Different Power Sharing Techniques for Converter-Interfaced DERs in an Autonomous Microgrid

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***Abstract*—This paper discusses three different techniques which can be used for power sharing control and adjustment among parallel converter-interfaced distributed energy resources in an autonomous microgrid. This ratio is decided by the distribution network tertiary controller and passed by the microgrid central controller to the primary controllers of each energy resource. In this paper limitations of the first two methods are discussed in detail and the proposed (third) method is designed such that it overcomes the limitations of the other two methods. The studies and discussions are validated for an autonomous microgrid under consideration through PSCAD/EMTDC-based simulations studies.**

***Index Terms*—Microgrid, Distributed Energy Resource (DER), Power Sharing.**

I. Introduction

It is expected that in near future, the modern power systems utilize distributed energy resources (DER) as an alternative to the expansion of the current electricity distribution networks [1-2]. Microgrids (MG) are systems with clusters of DERs and loads. To deliver high quality and reliable power, the MG should appear as a single controllable unit that responds to changes in the system [3]. In MGs, DERs are connected to the network through coupling inductances and are controlled to deliver the desired active and reactive power to the system. General introduction on MG basics, including the architecture, protection and power management is given in [4-5]. A review of ongoing research projects on MG in US, Canada, Europe and Japan is presented in [5-6]. Different power management strategies and controlling algorithms for a MG are proposed in [7-10]. Reference [11] has evaluated the feasibility of MGs operation during islanding and synchronisation periods.

A three-level hierarchical control architecture can be identified for MG control as presented in [6]. The distribution network tertiary controller analyses the data such as load/ weather forecast, electricity market and economic dispatch to define the references for the output power of each DER within the MG. These references are communicated to the MG secondary (central) controller which passes this information to the primary level controllers. The primary controllers are within each DER and are responsible for controlling the DER outputs based on the references received from the central controller. Hence, the required output of a DER can vary from zero to its maximum capacity based on the commands of the tertiary controller.

The power sharing among the DERs can be achieved by controlling two independent quantities, frequency and fundamental voltage magnitude, of the DERs based on droop control [12-15]. To realize a power ratio among the DERs, droop controller coefficients need to be designed properly [14]. This paper discusses three different techniques that can be used for power sharing adjustment among the DERs. The first method, used by majority of the researches is based on designing the coupling inductances between the DERs and the network such that their ratio becomes reciprocal to the desired ratio of the output powers of the DERs. The main disadvantage of this method is that the output power ratio is predefined and cannot be modified dynamically. The second method, proposed in [16], is controlling the output active power among the DERs solely by adjusting the droop control coefficients. By this method, any desired output active power ratio can be achieved among the DERs irrespective of the ratio of their coupling inductances. However, the main limitation of this method is that there is no control over the reactive power output ratio among the DERs.

In this paper, a different technique is been proposed to adjust both the output active and reactive power of the DERs, irrespective of their coupling inductances. In this method, the converter of each DER is controlled such that it imposes a small internal inductance, referred to as balancing inductance, into the DER system. The main advantage of this method is that it can be dynamically adjusted. Through extensive simulation results carried out by PSCAD/EMTDC, it is demonstrated that the output power ratio among the available DERs in an autonomous MG can be controlled however their coupling inductances are not reciprocal.

II. Microgrid Structure and Control

Let us consider the fundamental MG structure as shown in Fig. 1. The considered MG system consists of two converter-interfaced DERs. DERs such as photovoltaic cells (PV), fuel cells and batteries are usually connected to the MG through voltage source converters (VSC) and a properly tuned filter. For simplicity, in this paper, each DER along with its VSC and filter structure is simply called DER system, as shown in Fig. 2. DER systems are connected through coupling induc-

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tances (L_T) to the feeder and are controlled to supply the load requirements within the MG. Although the loads can be distributed throughout the MG, a centralized load is shown in Fig. 1. It is to be noted that the considered DER systems in this paper are working in voltage control mode and their instantaneous output power, are within their maximum capacities.

A. MG Hierarchical Control System

For proper operation of a MG within a distribution network, a three-level hierarchical control system is presented and discussed in [6], as shown in Fig. 1. This hierarchical control system constitutes of the primary controllers of each DER system, the central controller of the MG and the tertiary controller of the electric network.

The primary controller is responsible for appropriate switchings in the converters of the DERs such that the desired output power is observed at the output of the DER converters. This controller is composed of two control loops– the outer-loop control which is responsible for proper output power control of DERs in the MG and the inner-loop control which is responsible for proper tracking of the generated references (by the outer-loop control) at the output of the DER converters. The primary control of the DERs, based on voltage-control strategy, is presented in [6].

The secondary controller is the central controller of the MG. This controller sends the desired (reference) output power to each DER in the system. In grid-connected mode, the desired output power of each DER converter is received from the tertiary controller. However, in autonomous mode, this controller sends reference signals to DER converters in the form of voltage magnitude and angle, based on monitoring the network voltage and frequency, whenever required. This controller runs in a slower time frame compared to that of the primary control [17].

The tertiary controller communicates with the central controllers in the MG. In general, this controller can utilize load/weather forecast, electricity market, economic dispatch and unit commitment information for optimal power flow of the network and MGs [18].

The main focus of this paper is the power sharing adjustment techniques among the DERs. This is achieved by modifying the primary control level of the DERs based on the settings that are defined by the secondary controller.

B. DER Converter Structure

The DERs are assumed to be connected to the MG through VSCs. The VSC structure consists of three single-phase H-bridges, using Insulated Gate Bipolar Transistors (IGBT), as shown in Fig. 2. Each IGBT has anti-parallel diode and snubber circuits. The outputs of each H-bridge are connected to a single-phase transformer, with 1 : a ratio, and three secondary windings of the transformers are star-connected. These transformers provide galvanic isolation as well as voltage boosting capability if required. As the converters are desired to be voltage-controlled, an LC filter is utilized for each phase at the outputs of the converter.

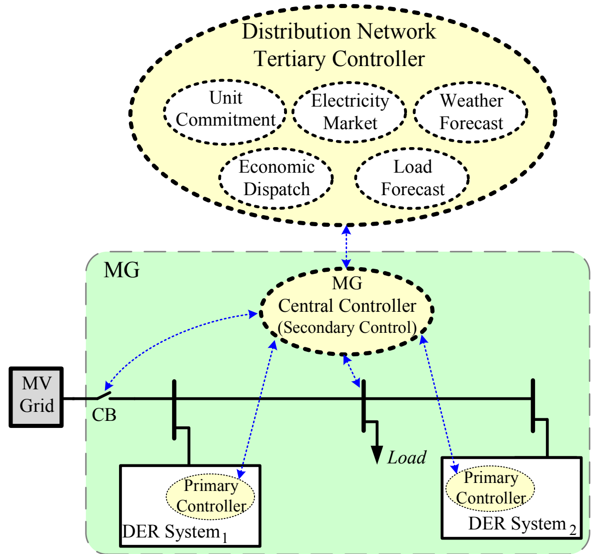

Fig. 1. Schematic diagram of the MG network under consideration along with its hierarchical control system.

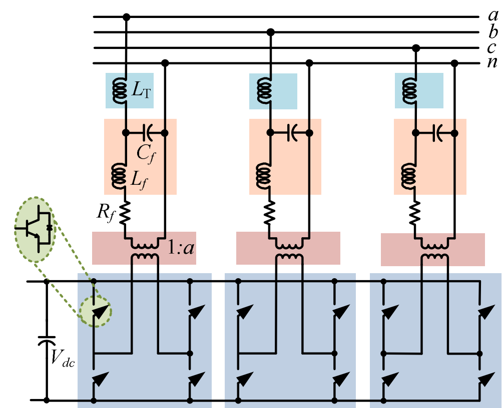

Fig. 2. VSC and filter structure schematic for the DER system.

In this figure, the resistance R_f represents the switching and transformer core losses. The filter inductance L_f and the filter capacitor C_f are designed to suppress the switching harmonics from the current and voltages.

C. Droop Control

The active power (p) and reactive power (q) supplied by the DER systems to the MG through the coupling inductance (L_T) are given by

$$s = p + jq = \left|V_j\right| \left(\frac{\left|V_i\right| \angle \delta_i - \left|V_j\right| \angle \delta_j}{\omega L_T} \right)^* \quad (1)$$

where $|V_i|$ and $|V_j|$ are the magnitude of the voltage of respectively the MG side and filter side at the two terminals of the coupling inductance (L_T), and δ_i and δ_j are the angle of the voltage at these two terminals, respectively. The average active power (P) and reactive power (Q) can then be calculated by passing p and q through low pass filters.

In autonomous mode, it is assumed that the frequency of the MG reduces by $\Delta\omega$, as the output active power of the

DER system increases from zero to the rated value (P_{rated}). The slop of this variation is referred to as m and calculated as

$$m = \frac{\Delta\omega}{P_{\text{rated}}} = \frac{2\pi\Delta f}{P_{\text{rated}}} \tag{2}$$

Assuming for two DERs with different ratings, $\Delta\omega$ is constant (i.e. $\Delta\omega_1 = \Delta\omega_2$), the ratio of P-f droop coefficient between the two DER systems is

$$m_1 P_{\text{rated},1} = m_2 P_{\text{rated},2} \;\Rightarrow\; \frac{m_1}{m_2} = \frac{P_{\text{rated},2}}{P_{\text{rated},1}} \tag{3}$$

Similarly, it is assumed that the voltage of the MG reduces by ΔV, when the output reactive power of the DER system increases from zero to the rated value (Q_{rated}). The slop of this variation is referred to as n and is calculated from

$$n = \frac{\Delta V}{Q_{\text{rated}}} \tag{4}$$

Assuming for two DERs with different ratings, ΔV is constant (i.e. $\Delta V_1 = \Delta V_2$), the ratio of Q-V droop coefficient between two DER systems is

$$n_1 Q_{\text{rated},1} = n_2 Q_{\text{rated},2} \;\Rightarrow\; \frac{n_1}{n_2} = \frac{Q_{\text{rated},2}}{Q_{\text{rated},1}} \tag{5}$$

Decentralized power sharing among two DER systems in the MG can be achieved by changing the voltage magnitude and angle of DER systems using the droop control. This can be expressed for DER-j as

$$\begin{aligned} f_j &= f_{\text{rated}} + m\left[\frac{X_{\text{line}}}{Z_{\text{line}}}(P_{\text{rated}} - P) - \frac{R_{\text{line}}}{Z_{\text{line}}}(Q_{\text{rated}} - Q)\right] \\ |V_j| &= V_{\text{rated}} + n\left[\frac{R_{\text{line}}}{Z_{\text{line}}}(P_{\text{rated}} - P) + \frac{X_{\text{line}}}{Z_{\text{line}}}(Q_{\text{rated}} - Q)\right] \end{aligned} \tag{6}$$

where $Z_{line}=R_{line}+jX_{line}$ is the equivalent impedance of the MG feeder between the DER and the load. If the MG feeder lines are assumed to have a higher $X_{\text{line}}/R_{\text{line}}$ ratio, the active and reactive powers are assumed to be decoupled. Hence, (6) is simplified further as

$$\begin{aligned} f_j &= f_{\text{rated}} + m(P_{\text{rated}} - P) \\ |V_j| &= V_{\text{rated}} + n(Q_{\text{rated}} - Q) \end{aligned} \tag{7}$$

For two DER systems, V_{rated} and δ_{rated} are the same for both of the DER systems while m, n, P_{rated} and Q_{rated} are as described in (2)-(4). Hence, the average output active and reactive power among two DERs can be expressed as

$$\frac{P_1}{P_2} = \frac{m_2}{m_1} \quad , \quad \frac{Q_1}{Q_2} = \frac{n_2}{n_1} \tag{8}$$

Now, let us consider the MG network of Fig. 1 with 2 DERs supplying a common load. DER-1 has a coupling inductance of $L_{\text{T},1}$ at its output while DER-2 has a coupling inductance of $L_{\text{T},2}$. DER-1 is connected to the load through a feeder impedance of $jX_{line,1}$ where DER-2 is connected to the load through a feeder impedance of $jX_{line,2}$. Assuming the voltage at load PCC is V_{load}, the active and reactive power supplied from each DER to the load can be expressed from (1) as

$$\begin{aligned} p_1 &= \frac{|V_{load}||V_1|\sin\delta_1}{\omega L_{\text{T},1} + \omega L_{\text{line},1}} \\ p_2 &= \frac{|V_{load}||V_2|\sin\delta_2}{\omega L_{\text{T},2} + \omega L_{\text{line},2}} \end{aligned} \tag{9}$$

where $|V_1|$ and $|V_2|$ are respectively the voltage magnitude at the output of DER-1 and DER-2 and δ_1 is the voltage angle difference between the output of DER-1 and the load while δ_2 is the voltage angle difference between the output of DER-2 and the load.

Since usually $X_{line} << \omega L_{\text{T}}$, the active/reactive power delivered from the DER system to the load is highly dependent on the coupling inductance at the output of the DER system and is not affected by the MG line reactance. Hence, (9) can be simplified as

$$\begin{aligned} p_1 &\approx \frac{|V_{load}||V_1|\sin\delta_1}{\omega L_{\text{T},1}} \\ p_2 &\approx \frac{|V_{load}||V_2|\sin\delta_2}{\omega L_{\text{T},2}} \end{aligned} \tag{10}$$

III. Power Sharing Control Methods

Below three different methods are discussed which can be used to control the output power among parallel converter-interfaced DERs in an autonomous MG.

A. Method-1

From (10), the ratio of the average active/reactive power between these two DER systems can be given as

$$\begin{aligned} \frac{P_1}{P_2} &= \frac{L_{\text{T},2}}{L_{\text{T},1}} \frac{|V_1|\sin\delta_1}{|V_2|\sin\delta_2} \\ \frac{Q_1}{Q_2} &= \frac{L_{\text{T},2}}{L_{\text{T},1}} \frac{|V_1|\cos\delta_1 - |V_3|}{|V_2|\cos\delta_2 - |V_3|} \end{aligned} \tag{11}$$

In many references such as [3,10], for simplicity, it is assumed that the output active/reactive power ratio among two DERs is reciprocal to their coupling inductances as

$$\frac{P_1}{P_2} = \frac{L_{\text{T},2}}{L_{\text{T},1}} = \frac{m_2}{m_1} \quad , \quad \frac{Q_1}{Q_2} = \frac{L_{\text{T},2}}{L_{\text{T},1}} = \frac{n_2}{n_1} \tag{12}$$

In other words, a DER with a greater output power should have a smaller coupling inductance and vice versa. To achieve (12), the following equations must be satisfied:

$$\begin{aligned} |V_1|\sin\delta_1 &= |V_2|\sin\delta_2 \\ |V_1|\cos\delta_1 &= |V_2|\cos\delta_2 \end{aligned} \tag{13}$$

This is the simplest technique for satisfying a desired output power ratio among parallel connected DERs in a MG. The technique reassures a desired ratio among both active and reactive powers. However, the main limitation of this technique is that the output power ratio among the DERs is locked by the ratio of the coupling inductances and cannot be adjusted or modified dynamically.

It is to be noted that it is desired that the voltage angle difference on two sides of the coupling inductance (i.e. δ_{ij}) to be a small value so that it is on the linear section of sinusoidal P-δ characteristic of (1). Similarly, it is desired that the voltage drop across the coupling inductance (i.e. $|V_1| - |V_{load}|$) to be small (i.e. 1-2 %).

B. Method-2

In general, it can be assumed that coupling inductances of the two DER systems can have a ratio of k where $k > 0$ and not equal to the ratio of the output active/reactive power.

To achieve a desired output active power ratio among the DERs in this method, the settings of P_{ref} and m need to be adjusted properly for one DER with respect to the second DER. In [16], it is shown that by changing P_{rated} to $P_{\text{rated,new}}$, Q_{rated} to $Q_{\text{rated,new}}$, m to m_{new} and n to n_{new} for one DER while keeping the P_{rated}, Q_{rated}, m and n for the other DER fixed, the ratio of the output active power among the two DERs can be adjusted. This is shown schematically in Fig. 3.

In such a case, we have

$$\begin{cases} \dfrac{P_1}{P_2} = k_p \\ \dfrac{L_{T,2}}{L_{T,1}} = k \end{cases} \Rightarrow \; |V_1|\sin\delta_1 = \frac{k_p}{k}|V_2|\sin\delta_2 = k'|V_2|\sin\delta_2 \qquad (14)$$

where $k' = k_p/k$. From (14), it can be seen that under such condition, the voltages at the outputs of both of the DER systems are correlated by a factor of k'. It is to be noted that under such condition, the ratio among the reactive powers of the two DER systems will be as

$$\begin{cases} \dfrac{Q_1}{Q_2} = k_q \\ \dfrac{L_{T,2}}{L_{T,1}} = k \end{cases} \Rightarrow \; |V_1|\cos\delta_1 - |V_3| = \frac{k_q}{k}\left(|V_2|\cos\delta_2 - |V_3|\right) \qquad (15)$$

Hence, from (14) and (15), it can be seen that in general $k_p \neq k_q$. Therefore, the output active power of the two DER systems can be controlled to be equal to the desired value of k_p while the ratio of the reactive power outputs among these two DER systems will not be equal to k_p. In [16], a detailed analysis is represented to show the limits of k_p and k_q.

It can be summarized that by using method-2, irrespective of the ratio of the coupling inductances for the two DERs, their output active power ratio can be varied dynamically. This is achieved by dynamically adjusting the settings of the droop control (P_{ref}, Q_{ref}, m and n). However, the output reactive power ratio of the two DERs will not match the ratio of the output active power.

C. Method-3

The main drawback of Method-2 is that the ratio of the output reactive power of the two DERs is not equal to the ratio of the output active power among them. This is mainly

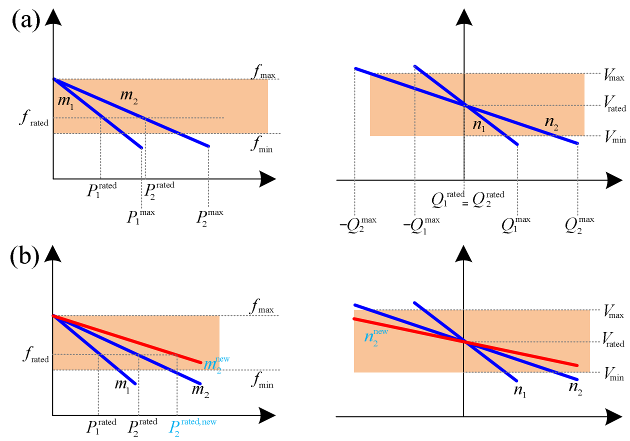

Fig. 3. (a) P-f and Q-V droop curves for two DERs, (b) Dynamic droop curve settings adjustment to provide dynamic power ratio change using Method-2.

due to the mismatch of coupling inductances ratio. This issue can be properly addressed if two balancing inductances are imposed to the DER systems to ensure that the total equivalent inductances match with the ratio of the desired output active/reactive power.

The balancing inductance will be imposed to the system by the modified control of the VSCs. After the balancing inductance is imposed to the DER systems, the voltage appearing at the output of each VSC will be slightly lower than the original value. The main objective of Method-3 is to define the voltage drop across this balancing inductance such that a desired active/reactive power ratio is achieved at the output of the DER systems, irrespective of the coupling inductance ratio. For this, it is desired to define a balancing inductance (L_{BI}) such that we have

$$\frac{P_1}{P_2} = \frac{L_{T,2} + L_{\text{BI},2}}{L_{T,1} + L_{\text{BI},1}} = \frac{m_2}{m_1}, \qquad \frac{Q_1}{Q_2} = \frac{L_{T,2} + L_{\text{BI},2}}{L_{T,1} + L_{\text{BI},1}} = \frac{n_2}{n_1}. \qquad (16)$$

Assuming $L_{\text{T},2}+L_{\text{BI},2} > L_{\text{T},1}+L_{\text{BI},1}$, it is easier to allocate a very small value for $L_{\text{BI},1}$ and define $L_{\text{BI},2}$ such that (16) is satisfied. It is to be noted that the defined values should not cause instability for the system.

For each DER system, let us assume that the phase voltage at the output of the VSC after imposing the balancing inductance (v_{ref}) is calculated from

$$v_{\text{ref}} = v_{\text{droop}} - v_{\text{BI}} \qquad (17)$$

where $v_{\text{droop}} = |V_{\text{droop}}|\angle\,\delta_{\text{droop}}$ is the original droop voltage defined by the secondary controller and v_{BI} is the voltage drop across the balancing inductance (BI). Eq. (17) can be expressed in $\alpha\beta$ coordinates as

$$\begin{aligned} |V_{\text{ref}-\alpha}| &= |V_{\text{droop}}|\cos\delta_{\text{droop}} + \omega L_{\text{BI}}\,|I|\sin\theta \\ |V_{\text{ref}-\beta}| &= |V_{\text{droop}}|\sin\delta_{\text{droop}} - \omega L_{\text{BI}}\,|I|\cos\theta \end{aligned} \qquad (18)$$

where L_{BI} is the imposed balancing inductance and $|I|\angle\theta$ is the phase-a current of the coupling inductance. Converting (18) into polar coordination, the reference voltage for the VSC output is calculated as

$$V_{\text{ref}} = \sqrt{|V_{\text{ref}-\alpha}|^2 + |V_{\text{ref}-\beta}|^2} \angle \tan^{-1} \frac{|V_{\text{ref}-\beta}|}{|V_{\text{ref}-\alpha}|} \tag{19}$$

This value will be used as the new voltage reference for phase-a of each VSC to track and generate at their output. Note that the same voltage with ± 120° will be applied for phase-b and c of each VSC. If both DERs reduce their VSC output voltage based on (19), a desired active/reactive power will be achieved among the DERs.

IV. Study Cases and Simulation Results

To investigate the performance of the proposed MG central controller, the MG system of Fig. 1(a) with 2 DERs (i.e. DER-1 and DER-2) is simulated in PSCAD/EMTDC. The parameters of network, DER converters and filters, coupling inductances, loads and the droop control coefficients are given in the Appendix. Several case studies are built; among which a few are discussed below.

Case-1: Method-1 results

It is assumed that the MG system is initially in steady-state and autonomous condition, with a total active load demand of approximately 0.88 pu where 1 pu is 5.8 kVA. The load is assumed to be a constant impedance load with a power factor of 0.7 lagging. At t = 1.5 s, this load is decreased to 0.77 pu and at t = 3 s, the network load is increased to 0.91 pu. The network active and reactive power demand is shown in Fig. 4(a).

The desired output active/reactive power ratio among DER-1 and 2 is $P_1/P_2 = Q_1/Q_2 = 2$ which is defined by the ratio of the coupling inductances as $L_{T,1}/L_{T,2} = 0.5$. In addition the droop control coefficients are designed to match this ratio as $m_1/m_2 = n_1/n_2 = 0.5$. Hence, (12) is satisfied. Fig. 4(b)-(c) show that by the designed droop coefficients and coupling inductances, the output active and reactive power ratio among the two DERs is always kept equal to the desired value.

Case-2: Method-2 results

Now, let us consider the same network as in Case-1 in which the two DERs have equal coupling inductances. By adjusting the droop coefficients, it can be seen from Fig. 5(a) that the two DERs manage to keep their output active power ratio almost equal to the desired value of 2 for all load changes explained in Case-1. However, the ratio of their reactive power is 0.58 and not equal to the ratio of the active power (Fig. 5b), as discussed in Section III(B).

Case-3: Method-3 results

Now, let us consider the network of Case-2 in which the balancing inductance discussed in Section III(C) is applied to both DERs. Considering that coupling inductance of the two DERs are $L_{T,1} = L_{T,2}$ = 30 mH, the balancing inductance of DER-1 (which has higher output power) is assumed to be a small value of 0.5 mH. Now, from (16), the balancing inductance which should be imposed to DER-2 is equal to 31.4 mH. Fig. 6(a)-(b) verify the effectiveness of the discussed balancing inductance in achieving the desired ratio of active/reactive power among the two DERs.

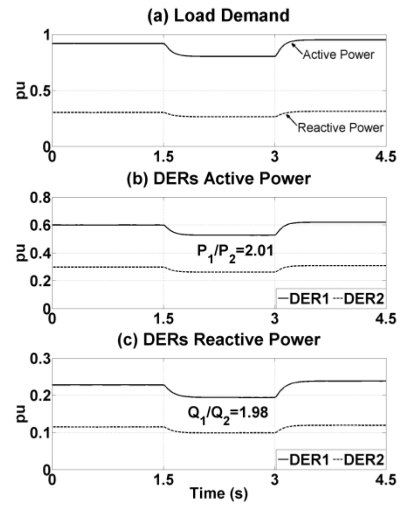

Fig. 4. Simulation results for Case-1.

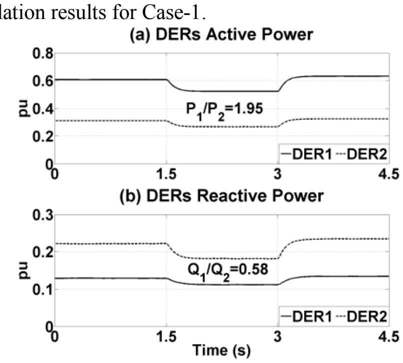

Fig. 5. Simulation results for Case-2.

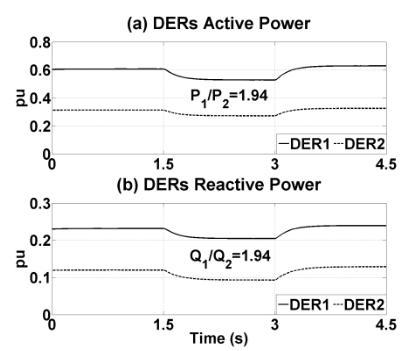

Fig. 6. Simulation results for Case-3.

V. Conclusion

Three different techniques are discussed in this paper for power sharing control and adjustment among parallel converter-interfaced DERs in an autonomous microgrid. The studies and discussions are validated through simulations in PSCAD/EMTDC. Method-1 reassures a desired output active/reactive power ratio among the DERs by designing a reciprocal ratio for the coupling inductances of the DERs. The main disadvantage of this method is that the ratio of the power depends to the ratio of the coupling inductances and cannot be change later. Method-2 overcomes this problem by modifying the settings for the droop control of one of the DERs versus the other. This method can satisfy a desired ratio of output active power among the DERs however the reactive power ratio can not be satisfied using this method.

Therefore, the second method can only be used if the active power ratio adjustment is desired. Method-3 can overcome the limitation of the other two methods by imposing a small voltage drop at the output of the converter of each DER. This small voltage drop needs to be calculated properly such that the new voltage at the converter output results in a desired output active/reactive power ratio among the DERs.

APPENDIX

Table I. Technical data of the network parameters of Fig. 1-2.

MV Network	220 Vrms L-L, 50 Hz
MV Line Impedance	R = 0.2 Ω, L =6.4 mH
VSCs and Filters for DER systems	R_f = 3 Ω, L_f= 0.7 mH, C_f = 50 μF, a = 3.67, V_{dc} = 90 V

Table II. Coupling inductances and droop control coefficients for DER-1,2 in simulation case studies.

DER	L_T [mH]			m [rad/kW]	n [V/kVAr]
	Case-1	Case-2	Case-3		
DER-1	30	30	30	3.1416	1.8
DER-2	60	30	30	1.5708	0.9

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