Control of Distributed Generation Systems
Part II: Load Sharing Control

M. N. Marwali, J.W. Jung, and A. Keyhani, Fellow, IEEE

Abstract—This paper is concerned with the control strategy for the parallel operation of distributed generation systems (DGS) in a standalone AC power supply. The proposed control method uses only low-bandwidth data communication signals between each generation system in addition to the locally measurable feedback signals. This is achieved by combining two control methods: droop control method and average power control method. The average power method with slow update rate is used in order to overcome the sensitivity about voltage and current measurement errors. In addition, a harmonic droop scheme for sharing harmonic content of the load currents is proposed based on the voltages and currents control algorithm presented in Part I: Voltages and Current Control. Simulation studies using two parallel three-phase PWM inverters (600 kVA) are presented to show the effectiveness of the proposed control.

Index Terms—Industrial power systems, Interconnected power systems, DC-AC power conversion.

I. INTRODUCTION

Recently, interest in distributed generation systems (DGS) is rapidly increasing, particularly onsite generation. This interest is because larger power plants are economically unfeasible in many regions due to increasing system and fuel costs, and more strict environmental regulations. In addition, recent technological advances in small generators, Power Electronics, and energy storage devices have provided a new opportunity for distributed energy resources at the distribution level, and especially, the incentive laws to utilize renewable energies have also encouraged a more decentralized approach to power delivery [1 – 16].

There exist various generation sources for DGS: conventional technologies (diesel or natural gas engines), emerging technologies (microturbines or fuel cells or energy storage devices) [2, 4, 6 - 12], and renewable technologies (small wind turbines or solar/photovoltaics or small hydro turbines) [3, 4, 10]. These DGS are used for applications to a standalone [11, 12, 16], a standby [2,9], a grid-interconnected [12], a cogeneration [7 - 9], peak shavings [2], etc. and have many advantages such as environmental-friendly and modular electric generation, increased reliability, high power quality, uninterruptible service, cost savings, on-site generation, expandability, etc.

Introduction of such DGS as combustion engine, small hydro, photovoltaic arrays, fuel cells, microturbines or battery energy storage systems, and cogenerations into power systems is very attractive for power utilities, customers and societies. Because, for utility, DGS can help to improve power quality and power supply flexibility, maintain system stability, optimize the distribution system, provide the spinning reserve and reduce the transmission and distribution cost, and can be used to feed customers in the event of an outage in the line or in the primary substation or during scheduled interruptions. Also, for society, the renewable energy can significantly reduce the emission from the traditional power plants. So many utility companies are trying to construct small distribution stations combined with several DGS available at the regions, instead of large power plants.

Basically, these technologies are based on notably advanced Power Electronics because all DGS require power converters, PWM techniques, and electronic control units [1 - 16]. That is, electrical power generated by all DGS is first converted into DC power, and then all the power fed to the DC distribution bus is again converted by DC to AC power converters into an AC power with fixed magnitude and frequency by control units using Digital Processing Processor (DSP). Therefore, in order to permit grid interconnection of asynchronous generation sources, advanced power electronic technologies are definitely required.

The research works in the recent papers about DGS focus on two applications: a standalone AC system and a grid-interconnection to the utility mains. In a standalone AC power supply, several DGS independently supply the loads with electrical power, like the parallel operation of the uninterruptible power supply (UPS) systems. In a grid-interconnected operation to AC mains, each DES is interconnected in parallel to the utility, and it directly provides power to AC mains in order to cover increased power required by the loads.

This paper is concerned with the control strategy for the parallel operation of distributed generation systems (DGS) in a standalone AC power supply. In particular, the paper focuses on proper power sharing of each DGS such as the real power, reactive power, and harmonic power in a standalone AC power supply, like the parallel operation of multiple UPS systems [16 - 22]. First of all, good load-sharing should be maintained under both locally measurable voltages/currents and the wire impedance mismatches, voltage/current measurement error mismatches that significantly degrade the performance of load-

The authors are with the Department of Electrical Engineering, Ohio State University, Columbus, OH 43210 USA (e-mail: Keyhani.1@osu.edu).
sharing. Key features of the proposed control method are that it only uses locally measurable feedback signals (voltages/currents) and uses relatively low bandwidth data communication signals (respective real power and reactive power) between each generation system.

To ensure good load-sharing, the scheme combines two control methods: droop control method and average power control method. In this method, the sharing of real and reactive powers between each DGS is implemented by two independent control variables: power angle and inverter output voltage amplitude. Especially, the average power method is used in order to significantly reduce the sensitivity about voltage and current measurement error mismatches. This scheme guarantees good load-sharing of the fundamental components of the load currents [21, 22, 26].

To ensure sharing of harmonic contents of the load currents, a harmonic droop sharing technique is proposed in this paper. The technique is based on the voltages and currents control developed in Part I: Voltages and Current Control [28]. The proposed harmonic droop technique has the advantage that it only affects the harmonic compensator gains and does not degrade the fundamental voltage regulation.

In this study, two three-phase PWM inverters (600 kVA) operating in parallel are implemented by digital computer simulation using Matlab/Simulink. Some simulation results under various operating conditions are also given.

II. DISTRIBUTED ENERGY SYSTEM DESCRIPTION

The configurations for two applications of DGS are shown in Fig. 1: a grid-interconnection and a standalone AC power supply. Fig. 1 (a) shows a schematic diagram of DGS used for a grid-interconnection application. As shown in Fig. 1 (a), DGS are interconnected to the conventional distribution lines in order to cover increased power required by the loads, so the distributed generation systems may spread around the distributed system that is connected to a grid system. In this application, DGS are connected to Medium Voltage Network or Low Voltage Network according to power ratings or voltage ratings available for the systems. Fig. 1 (b) shows the network structure of distributed generation systems used for a standalone AC power supply, and each distributed energy system supply power to the loads, like the parallel operation of UPS units in the emergency mode operation. As shown in Fig. 1 (b), this architecture may require for each DGS to operate independently because the distance between DGS units may make data communication impractical and the control should be based on those variables that can only be measured locally at the inverter. However, recently data communication between units can easily be realized by the rapid advances in the field of communication.

![Fig. 1 Configurations for two applications of DES](image1)

Fig. 1 Configurations for two applications of DES

![Fig. 2 Control unit communications between DGS units](image2)

Fig. 2 Control unit communications between DGS units

Fig. 2 shows a schematic diagram for data communication between Remote Terminal Unit (RTU) and RTU for each DES to exchange power information (real power and reactive power) in a standalone AC power system.
DGS circuit model in a standalone AC power system is shown in Fig. 3. This model consists of two three-phase PWM inverters running in parallel supporting two loads. The power converter of each DGS studied in this paper is a DC/AC voltage source inverter, and each inverter is equipped with an LC output filter and a Δ/Y transformer (600 kVA, Np: Ns = 245: 208). In this Figure, in order to simplify circuit analysis, generation sources such as combustion engine, small hydro, photovoltaic arrays, fuel cells, micro turbines or battery energy storage systems, etc., can be modeled as dc voltage sources (VDC1 and VDC2).

III. DGS CONTROL REQUIREMENTS

In general, the droop technique [16 – 22, 27] has been widely used as a load-sharing scheme in conventional power system with multiple generators. In this droop method, the generators share the system load by drooping the frequency of each generator with the real power (P) delivered by the generator. This allows each generator to share changes in total load in a manner determined by its frequency droop characteristic and essentially utilizes the system frequency as a communication link between the generator control systems [16-20]. Similarly, a droop in the voltage amplitude (Vmax) with reactive power (Q) is used to ensure reactive power sharing.

Since this load sharing technique is based on the power flow theory in an ac system, which states that the flow of the active power (P) and reactive power (Q) between two sources can be controlled by adjusting the power angle and the voltage magnitude of each system – i.e. the active power flow (P) is predominantly controlled by the power angle, while the reactive power (Q) is predominantly controlled by the voltages magnitude, this theory is explained in Fig. 4. Fig. 4 indicates critical variables for load-sharing control of paralleled power converters. The Figure shows two inverters represented by two voltage sources connected to a load through line impedance represented by pure inductances L1 and L2 for simplified analysis purpose.

The complex power at the load due to inverter i is given by:
\[ S_i = P_i + jQ_i = V_i I_i^* \] (1)

\[ E_i \angle \delta_i \quad V \angle 0 \quad E_j \angle \delta_j \]
\[ I_i \quad j\omega L_i \quad j\omega L_j \]
\[ I_2 \]

This gives the active and reactive power flowing from the i-th inverter as:

\[ I_i^* = \left[ \frac{E_i \cos \delta_i + jE_i \sin \delta_i - V}{j\omega L_i} \right]^* \] (2)

\[ \therefore S_i = \left[ \frac{E_i \cos \delta_i + jE_i \sin \delta_i - V}{j\omega L_i} \right]^* \] (3)
From equations (1) thru (5), it can be seen that, if \( \delta_1 \) and \( \delta_2 \) are small enough, then the real power flow is mostly influenced by the power angles \( \delta_1 \) and \( \delta_2 \), while the reactive power flow predominantly depends on the inverter output voltages \( E_1 \) and \( E_2 \). This means that to certain extent the real and reactive power flow can be controlled independently. Since controlling the frequencies dynamically controls the power angles, the real power flow control can be equivalently achieved by controlling the frequencies of the voltages generated by the inverters.

Therefore, as mentioned above, the power angle and the inverter output voltage magnitude are critical variables that can directly control the real and reactive power flow for proper load-sharing of power converters connected in parallel.

Similarly, the above control theory can be applied to parallel operation of distributed energy systems in a standalone AC power supply application. In general, there is large distance between inverter output and load bus, so each DGS is required to operate independently as using only locally measurable voltages/currents information. In addition, there is also long distance between DGS units, so data communication between DGS units may be impractical [16 - 20]. However, in recent years, data communication between DGS units can easily be implemented by the rapid advances in the field of communication.

Therefore, the paper considers the parallel operation of power converters in a standalone AC system under signal communications between units in order to ensure exact load-sharing of each DGS unit. In particular, this research focuses on proper load-sharing between each unit, and the load-sharing should be also guaranteed under the wire impedance mismatches, voltage/current measurement error mismatches, and interconnection tie-line impedance effect that can heavily affect the performance of load-sharing [20 - 22].

Control constraints considered in this paper are summarized as follows:

- locally measurable feedback signals (voltages/currents)
- data communications between each DGS about real power and reactive power
- wire impedance mismatches between inverter output and load bus
- voltage/current sensor measurement error mismatches
- tie-line impedance between loads

To overcome the above control constraints, a new droop technique using both average power method and harmonic droop control is proposed.

IV. PROPOSED LOAD SHARING CONTROL ALGORITHM

A. Combined Droop Control Method and Average Power control method

In order to guarantee exact load-sharing of the real power (P) and the reactive power (Q) between DGS units, the conventional droop method should be modified by a new control algorithm. To do this, a combination of the droop method, the average power control method, and harmonic sharing control loop is proposed for load-sharing of paralleled inverters. Fig. 5 shows a Simulink block diagram for the real power sharing control. In this Figure, phase angle (\( \Delta \phi \)) is chosen as the control variable instead of frequency used as a control variable in a conventional droop method because the phase angle is not varied due to constant real power in steady-state time, and then it make the frequency remain at nominal value (60 Hz), unlike some frequency deviations of the conventional droop method. As shown in Fig. 5, the difference between real-time active power (\( P_q \) or \( P_d \)) of each unit and the rating real power (\( P_{0 \_qd} \)) of each unit is multiplied by a droop coefficient (\( m_1 \)). In addition, the difference between the active power (\( P_q \) or \( P_d \)) of each DGS unit and the average real power (\( P_{avg \_qd} \)) is finally equal to zero by a discrete-time integrator in steady-state time. As a result, the active power between the DGS units is properly shared according to the power ratings of each DGS unit.

The Simulink block diagram for the reactive power (\( Q_q \) or \( Q_d \)) sharing control is implemented in Fig. 6. As shown in Fig. 6, the amplitude of a reference voltage (\( V_{max \_qd} \)) is decided by the average reactive power (\( Q_{avg \_qd} \)) and the reactive power of each unit. The difference between real-time reactive power (\( Q_q \) or \( Q_d \)) of each unit and the rating reactive power (\( Q_{0 \_qd} \)) of each unit is multiplied by a droop gain (\( n_1 \)). In addition, by a discrete-time integrator, the reactive power (\( Q_q \) or \( Q_d \)) of each DGS unit is also finally equal to an average reactive power (\( Q_{avg \_qd} \)) in steady-state time. In order that the amplitude of the reference load voltage is generated, the nominal load voltage (\( V_{nom} (480 \times \sqrt{2}) \)) is also added to the results by the droop gains of the average reactive power (\( Q_{avg \_qd} \)) and the reactive power (\( Q_q \) or \( Q_d \)).
From Fig. 5 and 6 above, the phase angle and voltage amplitude of the reference load voltage are obtained from the following equations:

**Q-Axis**

**Phase angle:**
\[ \phi_q(k + 1) = \phi_q(k) + m_2 (P_q - P_{avg,q}) \]
\[ \Delta \theta_q(k) = \phi_q(k) + m_1 (P_q - P_{0,q}) \]
\[ \theta_q(k) = \theta_{ref}(k) + \Delta \theta_q(k) \]

**Amplitude:**
\[ V_q(k + 1) = V_q(k) + n_2 (Q_q - Q_{avg}) \]
\[ \Delta V_q(k) = V_q(k) + n_1 (Q_q - Q_{0,q}) \]
\[ V_{max,q}(k) = V_{nom} + \Delta V_q(k) \]

**Voltage Reference:**
\[ V_{ref,q}(k) = V_{max,q} \cdot \sin(\theta_q(k)) \]

**D-Axis**

**Phase angle:**
\[ \phi_d(k + 1) = \phi_d(k) + m_2 (P_d - P_{avg,d}) \]
\[ \Delta \theta_d(k) = \phi_d(k) + m_1 (P_d - P_{0,d}) \]
\[ \theta_d(k) = \theta_{ref}(k) + \Delta \theta_d(k) \]

**Amplitude:**
\[ V_d(k + 1) = V_d(k) + n_2 (Q_d - Q_{avg,d}) \]
\[ \Delta V_d(k) = V_d(k) + n_1 (Q_d - Q_{0,d}) \]
\[ V_{max,d}(k) = V_{nom} + \Delta V_d(k) \]

**Voltage Reference:**
\[ V_{ref,d}(k) = V_{max,d} \cdot \sin(\theta_d(k)) \]

where, \( m_1 \) and \( n_1 \): droop gain for real power and reactive power, respectively; \( m_2, n_2 \): error gain between average real power \( (P_{avg,q}) \) and real power \( (P_q) \) of each unit, average reactive power \( (Q_{avg,q}) \) and reactive power \( (Q_q) \) of each unit, respectively; \( P_{0,q}, Q_{0,q} \): real and reactive power rating of each unit, respectively; \( V_{nom}, f_{nom} \): nominal voltage amplitude \((480\cdot\sqrt{2} \text{ V})\), nominal frequency \((60 \text{ Hz})\), respectively \( \theta_{ref} \): \( 2\cdot\pi \cdot f_{nom} \cdot t \).

**B. Harmonic Sharing Control Loop**

The above combined droop method and average power control method does not guarantee the harmonic components of the load current to share because it affects only the phase and magnitude of the fundamental output voltage. A means is required to share the harmonic components of the load currents based on its harmonic contents. The control gains affecting the harmonics in the voltage controller designed in [28] can be adjusted based on the harmonic contents of the load current at that harmonic frequency. For example, the pole frequencies of the harmonic compensator can be shifted by the harmonic contents of the load current at those frequencies. This is illustrated in Fig. 7, where \( I_3, I_5, \) and \( I_7 \) denote the harmonic load currents at third, fifth, and seventh harmonics respectively, and \( \omega_3, \omega_5, \omega_7 \) are the third, fifth, and seventh harmonic frequencies of the harmonic compensator poles. First of all, the harmonic droop loop added has the advantage that it does not degrade the fundamental component; it only affects the individual harmonic when it exists.

The \( \omega_3, \omega_5, \) and \( \omega_7 \) are computed from the harmonic droop control in Fig. 7:
\[ \omega_3 = \omega_{0} \cdot m_3 I_3, \omega_3 = 2\pi \cdot 3\cdot 60, \]
\[ \omega_5 = \omega_{0} \cdot m_5 I_5, \omega_5 = 2\pi \cdot 5\cdot 60 \]
\[ \omega_7 = \omega_{0} \cdot m_7 I_7, \omega_7 = 2\pi \cdot 7\cdot 60 \]

The resulting voltage controller developed in [28] with the harmonic drooping control added is shown in Fig. 8.

**V. SIMULATION RESULTS**

Simulations were performed using Matlab/Simulink v6.1 with Power System Block-set (PSB). For speed of simulations, the PWM Bridge IGBT inverter has been modeled as an ideal voltage controlled source with a delay of half the sampling time of the actual PWM signal. Fig. 9 shows Simulink block diagrams for the simulated distributed generation systems. This model is composed of two DGS units, two loads, wire impedances (\( Z_1 \) and \( Z_2 \)), and tie-line impedance. Two linear transformers are used for the isolation transformers, and a series inductance and resistance representing the leakage impedance and losses of each transformer are respectively 3 % p.u. The series inductance and resistance of the transformers are denoted as \( L_T \) and \( R_T \) respectively. The powers information is exchanged between units every 0.5 second.

The nominal values of the circuit components for simulations are as follows:

**Rated Output Power of Each DGS System = 600 kVA**
**AC Load Voltage = 480 V (RMS)**
**\( \Delta Y \) transformer = 600 kVA, 980 V/480 V, 60 Hz**
**\( V_{DC} = 2200 \text{ V AC, PWM Frequency = 5.4 kHz} \)**
**\( T_s \) (Sampling Period) = 185 \mu\text{sec}, T_d \text{ (Delay Time) =} \frac{T_s}{2}**
**\( L_T = 5 \mu\text{H, } C_I = 300 \mu\text{F, } L_f = 31 \mu\text{H, } R_f = 0.0115 \Omega, \text{ } C_L = 90 \mu\text{F} \)**
As explained in previous section, each PWM inverter’s output voltage and current are controlled using dual loop control system, with outer loop (RSC) controlling the output voltage and the inner loop (DSMC) controlling the inverter current.

The droop coefficients are given as follows:
\[
\begin{align*}
m_1 &= -2e-6 \text{ rad}/\text{wat} \\
m_2 &= -10e-6 \text{ rad}/\text{wat} \\
n_1 &= -2e-4 \text{ V}/\text{var} \\
n_2 &= -20e-4 \text{ V}/\text{var} \\
m_3 &= m_5 = m_7 = -2e-2
\end{align*}
\]

In this study, the two PWM inverters are assumed to have identical characteristics i.e. they have matched circuit components equal to their nominal values. To verify the performance of the proposed droop method for load-sharing control, tie-line impedance, wire impedances mismatches and voltage/current sensor measurement error mismatches are considered in this simulation.

The following cases are simulated:

**All Cases:**

- **Unit 1:** \( Z_1 = R_1 + jX_1 \) (\( R_1 = 0.01\Omega \)/\( L_1 = 0.5 \text{ mH} \))

  - Voltage measurement error: \( V_p \) [\(+0.1\%, -0.1\%, +0.1\%\)], \( V_L \) [\(+0.1\%, -0.1\%, -0.1\%\)]
  - Current measurement error: \( I_i \) [\(+0.1\%, +0.1\%, -0.1\%\)], \( I_L \) [\(+0.1\%, -0.1\%, -0.1\%\)]

- **Unit 2:** \( Z_2 = R_2 + jX_2 \) (\( R_2 = 0.02\Omega \)/\( L_2 = 1 \text{ mH} \))

  - Voltage measurement error: \( V_p \) [\(+0.1\%, +0.1\%, -0.1\%\)], \( V_L \) [\(+0.1\%, -0.1\%, +0.1\%\)]

  - Current measurement error: \( I_i \) [\(+0.1\%, -0.1\%, +0.1\%\)], \( I_L \) [\(+0.1\%, -0.1\%, +0.1\%\)]

  - Zt = Rt + jXt (\( R_t = 0.02\Omega \)/\( L_t = 1 \text{ mH} \))

**Case 1:**

- Power Ratings of DGS unit 1 and 2: 600 kVA, respectively

  - Load 1: \( P_{load1} = 480 \text{ kW} / Q_{load1} = 360 \text{ kVar} \) (p.f = 0.8)
  - Load 2: \( P_{load2} = 480 \text{ kW} / Q_{load2} = 360 \text{ kVar} \) (p.f = 0.8)

**Case 2:**

- Power Ratings of UPS unit 1 and 2: 600 kVA, 500 kVA, respectively

  - Load 1: \( P_{load1} = 400 \text{ kW} / Q_{load1} = 300 \text{ kVar} \) (p.f = 0.8)
  - Load 2: \( P_{load2} = 480 \text{ kW} / Q_{load2} = 360 \text{ kVar} \) (p.f = 0.8)

**Case 3:**

- Power Ratings of UPS unit 1 and 2: 600 kVA, respectively

  - Load 1: \( P_{load1} = 480 \text{ kW} / Q_{load1} = 360 \text{ kVar} \) (p.f = 0.8)
  - Load 2: \( P_{load2} = 240 \text{ kW} \Rightarrow 480 \text{ kW} \) (after 1.6 sec)

  - \( Q_{load2} = 180 \text{ kVar} \Rightarrow 360 \text{ kVar} \)

All cases are assumed that \( Z_2 \) is twice of \( Z_1 \), the signs of voltage/current sensor errors of unit 1 are opposite to those of unit 2. In Case 1, power rating and load of unit 1 are equal to those of unit 2. Case 2 is supposed that power ratings and loads of two DGS units are different, unlike Case 1. Case 3 is assumed that load 2 becomes twice after 1.6 seconds. Finally, Case 4 is simulated under non-linear loads with three-phase bridge diode. In these simulations, the first three cases (Fig. 10 to Fig. 12) were done for linear loads, while the last case was simulated under nonlinear loads.

Fig. 10 shows very good load-sharing of the real and the reactive powers under the conditions that both units and loads are identical. Fig. 11 shows the results under different power ratings and loads, and these results also show that the loads are properly shared according to the power capability of each unit. As shown in Fig. 12, even when the load 2 is increased suddenly to twice its value after 1.6 seconds, the results definitely show so good a
power sharing. Two nonlinear loads that consist of a three-phase bridge, a large capacitor, and a small resistor are implemented, and the results are also given in Fig. 13.

VI. CONCLUSIONS

This paper has described a new droop control method that can properly control the load-sharing such as the real, reactive, and harmonic powers for parallel operation of distributed generation systems in a standalone AC power system [16 - 22]. The proposed scheme is implemented by combined droop method, average power control method, and harmonic sharing control loop using power information exchange between each DGS unit. In particular, the average power control method can significantly reduce the sensitivity about voltage and current measurement errors, and the harmonic control loop is also added to guarantee harmonic power sharing under nonlinear loads. With reference to the above simulation results (Fig. 10 to Fig. 13), it is shown that the proposed control method is very effective for each DGS to properly share the loads such as the real, reactive, harmonic powers in standalone AC power system.

VII. REFERENCES


VIII. BIOGRAPHIES

Mohammad N. Marwali see Part I.

Jin W. Jung:

Ali Keyhani: see Part I.
Fig. 10 Simulation Results for Case 1

(a) Load currents (V_{11} and V_{12})
(b) Real Powers (P_1 and P_2)
(c) Reactive Powers (Q_1 and Q_2)

Fig. 11 Simulation Results for Case 2

(a) Load currents (V_{11} and V_{12})
(b) Real Powers (P_1 and P_2)
(c) Reactive Powers (Q_1 and Q_2)

Fig. 12 Simulation Results for Case 3

(a) Load currents (V_{11} and V_{12})
(b) Real Powers (P_1 and P_2)
(c) Reactive Powers (Q_1 and Q_2)

Fig. 13 Simulation Results for Case 4

(a) Load currents (V_{11} and V_{12})
(b) Real Powers (P_1 and P_2)
(c) Reactive Powers (Q_1 and Q_2)