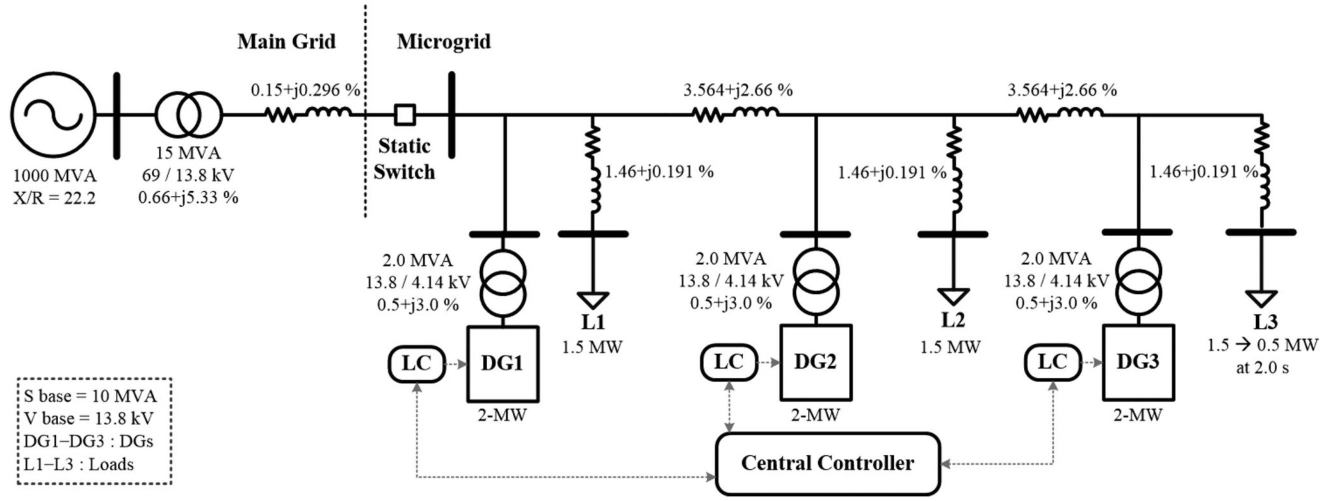

Fig. 1. Studied microgrid configuration.

action may lead to (small) errors in power sharing due to variations in the impedance among DG units. Therefore, following frequency recovery, the active power sharing among DG units is readjusted to the predetermined ratio using a compensation control scheme. The control method was modeled and tested using MATLAB/Simulink, and the simulation results demonstrate the effectiveness of the approach.

The remainder of the paper is organized as follows. Section II describes the microgrid system configuration. Section III explains the proposed DG control method for active power sharing and self-frequency recovery. Section IV details simulation results and provides a discussion. Section V provides a conclusion and identifies areas for future work.

II. Microgrid Configuration

Fig. 1 shows the configuration of the microgrid investigated here, which is based on that described in [5], [14], and [15], with some slight modifications. Here, the microgrid consists of a static switch, a CC, LCs, loads, and DGs. The static switch is located at the point of common coupling. By opening the static switch, the microgrid becomes isolated from the main grid. The CC executes overall control of the microgrid, including protection, power sharing, mode transition, and economic scheduling via a communications system. The main objectives of the CC are typically to maintain the system frequency and voltage at the specified level, as well as to operate the microgrid economically; here, however, the CC was used only for compensation control (see Section III), assuming that the dispatched output power for each DG unit has already been determined by the CC. The proposed compensation control method is used for a short duration to reduce the dependence of the DG control system on the communications infrastructure; this is important due to the potential for failure of the communications network, which decreases system reliability. The main function of the LC is to control the power and/or frequency, as well as the voltage of DGs (or controllable loads) in response to a disturbance or change in load. In this study, because there are no controllable loads, the role of the LC is to control the DG units.

In terms of active power control, DGs can be categorized as either dispatchable or non-dispatchable [4], [5], [16]. Dispatchable DGs, such as microturbines and fuel cells, are capable of producing controlled active power on demand, and are, thus, assigned the task of regulating the voltage and frequency during islanded operation [5], [16], [17]. In contrast, non-dispatchable DGs, such as photovoltaic cells and wind turbines, usually cannot be dispatched, because their output power depends mainly on the weather, rather than the load [5]. Here, three 2-MW DG units with voltage ratings of 4.14 kV were included in the microgrid, all of which were dispatchable. All the inverters included in the simulation were modeled as switch (IGBT/diode) model to reflect dynamic characteristics of switching operation. *LC* filters were also included at the terminal of each inverter to filter harmonics out. The inductance and the capacitance of each *LC* filter are 5 mH and 50 μF, respectively. The nominal voltage of the microgrid was 13.8 kV, and the frequency was 60 Hz.

III. Proposed DG Control Method

The proposed control scheme for the *i*th DG unit is shown in Fig. 2, where the subscript *i* refers to the index of the DG; $P_{i,\mathrm{dis}}$ and $Q_{i,\mathrm{dis}}$ are the dispatched values of the active and the reactive power, respectively, from the CC; P_i and Q_i are the active and the reactive output powers of the DG, respectively; f_{nom} and V_{nom} are the nominal frequency and the voltage, respectively; $f_{i,\mathrm{ref}}$ and $V_{i,\mathrm{ref}}$ are the reference frequency and the voltage, respectively; f_i is the output frequency of the DG; $v_{abc,\mathrm{ref}}$ is the three-phase voltage reference input to the voltage source; *a* and *b* are the nodes of the switch; m_i and n_i are the droop coefficients of frequency droop and voltage droop, respectively; and k_f and k_c are the integral gains for the self-frequency recovery control and the compensation control, respectively. The coefficient c_i and the terms $\Delta P_{\mathrm{dis,tot}}$ and $\Delta P_{i,\mathrm{dis}}$ are defined in Section III-C, which describes compensation control.

Note that the proposed control scheme shown in Fig. 2 controls the active power by adjusting the output frequency. This means that the proposed method cannot be applied to low-voltage networks, because with low-voltage networks the

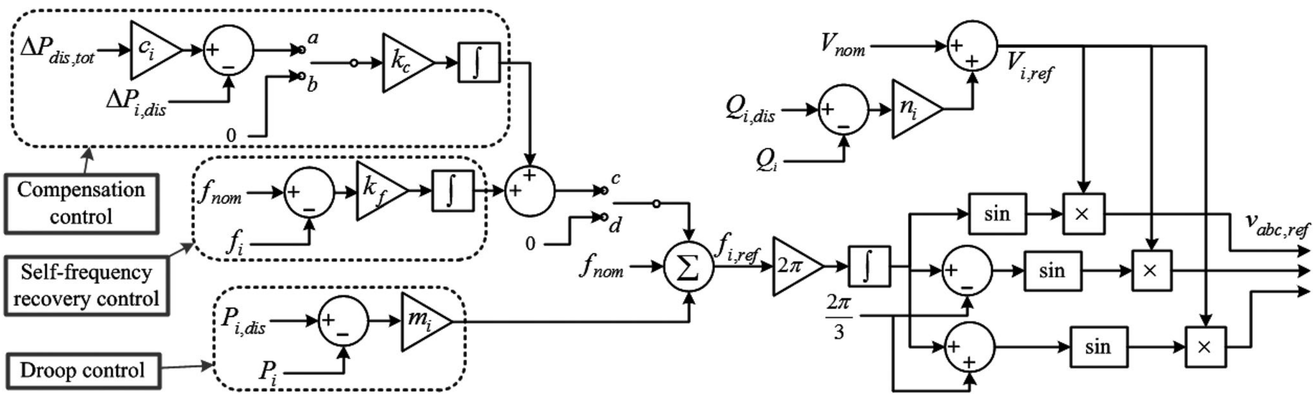

Fig. 2. Proposed control scheme for distributed generation DG units.

resistance is much larger than the reactance, and hence the voltage angle is more strongly related to the reactive power than the active power [18]. For this reason, the proposed control method is intended for medium-voltage microgrids rather than low-voltage microgrids.

This paper focuses on active power sharing and frequency control. The control method for the reactive power sharing uses conventional reactive power–voltage magnitude (*Q*–*V*) droop control. For this reason, the reference of the voltage magnitude $V_{i,\mathrm{ref}}$ is expressed as follows:

$$V_{i,\mathrm{ref}} = V_{\mathrm{nom}} + n_i \left(Q_{i,\mathrm{dis}} - Q_i\right). \tag{1}$$

The reference voltage magnitude is determined from the deviation of the output reactive power from its dispatched value (which is usually zero with a unity power factor); therefore, the reference voltage magnitude is proportional to the *Q*–*V* droop coefficient n_i. The details of the reactive power-sharing scheme are not discussed here.

The control scheme used for determining the frequency reference $f_{i,\mathrm{ref}}$ can be divided into three components: conventional droop control, self-frequency recovery control, and compensation control. Each component is discussed separately in the following three sections.

A. Droop Control

For basic control of active power sharing, the conventional *P*–*f* droop control was applied. The output frequency f_i can be expressed as

$$f_i = f_{\mathrm{nom}} + m_i \left(P_{i,\mathrm{dis}} - P_i\right). \tag{2}$$

The reference output frequency was determined from the deviation of the active power from the dispatched value (determined by the CC), which is proportional to the *P*–*f* droop coefficient m_i. As shown in Fig. 2, without self-frequency recovery control or compensation control, the frequency deviation from the nominal value can be determined using droop control only. With droop control, the exact load sharing among DG units is proportional to the droop coefficients. This process can be implemented by exchanging the same output frequency of each DG unit in the steady state; however, because the frequency will inevitably deviate from the nominal value and must be restored according to the grid code requirements, an additional control scheme for the frequency restoration is required.

Conventionally, secondary load–frequency control is used [8]; however, with this control method, other DG units must be controlled separately during frequency restoration. Therefore, there is a drawback in that the active power sharing must be recalculated following frequency control. Moreover, with large frequency deviations, secondary frequency control units will change significantly in their output power. Imposing too much output burden to a specific unit (secondary frequency control unit) may make it reach its output limit. Typically, generation cost of DG unit exponentially increases proportional to the output power [19]. Hence the load–frequency control method may be economically inefficient. Self-frequency recovery control was developed to eliminate separate frequency control, which may impose too great a burden on the frequency control unit, as well as to share frequency restoration in proportion to a predetermined ratio (here, we used the droop coefficient).

B. Self-Frequency Recovery Control

The principal objective of self-frequency recovery control is to distribute the measures required to achieve frequency recovery among the DG units that participate in active power sharing using *P*–*f* droop control according to a predetermined ratio. The frequency restoration of the *i*th DG unit due to self-frequency recovery control can be expressed as

$$\Delta f_{i,\mathrm{res}} = k_f \int \left(f_{\mathrm{nom}} - f_i\right) dt \tag{3}$$

where k_f is all the same value for every DG unit, which means that the burden of frequency restoration is shared equally among the DGs.

In the transient state (and in contrast to the steady state), the instantaneous output frequencies may differ among DG units due to differences in the impedance of each DG unit, as well as the location of the change in the load. The difference in transient output frequency between DG units due to differences in impedance can be explained using a simple power system network model, as shown in Fig. 3. In this model, *P* is the active power from the sending end to the receiving end; *R* and *X* are the resistance and reactance of the network impedance, respectively; V_s and V_r are the voltage magnitudes of the sending end and

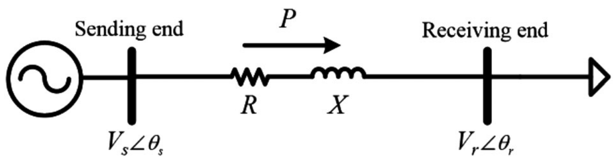

Fig. 3. Single-line diagram of a simplified islanded microgrid.

the receiving end, respectively; and θ_s and θ_r are the voltage angle of the sending end and the receiving end, respectively. The active power can be expressed as follows [20]:

$$P = \frac{RV_r V_s \cos(\theta_s - \theta_r) + V_r V_s \sin(\theta_s - \theta_r) - RV_r^2}{R^2 + X^2}. \quad (4)$$

In medium- or high-voltage networks, the resistance is assumed to be much smaller than the reactance (*i.e.*, $R \ll X$), and the voltage angle difference is assumed to be small (i.e., $\theta_s - \theta_r = \delta \approx 0$, such that $\sin\delta \approx \delta$ and $\cos\delta \approx 1$. The active power flow across the impedance can therefore be simplified to

$$P \approx \frac{V_r V_s (\theta_s - \theta_r)}{X}. \quad (5)$$

Because the voltage magnitudes at the DG units differ slightly in medium-voltage networks, from (5), it follows that the voltage angle difference across an impedance is proportional to the impedance for active power flow. Hence, for a change in load, the voltage angle deviations will differ among DG units if the impedances across the load and the DG units vary. The output frequency of the *i*th DG unit can be expressed as a function of the output voltage angle θ_i as follows:

$$\int 2\pi f_i dt = \theta_i. \quad (6)$$

Consequently, from (3) and (6), the difference in voltage angle deviations among DG units leads to different frequency restorations Δf_{res}. These differences lead to unequal sharing of the output active power among the DG units, and as a result, the ratio of active power sharing among DG units no longer varies in proportion to the *P–f* droop coefficients of the DG units.

Note that the influence of voltage magnitude on the active power is not considered since medium-voltage network is studied in this paper. The influence of voltage magnitude on the active power is significant at low-voltage networks [21].

C. Compensation Control

To offset the errors in active power sharing caused by self-frequency recovery control, a compensation control scheme was developed, as shown in Fig. 2. The main purpose of the compensation control is not to reduce transient frequency difference but to reduce the active power sharing error. Even if the transient frequency difference is small, the active power difference may be large since it depends on time of integration of the frequency difference and magnitude of line impedance (see (5)). The output active power deviation of the *i*th DG is given by

$$\Delta P_{i,\text{dis}} = P_i - P_{i,\text{dis}}. \quad (7)$$

The aggregate of all DG units can be found by summing the contributions from each unit; i.e.,

$$\Delta P_{\text{dis,tot}} = \sum_{i=1}^{N} \Delta P_{i,\text{dis}}. \quad (8)$$

where N is the number of DG units participating in active power sharing. Because the objective of compensation control is to share the active power according to the ratio of the droop coefficients (i.e., $m_1, \ldots, m_N$), $\Delta P_{\text{dis,tot}}$ should be distributed among the DG units considering the droop coefficients. Hence, the parameter c_i (see Fig. 2) was determined as follows:

$$c_i = \frac{1/m_i}{\sum_{j=1}^{N} (1/m_j)}. \quad (9)$$

By multiplying c_i by $\Delta P_{\text{dis,tot}}$, we obtain the contribution of the *i*th DG unit to frequency recovery. Consequently, the compensation recovery control can be expressed as

$$\Delta f_{i,\text{com}} = k_c \int \left(c_i \Delta P_{\text{dis,tot}} - \Delta P_{i,\text{dis}_i} \right) dt. \quad (10)$$

To communicate between the CC and DG units, and to assign $\Delta P_{\text{dis,tot}}$, a communications system is required, which may decrease system reliability. For the DG units to reduce their dependence on the communications system, a switch (see Fig. 2) was incorporated into the compensation control. Ordinarily, the switch is connected to node *b*; in this state, the communications system is unnecessary and all DG units are controlled only using droop control and self-frequency control. If the microgrid operator decides to offset the active power sharing error, for all DG units, the switches are changed to node *a* by the CC. Using this switch, the communications system is utilized only when the microgrid operator requires it or it can be automatically operated by periodical signal. Either way, the communication system failure does not significantly harm the system stability since it only concerns the active power sharing error. Moreover, compensation can be achieved in a short time (less than 1 s, as shown by the simulation results in Section IV). However, in order to enhance the system reliability, a switch composed of node *c* and *d* is incorporated into the controller as shown in Fig. 2. In the normal operation, the switch is connected to node *c*. If the communication failure happens, the switch is connected to node *d* and the controller operates as *P–f* droop controller.

By combining these three control schemes, the reference output frequency of the *i*th DG unit can be expressed as

$$f_{i,\text{ref}} = f_{\text{nom}} + m_i(P_{i,\text{dis}} - P_i) + k_f \int (f_{\text{nom}} - f_i)dt + k_c \int (c_i \Delta P_{\text{dis,tot}} - \Delta P_{i,\text{dis}})dt. \quad (11)$$

IV. Case Study

To verify the effectiveness of the proposed control method for DG units, case studies were implemented. Table I lists the simulation parameters for all scenarios. The control performance of the microgrid was investigated for mode transition (i.e., when the static switch was opened at 1 s) and for the load change (i.e.,

TABLE I
SIMULATION ENVIRONMENT SETTING

Microgrid components		Setting
Static switch		Closed → Opened at 1 s
DG units	$P_{1,\mathrm{dis}}$	1.3 MW
	$P_{2,\mathrm{dis}}$	1.3 MW
	$P_{3,\mathrm{dis}}$	1.3 MW
	$Q_{1,\mathrm{dis}}$	0 MVAR
	$Q_{2,\mathrm{dis}}$	0 MVAR
	$Q_{3,\mathrm{dis}}$	0 MVAR
Loads	L1	1.5 MW
	L2	1.5 MW
	L3	1.5 MW → 0.5 MW at 2 s
Integral gains	k_f	20
	k_c	10

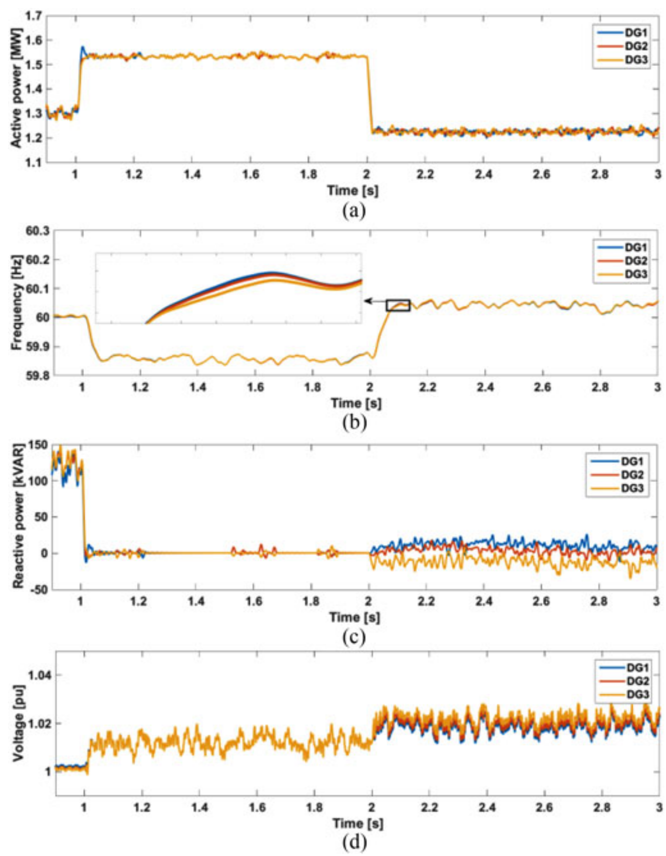

Fig. 4. Simulation results for Case I by adopting the conventional *P–f* droop control method. (a) Output active power (*P*). (b) Output frequency (*f*). (c) Output reactive power (*Q*). (d) Output voltage (*V*).

when L3 was decreased at 2 s). Two scenarios were investigated for different ratios of active power sharing, and for each the proposed control method was compared with conventional *P–f* droop control.

A. Case I

The change in the active power load should be shared equally among the DG units; therefore, the *P–f* and *Q–V* droop coefficients were equal for each DG unit (i.e., $m_1 = m_2 = m_3 = 0.02$, $n_1 = n_2 = n_3 = 0.01$).

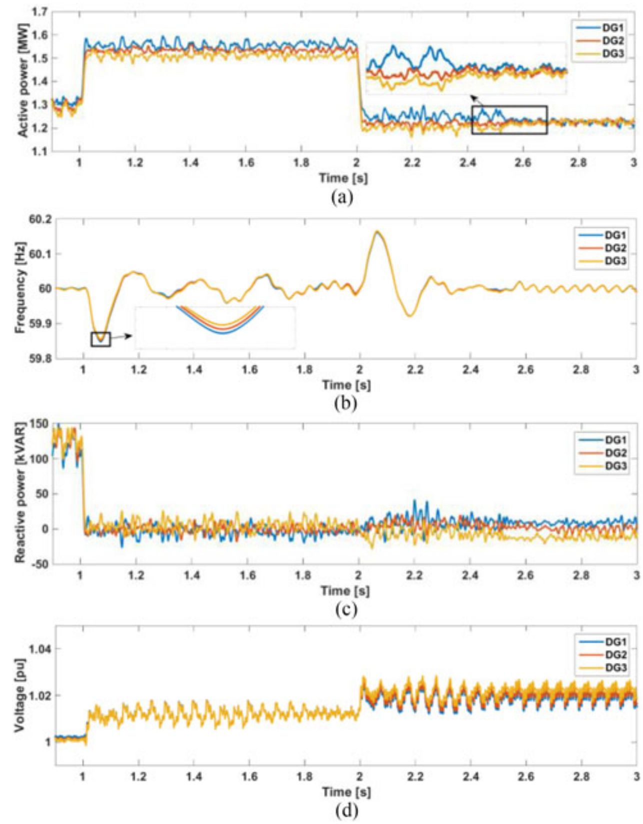

Fig. 5. Simulation results for Case I by adopting the proposed control method. (a) Output active power. (b) Output frequency. (c) Output reactive power. (d) Output voltage.

Fig. 2 shows the DG controller for the conventional control method, which enables both self-frequency recovery control and compensation control. Fig. 4(a) shows the simulated active power of each DG unit conventional *P–f* droop control. Prior to islanded operation of the microgrid, each DG unit injected 1.3 MW (i.e., the dispatched value from the CC) into the grid. Because the total load was 4.5 MW (L1 + L2 + L3 = 4.5 MW), 0.6 MW of active power was injected from the main grid. At 1 s, the static switch was opened and the microgrid became islanded; hence, 0.6 MW of additional active power was required from the DG units. As shown in Fig. 4(a), this additional 0.6 MW of active power was equally shared among the DG units, as the droop coefficients were equal. At 2 s, the load L3 decreased from 1.5 to 0.5 MW. At 1 s, the active power sharing differed slightly among the DGs; however, in the steady state, each DG unit injected the same amount of active power. This process can be implemented according to (2), such that the output frequency of each DG unit was equal in the steady state, as shown in Fig. 4(b). However, as described in (5) and (6), the output frequency of each DG unit will differ [see the magnified view in Fig. 4(b)]. With the conventional method, frequency deviations are inevitable, as shown in Fig. 4(b).

Fig. 4(c) and (d) show the reactive power and the voltage, respectively. Since there are no reactive power load, the output

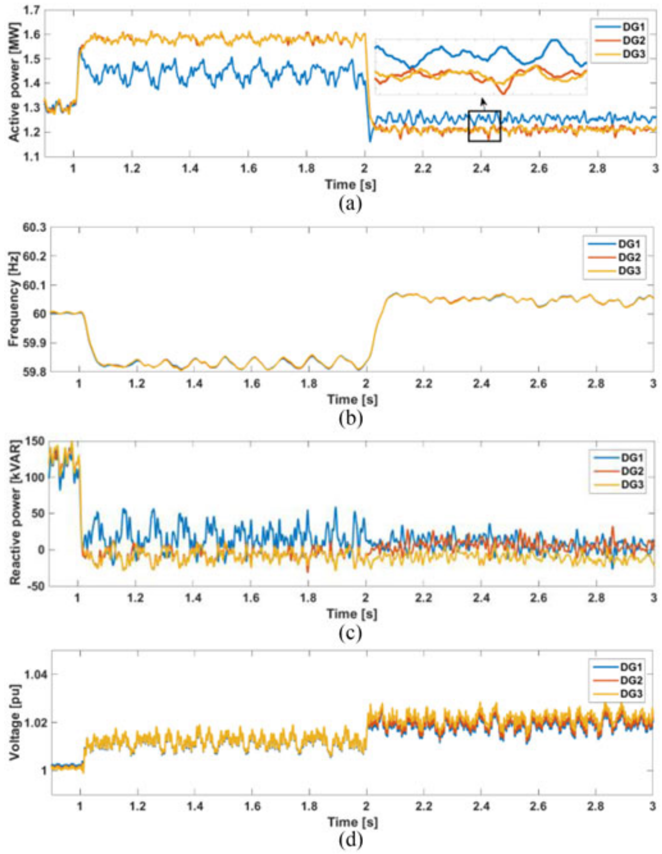

Fig. 6. Simulation results for Case II by adopting the conventional *P–f* droop control method. (a) Output active power. (b) Output frequency. (c) Output reactive power. (d) Output voltage.

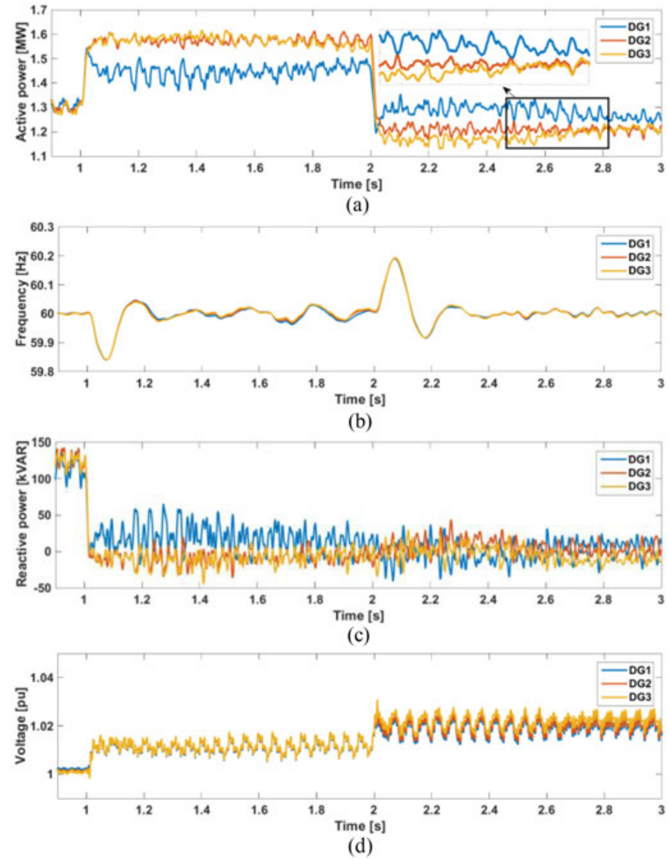

Fig. 7. Simulation results for Case II by adopting the proposed control method. (a) Output active power. (b) Output frequency. (c) Output reactive power. (d) Output voltage.

reactive powers are exactly zero at 1–2 s in Fig. 4(c). This is because for all DG units, the active and reactive power loads are same with same electrical distances (see Fig. 1). However, at 1 s, since the load L3 is changed and the voltage deviation is happened, the output reactive powers become slightly different from each other. The voltage swell after at 1 s in Fig. 4(d) is due to the filter capacitance of each DG unit.

The frequency should recover to the nominal value, according to the grid code requirements. To achieve this, another DG unit must be controlled separately during frequency restoration. As discussed in the previous section; too great a burden may be imposed on the frequency control units if the load change is large.

To eliminate the requirement for secondary frequency control, as well as to share the burden of frequency restoration, self-frequency recovery control was implemented with compensation control. Fig. 5(a) shows the simulated active power. Following the transition from grid-connected mode to islanded mode at 1 s, the additional required active power was shared among the DG units. In contrast to the conventional method, the DG units were unable to share the active power equally [see at 1–2.5 s of Fig. 5(a)], despite equal droop coefficients, because the self-frequency recovery control term was added to the controller. Self-frequency recovery control resulted in active power sharing error, as described in Section III. Following the change in load at 2 s, the error in the active power sharing increased. To offset this, compensation control was activated at 2.5 s. From 2.5–2.7 s, the active power sharing error was eliminated; moreover, the frequency was restored to the nominal value almost immediately following the load change, as shown in Fig. 5(b). As discussed in the previous section, the output frequencies of the DG units differed in the transient state [see the magnified part of Fig. 5(b)]; however, they recovered to the nominal value in the steady state. Fig. 5(c) and (d) show the reactive power and the voltage, respectively, and the simulation results are similar to those of the conventional case as shown in Fig. 4(c) and (d).

B. Case II

To verify that the active power can be shared according to the desired ratio using the proposed control method, the *P–f* and *Q–V* droop coefficients were set as follows: $m_1 = 0.04, m_2 = m_3 = 0.02,\ n_1 = n_2 = n_3 = 0.01$. Consequently, DG2 and DG3 should share the load, and change twice as much as DG1. Fig. 6(a) shows the simulated active power with the conventional *P–f* droop control method. After the static switch was opened as 1 s, the active power that was injected from the main grid was shared among the DG units according to the predetermined ratio (based on the droop coefficients). At 2 s, the load L3 changed, and this change was shared among the DG units. As can be seen from the magnified part of Fig. 6(a),

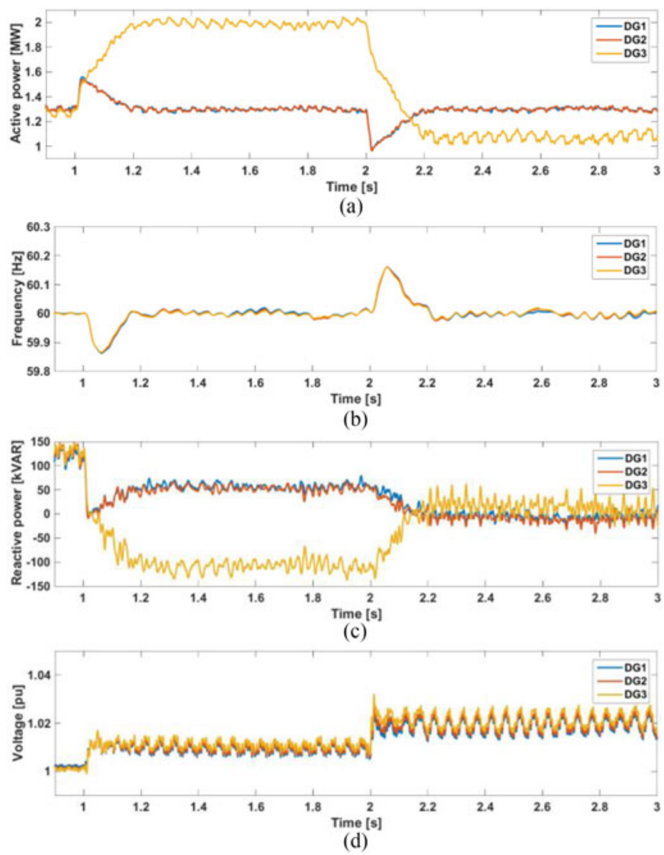

Fig. 8. Simulation results for Case III by adopting the conventional load–frequency control method. (a) Output active power. (b) Output frequency. (c) Output reactive power. (d) Output voltage.

at 2.4 s the active power outputs of DG2 and DG3 were equal, which means that the active power was shared according to the predetermined ratio. As with Case I, frequency deviation was inevitable, as shown in Fig. 6(b). The frequency deviation requires frequency restoration control. The output frequency difference among the DG units was not addressed again in this case, because it was already discussed in Case I. Fig. 6(c) and (d) show the reactive power and the voltage, respectively. Since the active power of DG1 is different from DG2 and DG3, it can be seen that the reactive power of DG1 is also different from DG2 and DG3. Hence, though its influence is small, it can be noticed that the active power and the reactive power are correlated even in the medium-voltage network.

Fig. 7 shows simulated results with the proposed control method. As can be seen from the magnified part of Fig. 7(a), at 1.4 s, the active power outputs of DG2 and DG3 differed (although they should have been equal as they had the same droop coefficient). As expected, active power sharing was not implemented accurately, even after the load change at 2 s [see Fig. 7(a)]. To compensate for these errors, compensation control was activated at 2.5 s. As a consequence, active power sharing was implemented accurately within 0.2 s (see 2.5–2.7 s), as shown in Fig. 7(a). As with Case I, the frequency was restored to the nominal value almost immediately following the mode transition at 1 s and the load change at 2 s.

Fig. 7(c) and (d) show the reactive power and the voltage, respectively, and the simulation results are similar to those of the conventional case as shown in Fig. 6(c) and (d).

C. Case III

In this case study, the conventional load–frequency control method is applied to the DG units to compare the load–frequency control method to the proposed control method. In this case, DG1 and DG2 adopt *P–f* droop control and DG3 acts as load–frequency control unit.

Fig. 8 shows the simulation results for Case III. As can be seen from Fig. 8(a), after load change at 1 and 2 s, DG1 and DG2 shares the transient load change by changing the output frequency [see Fig. 8(b)] and then DG3 recovers the frequency. By imposing a burden of load change to a specific DG unit (DG3 in this case) instead of sharing it among all DG units, output power of DG3 reaches its maximum power. Since the generation cost exponentially increases proportional to output power [19], imposing too much output burden to a specific unit may be economically inefficient and this is the most significant disadvantage compared to the proposed method. Fig. 8(c) and (d) show the reactive power and the voltage, respectively. Again, it can be noticed that the active power and the reactive power are correlated with each other.

V. Conclusion and Future Works

We have described a control method for DG units to implement accurate active power sharing and self-frequency recovery in an islanded microgrid. Islanded microgrids have low inertia, and so they are vulnerable to the frequency disturbances, and frequency recovery is important. Conventionally, frequency restoration is implemented via secondary frequency control units, where the active power sharing units and the frequency control units are controlled separately. Specific units (i.e., frequency control units) are required to account for changes in load, which may cause them to reach their output limit more quickly and hence to increase generation cost exponentially. Moreover, if the frequency deviation is too great, this may lead to a loss of capability of the frequency control units, especially in a small isolated power system such as an islanded microgrid. Hence, it is desirable to share the frequency deviation among all DG units according to a predetermined ratio. As shown by the results of the simulation case studies, the frequency was restored almost immediately following frequency deviation using self-frequency control, and the active power was shared according to droop control and compensation control.

The effectiveness of the proposed method was verified; however, further work is required, particularly in how to determine the ratio of the active power sharing (i.e., how to determine the droop coefficients). Although sharing the frequency restoration among all DG units may be preferable to using only some specific DG units for this (i.e., frequency control units) from the perspective of generation cost and the remaining power of frequency control units, the optimal ratio of the active power sharing among DG units should be determined based on a specific objective. For instance, this ratio could be the loss sensitivity or generation cost of the DG units.

Another area for the future work is the communications delay. Although a communications system is required only for a short duration (to implement compensation control), the communications delay may affect the control stability [22]. Hence, determining the appropriate integral gain is desirable, which may avoid instabilities in the compensation control method.

Moreover, the proposed control method should be modified so that it can be applied to low-voltage networks. Our method adjusts the reference DG output frequency; however, this control scheme can be implemented only for medium- or high-voltage networks, in which the frequency and reactive power are well decoupled because the reactance of the network is larger than the resistance. Even in a medium voltage network, it can be seen that the correlation between active and reactive power still exists as shown in Cases II and III.

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