A Triple-Droop Control Scheme for Inverter-Based Microgrids

F. Luo, Y. M. Lai, Chi K. Tse
Department of Electronic and Information Engineering
The Hong Kong Polytechnic University
Kowloon, Hong Kong
E-mail: Fei.Luo@connect.polyu.hk

K. H. Loo
Faculty of Engineering
The Hong Kong Polytechnic University
Kowloon, Hong Kong

Abstract—**In this paper, a power management control scheme based on triple-droop control strategy is proposed for low-voltage microgrid system. The proposed control method is based on traditional *P/f* and *Q/V* droop control, but adds two other levels of droop control in response to the DC bus voltage conditions. One of them regulates the output power of micro-source (MS), while the other adjusts the output parameters of Droop Control 1. With this control scheme, the output power of MS can be adjusted automatically without the need for communication among the MS systems. The proposed control scheme is proven as capable of operating in both autonomous mode and grid-connected mode. In addition, the droop-controlled VSI systems ensure a smooth transition from grid-connected mode to autonomous mode without the need for mode-switching or communication. The design methodology of the triple-droop control scheme is presented in this paper. The effectiveness of the proposed scheme and design methodology are verified by simulation results on PSIM.**

Keywords-Distributed generation (DG); droop control; microgrid; seamless mode transfer; grid-connected inverters; autonomous operation.

I. INTRODUCTION

The concept of Smart Grid is widely considered as the future direction of utility grid's development. A smart grid in general consists of a collection of microgrids as its basic building block [1], where its main function is to ensure an efficient and reliable power delivery from renewable energy sources. In general, a microgrid is defined as an interconnected network of distributed energy systems (loads and resources) that can function in two basic modes: grid-connected and autonomous mode [1]. This definition also sets the three basic functions of a microgrid:

- To maintain the voltage's amplitude and frequency in a microgrid within a normal range when operating in autonomous mode;
- To distribute active power and reactive power from energy sources to loads when operating in autonomous mode;
- To perform power exchange between microgrid and the main power grid when operating in grid-connected mode;
- To ensure a smooth transfer between autonomous mode and grid-connected mode.

These requirements impose many challenges to the control of microgrid. Presently, droop control [2] has been accepted as a popular decentralized control strategy. Compared to centralized control, droop control has enabled an automatic sharing of active and reactive powers among inverters in an autonomous microgrid. Since communication is not needed between the invetrters, the reliability of the microgrid system is improved. Previous researches on droop control were mainly focused on its applications in autonomous microgrids [3-6], where its feasibility was clearly demonstrated. In [7], a droop-based hierarchical control was proposed, which can work in both autonomous and grid-connected modes. It verified that droop-based control scheme has the capability to work in grid-connected mode. However, with this control method, communication channel has to be employed, which controls the output power of DC micro-sources (MS) and informs the inverter's controller to switch to different references during mode-switching. Furthermore, the switching between references makes the mode transfer unsmooth. In [8, 9], a control scheme based on the changes of the DC bus voltage generated by MS was introduced, where the output power of the inverter is adjusted according to the output power of MS. In short, there are some areas for research in the interaction between MS and inverters.

In order to overcome these disadvantages, a triple-droop control scheme is proposed in this paper, which offers the following desirable features:

- No communication is required during normal operation;
- Enables automatic sharing of power among inverters;
- Compatible with both autonomous and grid-connected modes;
- Enables a seamless transfer from one mode to another;

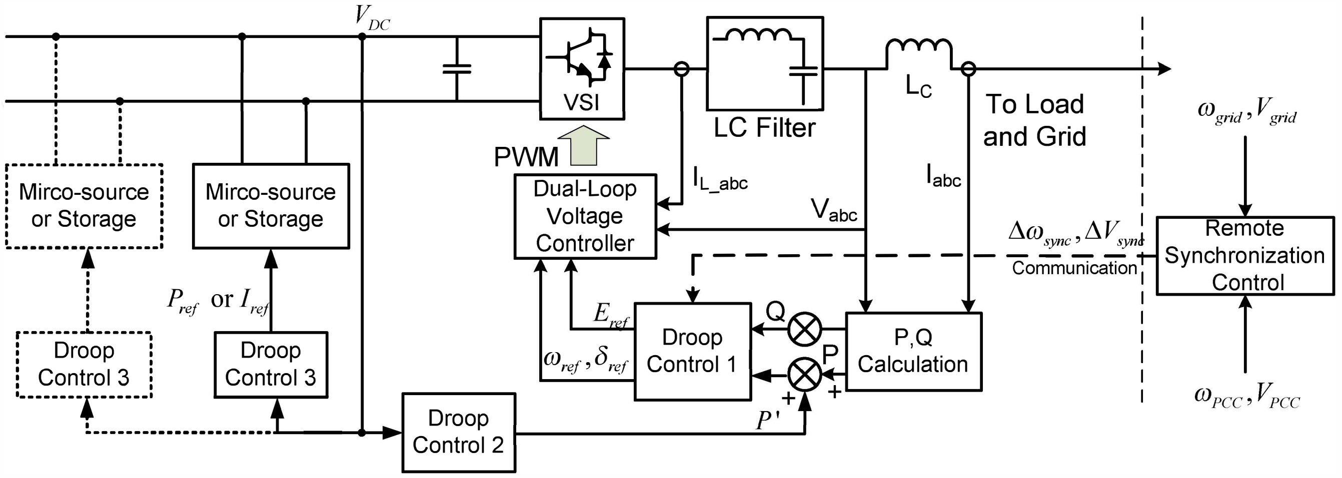


Figure 1. The proposed triple-droop control scheme.

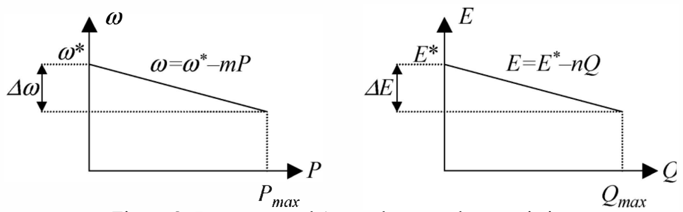


Figure 2. Droop control 1: steady-state characteristic.

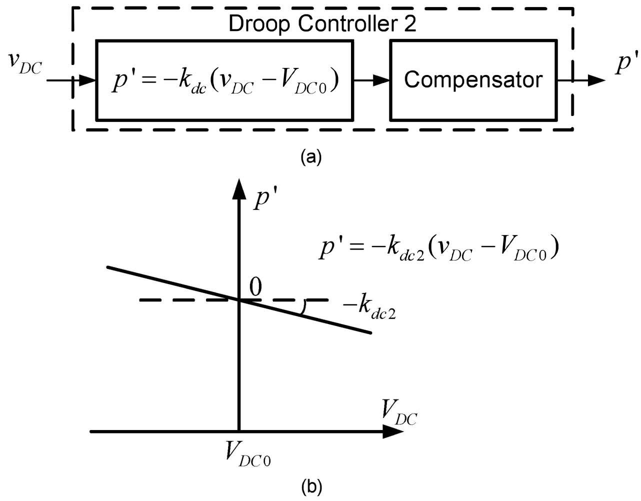


Figure 3. Droop control 2: (a) controller's block diagram (b) steady-state characteristic.

- Capable of adjusting the output power of MS without communication.

In Section II, the proposed control scheme is discussed. The configuration of the microgrid system implemented with the proposed control scheme is given in Section III, followed by an outline of the design methodology in Section IV. Finally, the proposed control scheme and microgrid system are verified by simulation results in Section V.

II. The Proposed Control Scheme

The proposed control scheme, which aims to control the power flow of inverter and MS, comprises of three droop controllers as shown in Fig. 1. The Droop Control 1, which generates voltage reference of a voltage source inverter (VSI), is the traditional *P/f* droop with a PID controller and *Q/V* droop with a PD controller [3]. Based on Droop Control 1, Droop Control 2 was introduced, which is designed to change the output of Droop Control 1 by adding a power offset *P'* to *P* according to the DC bus voltage conditions. Finally, Droop Control 3 determines the output power references for the individual MS according to the DC bus voltage conditions. In the following part, the details of the three droop controls and other issues are discussed.

A. Droop Control 1

This traditional *P/f* and *Q/V* droop strategy have been extensively researched and discussed in the past literature [3]. Their steady-state characteristics are given by Eqs. (1) and (2), and depicted in Fig. 2.

$$\omega = \omega^* - mP \tag{1}$$

$$E = E^* - nQ \tag{2}$$

P and Q are the active and reactive power calculated from the output voltage and current of the inverter; ω and E are the frequency and amplitude of the voltage reference. Droop Control 1 regulates the output power of the voltage source inverter (VSI) with a dual-loop voltage controller. It stabilizes the microgrid system and achieves automatic power sharing between inverters.

Droop Control 1 can be rewritten in the form of Eq. (3), which represents the relationship between the static frequency ω and the output active power P. At the static frequency ω_0, the output active power of the inverter is P_0.

$$P = P_0 - \frac{1}{m}(\omega - \omega_0) \tag{3}$$

B. Droop Control 2

With Droop Control 1, the inverters in a microgrid system are able to share power proportionally in accordance to their individual droop parameters m. However, in all circumstances,

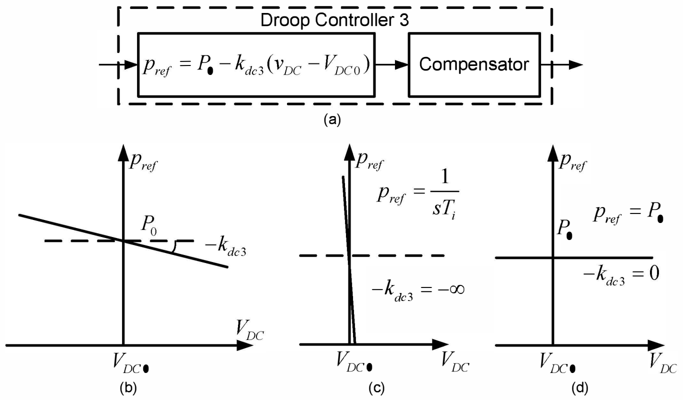


Figure 4. Droop control 3: (a) controller's block diagram; (b) Type-I; (c) Type-II; (d) Type-III power controller.

the inverters must balance its output active power with the input power derived from the MS. For this reason, Droop Control 2 is introduced which adds a power offset P' to the calculated active power P. With this power offset, Eq. (3) of Droop Control 1 is modified and becomes Eq. (4).

$$P + P' = P_0 - \frac{1}{m}(\omega - \omega_0) \tag{4}$$

At steady state, for instance when $\omega = \omega_0$, the inverter's active output power under the action of Droop Control 2 becomes (P_0 – P') instead of P_0.

In general, Droop Control 2 makes the power offset P' a function of the DC bus voltage's variations, hence it is possible to limit the output active power of the inverter according to the power capability of the MS. The details of Droop Control 2 are shown in Fig. 3. The input to the controller is the DC bus voltage V_{DC}. The controller consists of two parts. The first part represents the DC gain, as given by Eq. (5).

$$P' = -k_{dc2}(V_{DC} - V_{DC0}) \tag{5}$$

The second part is a compensator, which defines the dynamic behavior of the controller and keeps the system stable. The DC gain of compensator should be unity so that the steady-state characteristic of the controller is determined by Eq. (5) only. The form and design methodology of compensator is discussed in Section VI.

C. Droop Control 3

Similar to Droop Control 1 which enables power sharing among inverters without communication, a similar function is achieved by Droop Control 3 for power sharing among MS attached to the same DC bus voltage. It defines the power references for individual MS based on the DC bus voltage conditions. Nevertheless, since different types of MS show different output power characteristics, the exact form of Droop Control 3 can be selected specific to the MS in use. In general, the steady-state characteristics of Droop Control 3 can take one of the three basic forms as discussed below:

- Type I: The power reference for MS, P_{ref}, changes proportionally with V_{DC} as given by Eq. (6). The DC gain $-k_{dc3}$ is finite and negative. With this form of droop control, the power demand from the DC bus is shared proportionally among the MS.

$$P_{ref} = P_0 - k_{dc3}(V_{DC} - V_{DC0}) \tag{6}$$

- Type II: An integrator is introduced to make DC gain $-k_{dc3}$ infinite. With this form of droop control, the output power of the MS will be adjusted in order to keep V_{DC} constant.
- Type III: The DC gain $-k_{dc3}$ is made equal to zero. With this form of droop control, the MS will be set to deliver a constant output power independent of the DC bus voltage conditions.

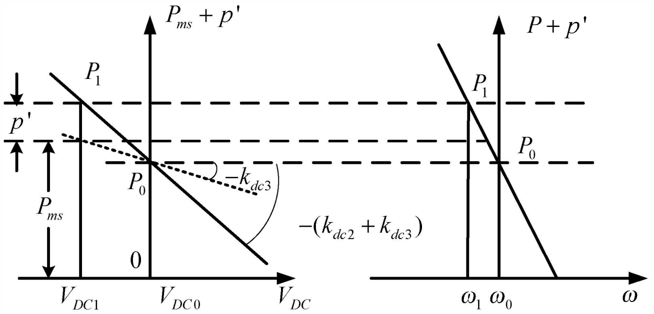


Figure 5. Operation of triple-droop control.

For all three types of Droop Control 3, a compensator is included to define the dynamic behavior of the controller and keeps the system stable.

D. Operation of Triple-Droop Control

It is assumed that the power flow between the MS and the inverter is well balanced, and the output power of the MS (P_{ms}) is equal to the output power of the inverter (P), as given by Eq. (7).

$$P_{ms} = P \tag{7}$$

If Droop Control 3 is implemented by a Type-I controller, and since $P_{ms} = P_{ref}$, Eq. (8) can be obtained by summing Eqs. (5) and (6) and comparing the resulting equation with Eq. (4).

$$\begin{aligned} P_{ms} + P' &= P_0 - (k_{dc3} + k_{dc2})(V_{DC} - V_{DC0}) \\ &= P_0 - \frac{1}{m}(\omega - \omega_0) \end{aligned} \tag{8}$$

This relationship between the DC bus voltage and the inverter's frequency is depicted in Fig. 5. Initially, when the output power of both the MS and inverter are both equal to P_0, it can be seen from Fig. 5 that the inverter's frequency is ω_0 and the DC bus voltage V_{DC0}. This is the initial equilibrium state. When a load increase occurs in the microgrid, the inverter responds by shifting its frequency from ω_0 to ω_1 in order to meet the new load power demand. Since a Type-I controller is employed, the DC bus voltage will keep shifting to a lower value until a new power flow balance is established between the MS and inverter. As shown in Fig. 5, the DC bus voltage will settle at V_{DC1} at the new equilibrium state. In both

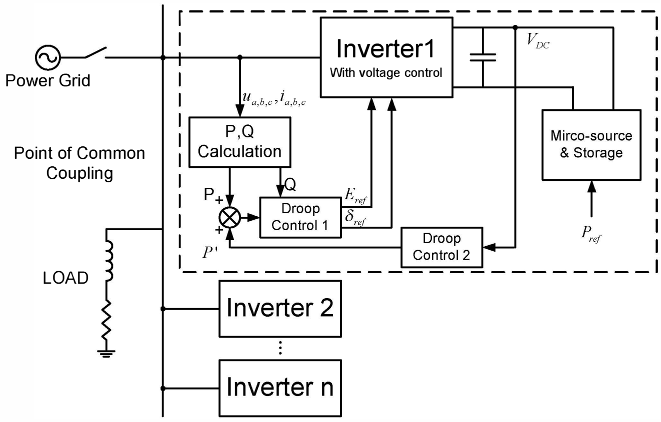


Figure 6. Structure of the proposed microgrid.

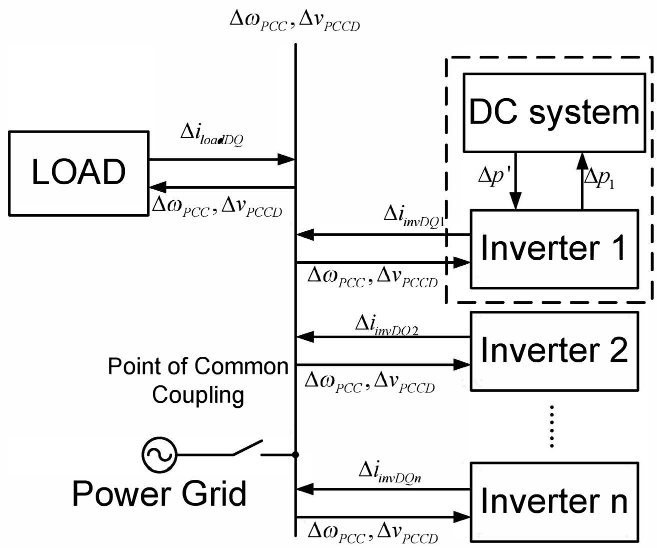


Figure 7. Block diagram of the small-signal model of the proposed microgrid.

equilibrium states, the power balance condition $P_{ms} = P$ must be fulfilled.

If Droop Control 3 is implemented by a Type-II controller, the power offset P' becomes zero as the DC bus voltage is always regulated at a fixed value of V_{DC0} since $k_{dc3} = \infty$. The power flow balance condition $P_{ms} = P$ holds, hence the MS is assumed to be an infinite power source that will deliver any active power required to keep the DC bus voltage constant. This assumption, nevertheless, is not always valid. Under this condition, the triple-droop control degenerates to the conventional single-droop control (with Droop Control 1 only being active).

Lastly, if Droop Control 3 is implemented by a Type-III controller, the MS is configured to output a constant power $P_{ms} = P_0$ since $k_{dc3} = 0$. For power flow balance must hold,

$$P_{ms} = P = P_0 \tag{9}$$

When there is an increase in load power from P_0 to P_1, Droop Control 2 will generate a power offset $P' = P_1 - P_0$. Since the MS can only output a constant power P_0, the additional load power demand must be supplied by another inverter system in the microgrid. In summary, due to the

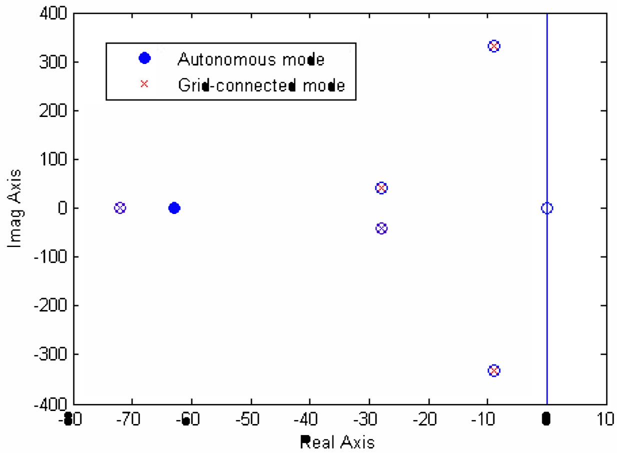


Figure 8. Poles of the inverter system.

interactivity between the different levels of droop control in the proposed scheme, the microgrid has the ability to work in both autonomous and grid-connected mode. This will be verified by simulation results in Section V.

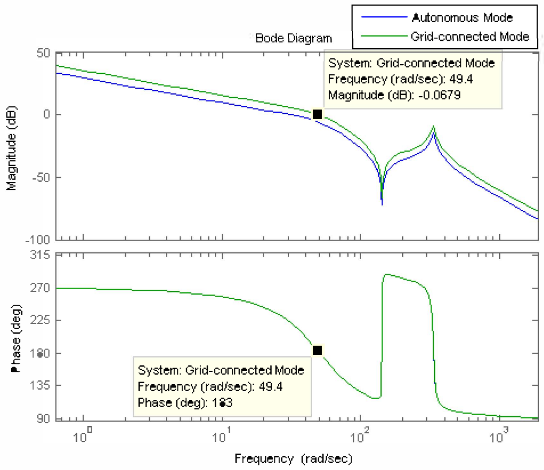
E. Remote Synchronization Control

In order to connect the microgrid to the power grid, the voltage at the PCC should be synchronized to the voltage of the power grid. The voltage synchronization strategy proposed in [7] is adopted in this paper. The remote synchronization control adjusts the frequency and amplitude of the voltage at the PCC by amending the setting of Droop Control 1 through a low bandwidth communication channel. This is the only part where communication is needed in the proposed microgrid structure. Nevertheless, the need for communication does not weaken the reliability of the system since synchronization is only needed at the point of connecting the microgrid to the power grid. An appropriate time can be chosen to close the static switch when a safe communication is established. After connecting to the power grid, synchronization control is no longer required. The voltage at the PPC is clamped by the power grid, and the triple-droop control is able to balance the power flow between the MS and inverter.

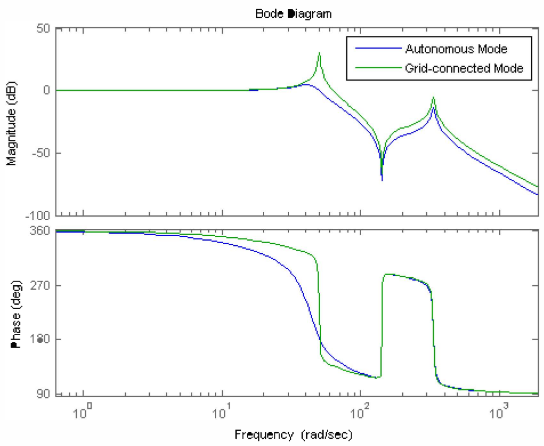
Remote Synchronization Control enables the transfer of the microgrid from autonomous mode to grid-connected mode. This control block is not required during the transfer from grid-connected mode to autonomous mode. The VSI is able to maintain the microgrid's voltage amplitude and frequency and balance the power flow automatically during the transition. This feature guarantees a reliable operation of the system.

F. Extendibility

Another advantageous feature of the proposed control scheme is its extendibility. With the control scheme, more MS or storages can be connected in parallel onto the DC bus, as shown in Fig. 1. The DC bus voltage is employed as the communication channel that signals power imbalance and forces each MS to share the load according to the setting of their Droop Control 3. Different MS can be programmed to have different settings for Droop Control 3 based on their specific output characteristics. One exception is that Type-II

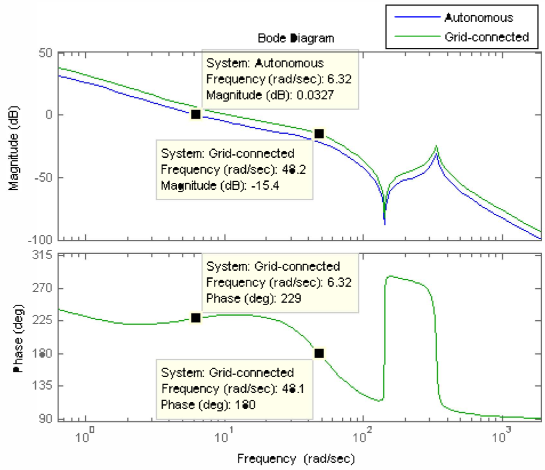


(a)

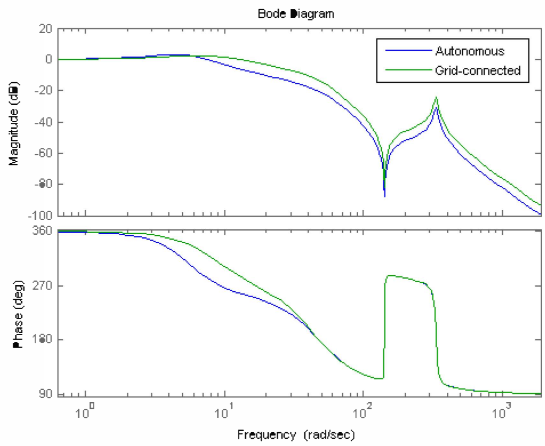


(b)

Figure 9. Bode plots of microgrid system without compensator: (a) open-loop, (b) closed-loop



(a)



(b)

Figure 10. Bode plots of microgrid system with compensator: (a) open-loop, (b) closed-loop

controller should not be used since communication is not permissible when the bus voltage is fixed.

TABLE I. PARAMETERS OF INVERTER SYSTEM WITH DROOP CONTROL 1

Item	Symbol	Value
Phases of Inverter	-	3
Coupling Inductor	L_{c1}, L_{c2}	1000 μH
Parasitic Resistor	r_{c1}, r_{c2}	10 mΩ
Common Load Resistor(Heavy)	R_L	50 Ω
Common Load Resistor(Light)	R_L	100 Ω
Common Load Inductor	L_L	0 mH
Nominal Output-Power	P_0	1450 W
Nominal Frequency	ω_0	314.16 rad/s
Nominal Amplitude	E^*	311.13 V
$P-\omega$ Droop	m	1×10^{-4}
$Q-E$ Droop	n	1×10^{-4}
$P-\phi$ Droop Proportional	m_p	5×10^{-9}
$P-\phi$ Droop Derivative	m_d	2×10^{-9}
$Q-E$ Droop Derivative	n_d	5×10^{-9}
Filter Cut-off Frequency	ω_c	62.8

III. THE PROPOSED MICROGRID SYSTEM

In the following discussion, emphasis will be given to the design and operation of Droop Control 2. For the MS, a general Type-III controller, which causes the MS to output constant power, is used for Droop Control 3. The structure of the proposed microgrid is shown in Fig. 6. In this microgrid, Inverter 1 is controlled by the proposed triple-droop control scheme, while Inverter 2 to Inverter n are controlled by traditional droop control. The load is an RL load. All inverters and load are connected to the point of common coupling (PCC) radially. The power grid is connected to the PCC through a static switch.

IV. DESIGN METHODOLOGY

The small-signal model of the proposed microgrid system is represented as block diagrams in Fig. 7. Each block represents a sub-system, and the variables on the arrows represent the small-signal input and output quantities. Due to space constraint, the small-signal modeling of the proposed system will not be elaborated here. Instead, only the main features are discussed.

In order to enable the system to operate stably in both autonomous and grid-connected mode, we proposed the

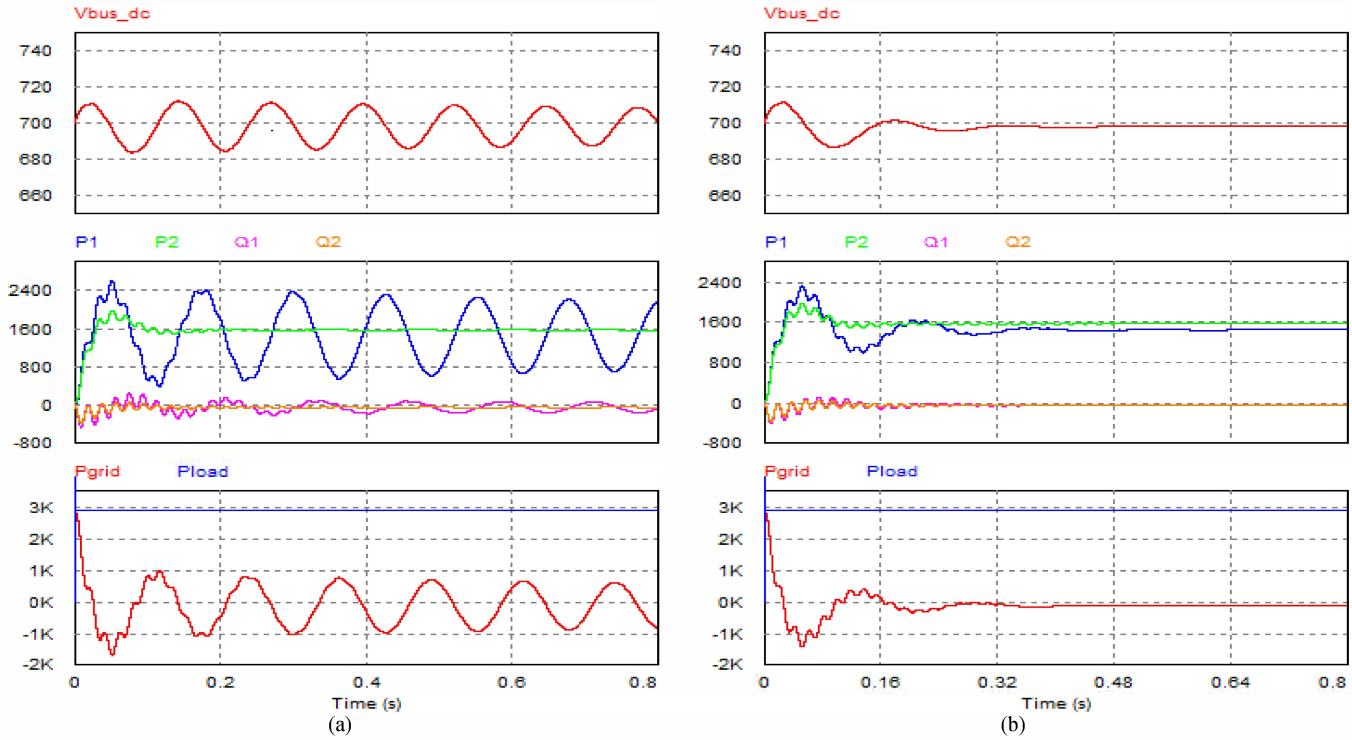


Figure 11. Transient response of the microgrid system in grid-connected mode following a small disturbance when (a) compensator, (b) no compensator is included.

following design procedure. In [2] and [3], the design methodology of Droop Control 1 has been well established. In this paper, the MS are assumed to output constant power, hence the design of Droop Control 3 can be ignored. As a result, in this section, the parameters of Droop Control 1 and other system parameters are directly listed and the stability of the system employing these parameters are first verified, followed by a detailed discussion on the design of Droop Control 2.

A. *Stability of inverter system*

In this paper, the number of inverters is chosen to be two (n = 2). The main parameters of the system are listed in Table I. The poles of the inverter system in both grid-connected and autonomous mode are plotted in Fig. 8, where stable high-frequency poles are omitted. All the poles in both modes are on the left half plane, which indicates that the inverter system without Droop Control 2 is stable.

B. *Design of steady-state characteristic of Droop Control 2*

The steady-state characteristic of Droop Control 2 is given by Eq. (5), which contains 2 parameters. V_{DC0} is chosen to be equal to the nominal bus voltage, so that no power offset is generated when the DC bus voltage is equal to its nominal value. Therefore, the value of k_{dc2} is determined from Eq. (10).

$$k_{dc2} = \frac{P_{\max}}{V_{DC\max} - V_{DC0}} \qquad (10)$$

where $V_{DC\max}$ and $P_{\max}$ is the maximum DC bus voltage and maximum active power, respectively. With this formulation, the inverter will attempt to output the maximum active power when the DC bus voltage reaches the maximum value.

TABLE II. PARAMETERS OF DC SYSTEM AND DROOP CONTROL 2

Item	Symbol	Value
Bulk Capacitor	C	2 mF
MS Output-Power	P_{ms}	1450 W
Nominal Output-Power	P_0	1450 W
Nominal DC Voltage	V_{DC0}	700 V
$V-p'$ Droop (Droop 2)	k_{dc2}	83 W/V
Zero of Compensator	ω_z	5.7 rad/s
Pole of Compensator	ω_p	2.5 rad/s

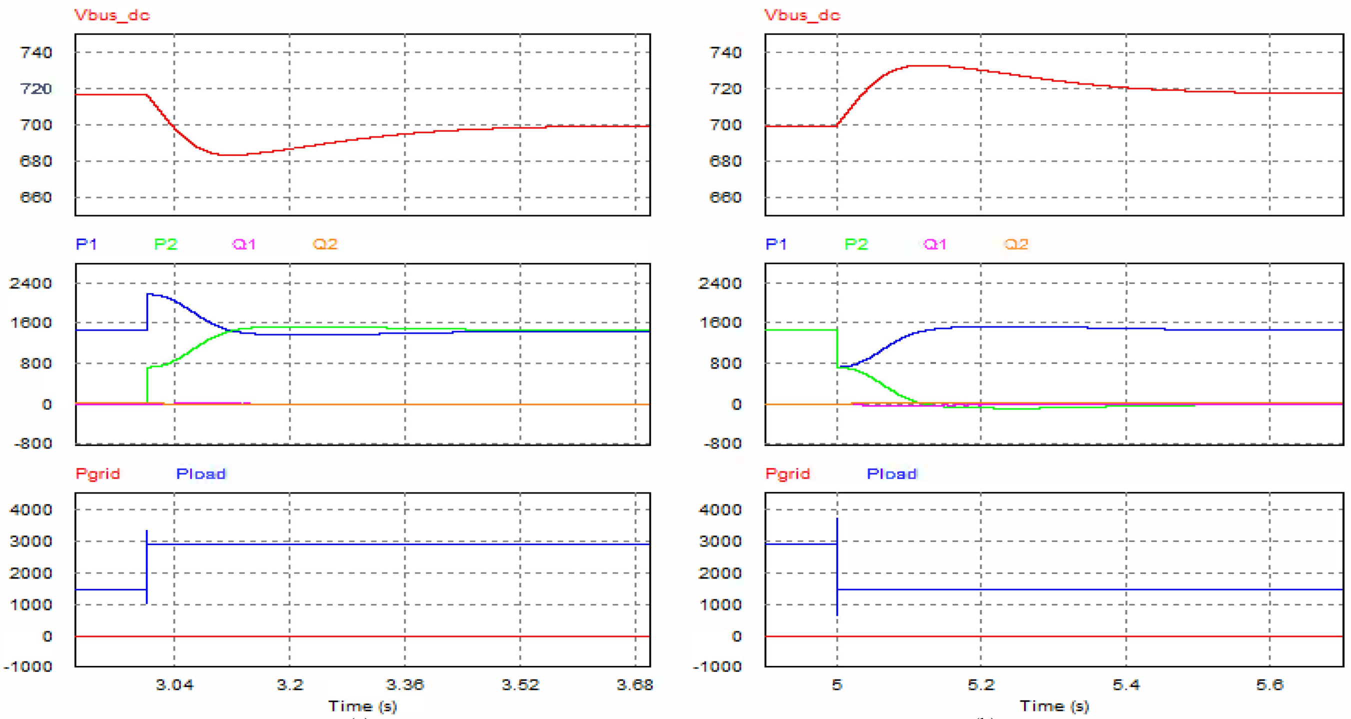
C. *Design of compensator in Droop Control 2*

The function of the compensator H_{comp} is to stabilize the microgrid system. If the system is stable without compensator, the compensator can be omitted. By setting H_{comp} = 1 as an initial value, the bode plots of the open-loop and closed-loop system in both autonomous and grid-connected mode are plotted in Fig. 9. The figures show that more damping is required although the system is inherently stable.

In order to damp the oscillations, a compensator having the form given by Eq. (11) is introduced.

$$H_{comp}(s) = \frac{1 + s/\omega_z}{1 + s/\omega_p} \qquad (11)$$

where ω_z and ω_p are the angular frequencies of the zero and pole of the compensator, respectively. The bode plots of the open-loop and closed-loop systems for both modes in the presence of compensation are plotted in Fig. 10. It shows that, after compensation is included, the phase margin and gain margin of the system in grid-connected mode have increased



(a) (b)

Figure 12. System dynamics under step increase in load.

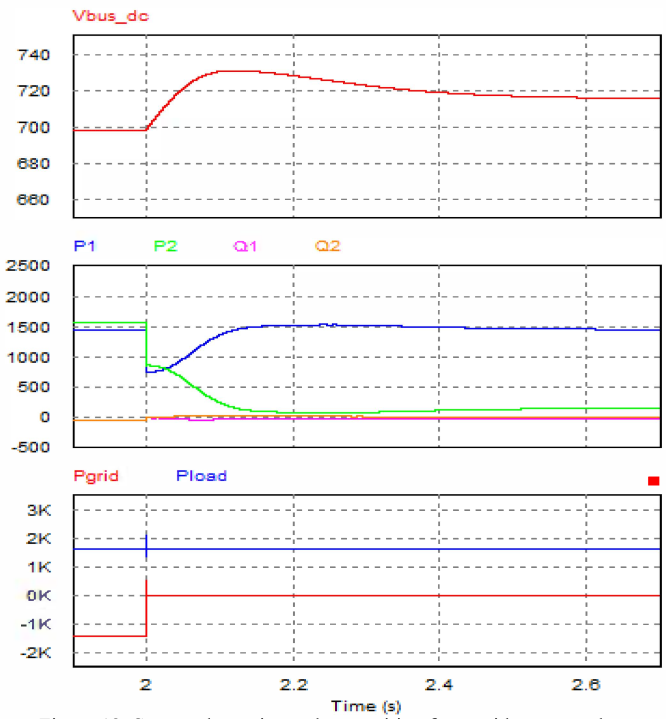


Figure 13. System dynamics under transition from grid-connected to autonomous mode

from almost zero to 49 degrees and 15.4 dB, respectively. With sufficient open-loop phase margin and gain margin, the resonant peak in the closed-loop responses has been effectively damped. The parameters of Droop Control 2 are given in Table II.

The proposed design methodology will be verified by the simulation results presented in the next section.

V. Simulation Results

To verify the feasibility of the triple-droop control scheme and its design methodology, the proposed microgrid system is simulated in PSIM, which is a simulation software specifically designed for power electronics and motor control. In Fig. 11 to Fig. 13, "P1" and "P2" represents the active output power of Inverter 1 and Inverter 2, respectively. Similarly, "Q1" and "Q2" are the reactive output power of the two inverters, "Vbus_dc" is voltage on the DC bulk capacitor, "Pload" is active power consumed by the load, and "Pgrid" is the active power injected from the power grid to the microgrid. By this definition, negative "Pgrid" means active power is exported by the microgrid to the power grid.

In order to verify the effectiveness of the compensator of Droop Control 2, simulation is performed for the case of the microgrid operating in grid-connection mode and a power disturbance is introduced. Fig. 11(a) shows simulation results for the case when no compensator is used. Clearly the system exhibits oscillatory behavior although it remains stable in operation. The oscillatory behavior indicates that the system should be more effectively damped as predicted by the Bode plots in Fig. 9(b). In contrast, Fig. 11(b) shows that the disturbance diminishes after 0.3 seconds when compensator is used.

Fig. 12(a) and Fig. 12(b) show the system dynamics under step increase and step decrease in load. When there is a load change in an autonomous system, the output powers of both inverters change at the same time in the same direction. The power difference between Inverter 1 and MS causes the DC bus voltage to vary and the effect is compensated through the action of Droop Control 2. Droop Control 1 acts to redistribute the power sharing between the two inverters.

Fig. 13 shows the transition of the microgrid system from grid-connected to autonomous mode. At $t = 2$ seconds when it is disconnected from the power grid, the microgrid has stopped injecting power into the power grid. The output powers of Inverter 1 and Inverter 2 decrease simultaneously at the transition point. However, following this, the DC bus voltage increases due to power imbalance on the DC bulk capacitor, and the output power of Inverter 1 changes under the action of Droop Control 2. The output power of Inverter 2 keeps decreasing under the action of Droop Control 1. Finally, the DC bus voltage has settled at a new and higher value, and the output active power of Inverter 1 becomes equal to the output power of the MS, while Inverter 2 adjusts its output and accounts for the power difference between Inverter 1 and the load.

VI. Conclusion

In this paper, a triple-droop control scheme is proposed. In general, Droop Control 2 adds a power offset to the output of Droop Control 1 to modify the voltage reference of inverter according to the DC bus voltage conditions. In concurrent to this, Droop Control 3 regulates the output power of MS based on the DC bus voltage conditions. With this formulation of control strategy, the power generated by the MS can be automatically adjusted without communication among the MS systems. Furthermore, the proposed control scheme is proven as capable of operating in both autonomous mode and grid-connected mode. In addition, the droop-controlled VSI systems ensure a smooth transition from grid-connected mode to autonomous mode without the need for mode-switching or communication. In the proposed system, communication is only required when reconnecting the microgrid to the power-grid. The design methodology of the triple-droop control scheme is presented in this paper. The effectiveness of the proposed scheme and design methodology are verified by simulation results on PSIM.

Acknowledgment

The research work was funded by the University Grants Committee of the Hong Kong Special Administrative Region, Research Grants Council Earmarked Research Grant (ERG) number PolyU-5193/10

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