JPE 16-3-32

http://dx.doi.org/10.6113/JPE.2016.16.3.1152
ISSN(Print): 1598-2092 / ISSN(Online): 2093-4718

Improved Reactive Power Sharing for Parallel-operated Inverters in Islanded Microgrids

Walid Issa†, Suleiman Sharkh*, Tapas Mallick**, and Mohammad Abusara**

†, **Renewable Energy Research Group, University of Exeter, Penryn, England, UK
*Electro-Mechanical Engineering Research Group, University of Southampton, Southampton, England, UK

Abstract

The unequal impedances of the interconnecting cables between paralleled inverters in the island mode of microgrids cause inaccurate reactive power sharing when the traditional droop control is used. Many studies in the literature adopt low speed communications between the inverters and the central control unit to overcome this problem. However, the losses of this communication link can be very detrimental to the performance of the controller. This paper proposes an improved reactive power-sharing control method. It employs infrequent measurements of the voltage at the point of common coupling (PCC) to estimate the output impedance between the inverters and the PCC and then readjust the voltage droop controller gains accordingly. The controller then reverts to being a traditional droop controller using the newly calculated gains. This increases the immunity of the controller against any losses in the communication links between the central control unit and the inverters. The capability of the proposed control method has been demonstrated by simulation and experimental results using a laboratory scale microgrid.

Key words: Communication loss, Droop control, Islanded inverters, Microgrids, Reactive power sharing.

I. INTRODUCTION

AC microgrids are aggregated systems of many distributed generation (DG) units, energy storage systems and local loads. They can operate either in the island mode or in the grid-connected mode. This increases the redundancy and reliability of the overall power system. When integrating renewable energy sources (such as solar, wind and hydro), power electronics-based inverters are used to interface these sources to the AC microgrid as shown in Fig. 1. The microgrid central controller (MGCC) exchanges information with the sources and their power electronic inverters via a low speed communication channel. A significant concern for these parallel-operated inverters is the load sharing issue. Many techniques use communication-based methods [1]-[6] to accomplish accurate load sharing. However, these techniques need a high-bandwidth communications infrastructure between all of the inverters. This increases the cost and decreases both the reliability and plug and play ability. Therefore, droop control, which mimics the behavior of synchronous generators [7]-[12], has been introduced to enable inverters to operate in parallel without any communication mechanism. However, the traditional droop control is known for its poor performance in reactive power sharing. For a droop controller to share reactive power accurately, the parallel-operated inverters must have the same output impedance including the cable's impedance, and they must generate the same output voltage. However, this cannot be guaranteed in practice due to parameter tolerance in the inverters' LC output filters, different interconnecting cable lengths and inaccuracy in the output voltage control.

Many strategies have been proposed to enhance reactive power sharing. An algorithm has been proposed in [13], which is based on an additional control signal injection. This solution injects signals with different frequencies (90Hz, 130Hz) to send information about the shared power between the inverters through the same distribution lines. However, this can increase the control complexity and can cause current distortion. Chia et al. [14] proposed a method to compensate for the line impedance mismatches, where the reactive power is controlled in proportion to the voltage derivative. Although this method minimizes the reactive power sharing error, it does not achieve equal sharing. It also adds more complexity to the system. In [15] a centralized controller has been proposed to compensate for the voltage drop caused by the droop controller and line

Manuscript received Apr. 14, 2015; accepted Dec. 7, 2015
Recommended for publication by Associate Editor Il-Yop Chung.
†Corresponding Author: wi209@exeter.ac.uk
Tel: +44-7513703925, University of Exeter
*Electro-Mechanical Engineering Research Group, University of Southampton, UK
**Renewable Energy Research Group, University of Exeter, UK

impedances. However, this entire process is executed in the MGCC and all of the parameters are sent by a communication link. As a result, any loss of this link will lead to the traditional droop limitations.

Li et al. [16] proposed an online estimator of the voltage drop caused by the transmission lines which is then used to refine the droop control gain to give an accurate Q sharing in the island mode. However, this algorithm needs the inverters to operate in the grid-connected mode initially to obtain a proper estimation of the voltage. In addition, the controller's complexity increases with the presence of local loads, which affects the estimation process.

In [17], a novel controller that is robust against computational errors and component mismatches is proposed. The accuracy of the controller does not depend on the output impedance. It measures the load voltage continuously through a wired link and employs an integral controller to achieve accurate sharing of the reactive power. However, this system works accurately for local inverters that are near each other and the local load. If the load is far away or the distance between the inverters is large, a wireless link could be used. However, any loss in this communication link - even for a short period of time - might lead to instability due to the existence of the integral controller. Furthermore, the controller does not take into account the cables' impedances, which contribute to sharing inaccuracy if a local output voltage is fed back.

Jinwei et al. [18] proposed a synchronized algorithm for guiding all of the units to share reactive power accurately by incorporating the measured reactive power in the frequency droop equation. However, this intentionally disturbs the active power sharing accuracy. In addition, if the load changes after compensation, the accuracy of the sharing deteriorates and the algorithm needs to be executed again. The authors in [19, 20] proposed an online estimation technique for line impedance using the harmonics of the line current and the PCC voltage to regulate the virtual impedance and to enhance the reactive power sharing accuracy. However, in addition to increasing complexity, this scheme is dependent on the existence of significant harmonics, which assumes the existence of non-linear loads during the estimation period.

In this paper, a novel controller for improving reactive power sharing is proposed. It reduces the risk of communication loss so it has a negligible effect on the stability and sharing accuracy. The proposed algorithm employs infrequent measurements of the PCC voltage to estimate the output impedance between the inverters and the PCC, and it readjust the voltage droop controller gains accordingly. The controller then reverts to being a traditional droop controller using the newly calculated gains. Therefore, it does not need to measure the PCC voltage continuously. This increases its immunity to losses of the communication links between the central control unit and the inverters. The controller can maintain good accuracy in the presence of changes in the load

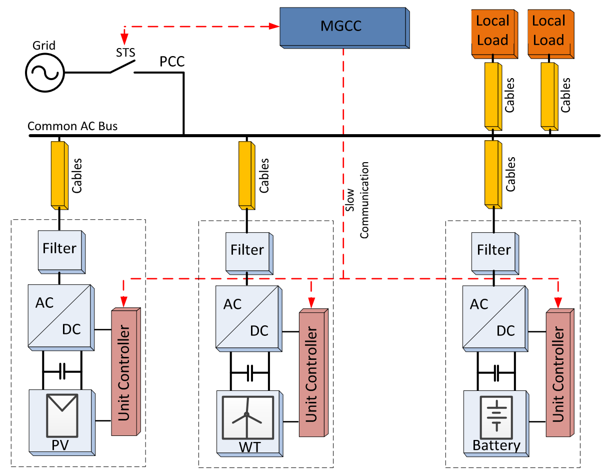


Fig. 1. General microgrid structure.

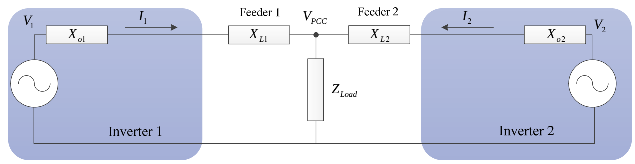


Fig. 2. Model of a simple islanded microgrid.

after the execution of the proposed algorithm. The capability of the proposed control method is demonstrated using simulation and experimental results obtained with a laboratory scale microgrid.

The paper is organized as follows: a small signal analysis of the reactive power sharing is discussed in section II; in sections III the proposed controller is presented; some simulation and experimental results are shown in sections IV and V, respectively; and finally some conclusions are given in section VI.

II. Reactive Power Flow in Islanded Microgrids

Fig. 2 shows a simple microgrid consisting of two inverters. Each inverter is modelled by a two-terminal Thevenin equivalent circuit where V and X_o represent the Thevenin voltage and impedance, respectively [21]. For a dominantly resistive output impedance, the P-V and Q-ω droop control is commonly used, while for an inductive output impedance, the P-ω and Q-V control is used [22]. In this paper, the output impedance is guaranteed to be inductive by using an inductive virtual impedance as described in [23]. As a result, the P-ω and Q-V droop control is employed. The two inverters are connected through different feeder impedances X_{L1} and X_{L2}. The traditional droop control equations for the inverter i are given by:

$$\omega_i = \omega^* - m_i P_i \tag{1}$$

$$V_i = V^* - n_i Q_i \tag{2}$$

where ω_i and V_i are the output frequency and voltage, ω^* and

V^* are the frequency and voltage set-points, m_i and n_i are the frequency and voltage droop gains, and P_i and Q_i are the active and reactive power, respectively.

A small signal deviation (denoted by '~') in the output voltage $\tilde{V}_i$ in (3) is given by:

$$\tilde{V}_i = -n_i \tilde{Q}_i \tag{3}$$

This means that a small deviation in V_i with respect to a small deviation in Q_i (around the equilibrium point) is a linear line with a slope of $-n_i$ and that the behavior of V_i is determined by:

$$V_i = V_{eq} + \tilde{V}_i \tag{4}$$

By choosing the equilibrium point V_{eq} to be V^*, the small signal expression is:

$$V_i = V^* - n_i \tilde{Q}_i \tag{5}$$

The current flow causes a voltage drop across X_o and X_L. Hence, the voltage at the point of common coupling V_{PCC} will be different from V_1 and V_2.

By defining the total impedance of the inverter i as $X_i = X_{oi} + X_{Li}$, the reactive power generated by the inverter i can be shown to be given by:

$$Q_i = \frac{V_i^2 - V_i V_{PCC} \cos\delta_i}{X_i} \tag{6}$$

where δ_i is the power angle between V_i and V_{PCC}. For a small power angle, $\cos\delta_i \approx 1$. Hence, the reactive power can be approximated as:

$$Q_i \approx \frac{V_i \Delta V_i}{X_i} \tag{7}$$

where:

$$\Delta V_i = V_i - V_{PCC} \tag{8}$$

A small change (denoted by '~') in the reactive power $\tilde{Q}_i$ due to a change in the voltage is given by:

$$\tilde{Q}_i \approx \frac{1}{X_i}\left(\Delta V_{eq} \cdot \tilde{V}_i + V_{eq} \cdot \Delta\tilde{V}_i\right) \tag{9}$$

where ΔV_{eq} and V_{eq} are the equilibrium voltage difference ΔV_i and inverter output voltage V_i, respectively, around which the small signal perturbation is performed. The symbol $\Delta\tilde{V}_i$ denotes a small change in ΔV_i. In other words $\Delta\tilde{V}_i = \tilde{V}_i - \tilde{V}_{pcc}$. Because $\Delta V_{eq} \ll V_{eq}$, and by choosing the equilibrium point $V_{eq} = V^*$, a small change in reactive power can be approximated by:

$$\tilde{Q}_i \approx \frac{V^*}{X_i} \Delta\tilde{V}_i \tag{10}$$

By deviating ΔV_i in (8), substituting it into (10) and rearranging, the inverter output voltage behavior around the equilibrium point can be expressed as:

$$V_i = V_{eq} + \tilde{V}_i = V^* + \tilde{V}_{PCC} + \frac{X_i}{V^*}\tilde{Q}_i \tag{11}$$

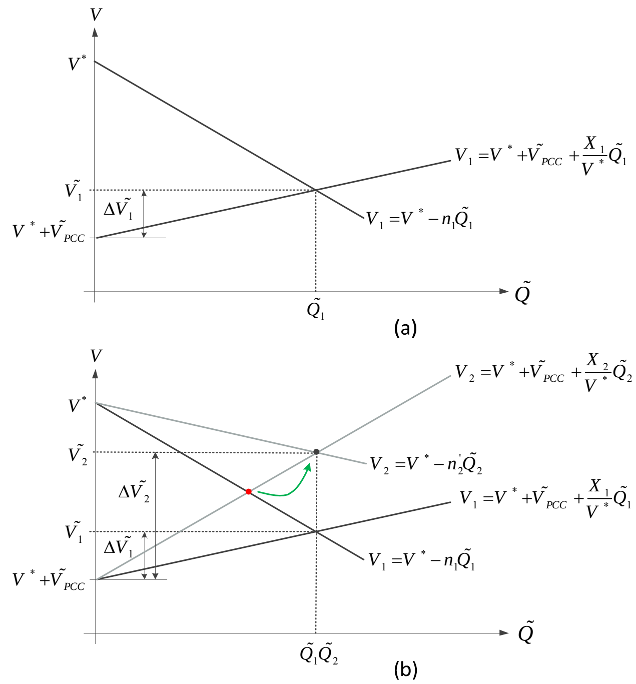


Fig. 3. Reactive power sharing affected by the voltage drop.

Both (5) and (11) define the relationship between V_i and $\tilde{Q}_i$ around the equilibrium. For inverter 1, Fig. 3(a) represents (5) and (11) graphically as two linear lines. The delivered reactive power is determined when the two lines intersect. If one inverter has a higher total impedance X_i, the slope X_i/V^* in (11) will be higher. In order to deliver the same reactive power as the other inverter, the voltage droop coefficient n_i (slope in (5)) needs to be reduced. This is illustrated in Fig. 3(b), where inverter 2 has a higher total impedance than inverter 1, $X_2 > X_1$. Therefore, for the two inverters to share the reactive power equally, the voltage droop coefficient of inverter 2 needs to be reduced accordingly.

By substituting (5) into (11) the following is obtained:

$$\tilde{Q}_i = \frac{-\tilde{V}_{PCC}}{n_i + X_i/V^*} \tag{12}$$

Hence, for the two inverters to share reactive power equally the following condition needs to be satisfied:

$$n_1 + X_1/V^* = n_2 + X_2/V^* \tag{13}$$

In order to have equal sharing of the reactive power, the droop gain n_i needs to be adjusted in proportion to $1/X_i$. Thus, inverters with a higher output impedance will have the voltage droop gains reduced. The new voltage droop gain n_i' is proposed to be calculated as:

$$n'_i = n_i \frac{X_{oi}}{X_i} \tag{14}$$

where X_{oi} is the nominal output impedance of the inverter. The output impedance X_i includes the inverter output impedance X_{oi} and the interconnecting cable impedances so that $X_i =$

$X_{oi} + X_{Li}$ (see Fig. 2). The impedance X_{oi} should be known for each inverter while the impedance X_i can be estimated as:

$$X_i = \frac{V^* . \Delta V_i}{Q_i} \tag{15}$$

To calculate the required value of X_i that is needed to scale the droop gain to finally improve the reactive power sharing, the value of X_i has to be calculated when all of the inverters share the reactive power adequately. Consequently, once an accurate reactive power sharing is obtained by using V_{PCC} [17] which is also used to calculate the voltage drop $\Delta V_i = V_i - V_{PCC}$, the output reactive power is measured and then the output impedance is estimated. Therefore, after the estimation process and retrieving the traditional droop controller with the new gain, it gives adequate sharing without V_{PCC}.

By readjusting the voltage droop gain according to (14), it can be guaranteed that the new droop gain is smaller than or equal to the original droop gain. This is quite important because if the droop gain is increased beyond the designed value, instability can occur [8]. Furthermore, the designer can add a limit on the droop gain range to ensure that the system stability has a higher priority than the reactive power sharing accuracy. It is worth mentioning that it is possible to measure the output impedance between the inverter and the PCC at the design stage, and to calculate the required droop gains. However, for an inverter within a microgrid, the impedances of the distribution cables and the other parallel inverters have a significant effect, which means that the output impedance will be variable, and a single gain value may not be sufficient.

III. Proposed Reactive Power Sharing Controller

The proposed controller scheme is shown in Fig. 4. It consists of two stages: in the first stage, the controller uses the PCC voltage to obtain accurate sharing between the inverters, to estimate X_i, and to calculate the new droop gain n_i'; in the second stage, the reactive power control uses the traditional voltage droop incorporating the new calculated droop gain n_i'. The two stages are explained below.

A. Stage 1

In this stage, the voltage drop $V^* - V_{PCC}$ is calculated and compared to ni*Qi, and the error signal is fed back to the controller through an integrator as proposed in [17] and shown in Fig. 4(a). The gain K_q is used to accelerate the transient response as required. In the steady state condition, the input to the integrator is zero which means that the reactive power is given by:

$$Q_i = \frac{K_q (V^* - V_{PCC})}{n_i} \tag{16}$$

If all of the inverters have the same n, the right hand side of (16) is the same in all of the inverters. Thus, equal sharing is achieved even if the output impedances are different. When the

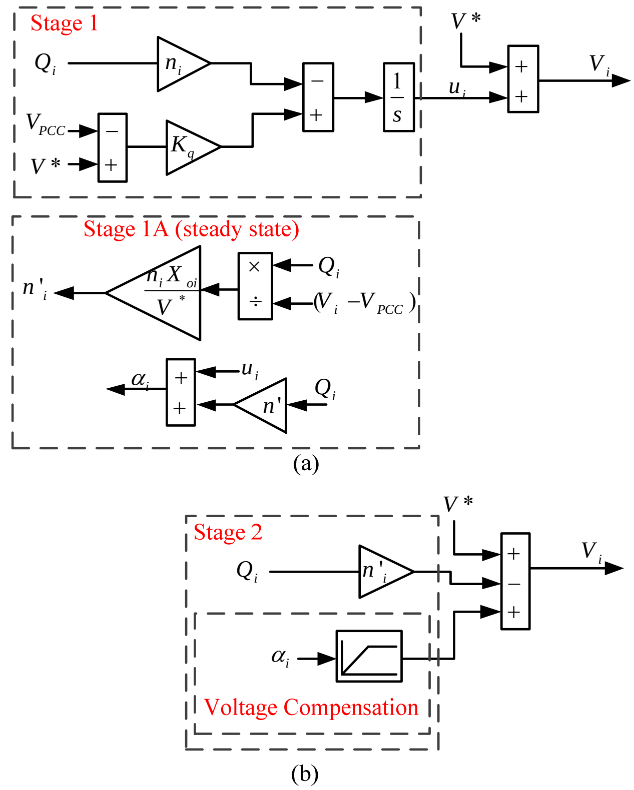


Fig. 4. Proposed controller scheme (a) Stage 1: Accurate power sharing. (b) Stage 2: Voltage compensation.

steady state condition is reached (determined by zero input to the integrator), the output impedance X_i is estimated using (15) and the new droop gain is calculated using (14). All of the new droop gains are set in proportion to $1/X_i$. Thus, the traditional droop control can be used without using the PCC voltage.

B. Stage 2

In this stage, a smooth transition from the closed loop control, which involves a measurement of the PCC voltage, to the traditional droop control using the newly calculated droop gains is performed. At the end of stage 1 (once the steady state condition is reached), the inverter output voltage is given by:

$$V_{i\,(Stage\,1)} = V^* + u_i \tag{17}$$

In stage 2, after adopting the new droop gain n' with the traditional droop loop, the inverter output voltage is given by:

$$V_{i\,(Stage\,2)} = V^* - n'_i Q_i + \alpha_i \tag{18}$$

where the offset α is added to make sure that the inverter voltage at the beginning of stage 2 is the same as that at the end of stage 1. Therefore, (17) and (18) should be equal. Hence, α is given as in (19) and it is calculated at the end of stage 1 as shown in Fig 4(a).

$$\alpha_i = u_i + n'_i Q_i \tag{19}$$

In stage 2 the offset α is added via a ramp function as shown in Fig. 4(b).

The proposed controller can be realized using a low-bandwidth communication link to connect each inverter

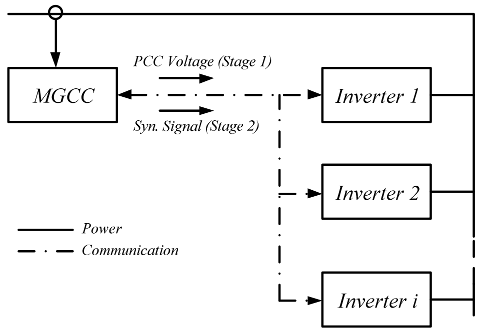


Fig. 5. Communication scheme for the proposed controller.

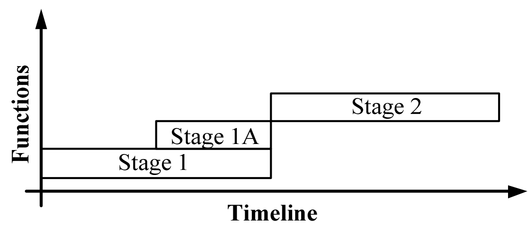


Fig. 6. Proposed algorithm stages timeline.

with the MGCC as shown in Fig. 5. This link sends the PCC voltage to all of the units simultaneously for stage 1 to get accurate Q sharing. Once the steady state condition is reached (Stage 1A) and flagged by the zero input to the integrator, the new droop gain n′ and the offset α are calculated as shown in the process timeline in Fig. 6. At the end of stage 1, a synchronization flag is sent so that all of the inverters activate stage 2 at the same time. In this stage, the new calculated value of n′ is used as the droop gain instead of the old value n.

IV. Simulation Results

A model of a microgrid with two inverters was built using Matlab/Simulink. Each inverter is modeled as an ideal voltage source with a series inductive output impedance as shown in Fig. 2. The system parameters are shown in Table I. The two inverters have identical parameters. However, an extra impedance is inserted between inverter 2 and the PCC to model the impedance of a long feeder. This part of the simulation is carried out to verify the proposed controller under different load conditions and to compare its performance with that of the traditional droop controller.

Fig. 7 shows the reactive power of the two inverters with the traditional droop control under different load conditions; low, medium and high corresponding to 10%, 50%, and 100% of the maximum reactive power rating of the microgrid (20kVar), respectively. It can be noticed that the two inverters do not share the reactive power equally. Table II summarizes the steady state values of the simulation results.

Fig. 8 shows the reactive power with the proposed controller under different load conditions. The traditional droop controller is used until time t = 5.5 sec when stage 1 is activated and the

TABLE I

Simulation Parameter Values

Symbol	Description	Value
m	Frequency droop gain	0.001
n	Voltage droop gain	0.001
V_o	Voltage set point	230 Vrms
f_o	Frequency set point	50 Hz
τ	Measurement filter time	0.5 sec
X_{o1}, R_{o1}	Output impedance for inverter 1	2500µH,0.1Ω
X_{o2}, R_{o2}	Output impedance for inverter 2	2500µH,0.1Ω
X_{Lf1}	Feeder line impedance for	0 µH
X_{Lf2}, R_{Lf2}	Feeder line impedance for	500µH, ,0.05Ω
K_q	V_{PCC} loop gain	10

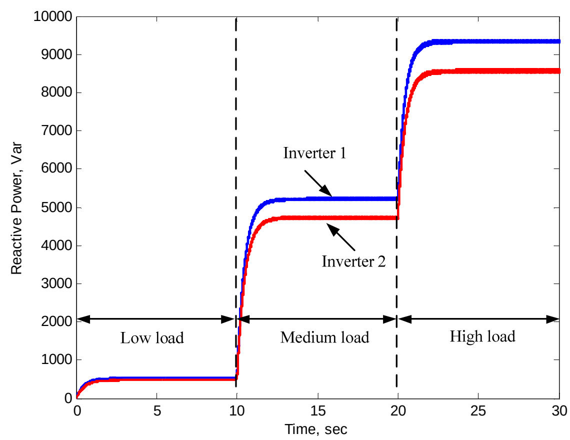


Fig. 7. Inverter's output power when low, medium and high loads are supplied using traditional droop control.

new droop gain n′ and the offset α are being calculated. At time t = 21 sec, stage 2 is activated and the controller reverts to the traditional droop control but with the new calculated droop gain n′. At t = 21 sec, there is a dip in the reactive power, which is due to the difference between the inverter voltage at the end of stage 1 and at the beginning of stage 2. This is fixed by adding the offset α which is done gradually via a ramp function. After the controller is settled and at time t = 32 sec, a sudden change in the reactive load is applied to test the ability of the proposed controller to maintain good reactive power sharing. In Fig. 8(a), the activation of the proposed controller occurs when the reactive load is low, followed by a sudden change in the reactive load from low to high. In Fig. 8(b), the activation of the proposed controller occurs when the reactive load is medium, followed by a sudden change in the reactive load from medium to high. In Fig. 8(c), the activation of the proposed controller occurs when the reactive load is high, followed by a sudden change in the reactive load from high to low. Finally, in Fig. 8(d), the activation of the proposed controller occurs when the reactive load is high, followed by a sudden change in the reactive load from high to medium. The simulation results for these simulation conditions are summarized in Table II which reveals an improvement of the

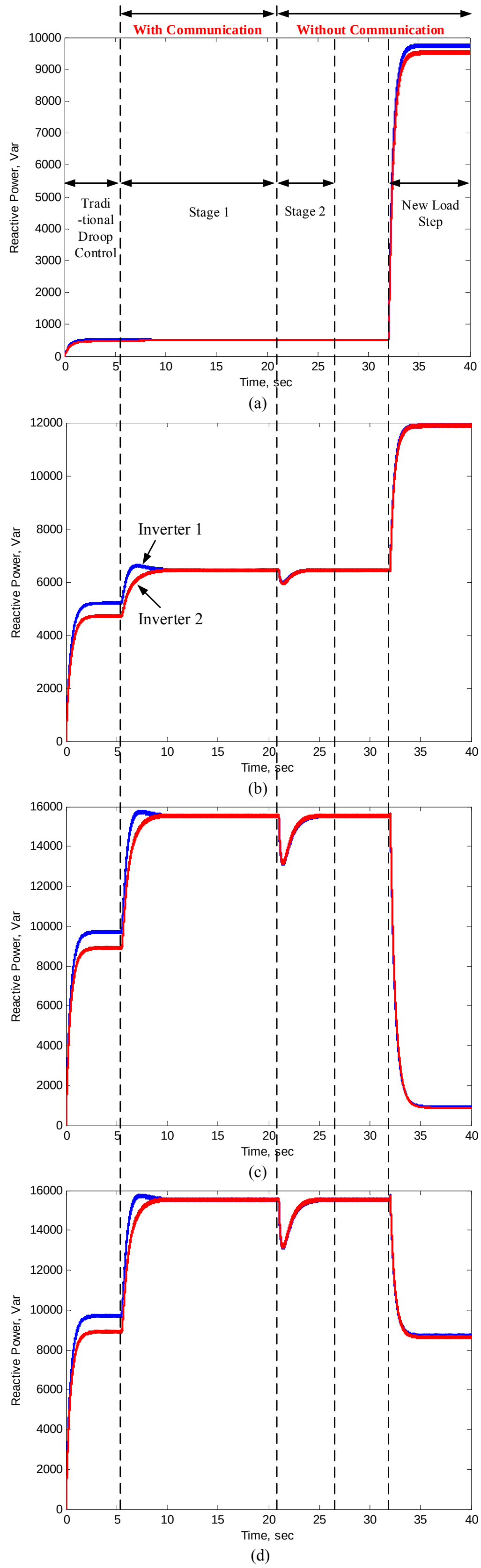


Fig. 8. Simulation results of the proposed controller after a new load step at 32sec from (a) low to high (b) medium to high (c) high to low (d) high to medium.

TABLE II
TRADITIONAL AND PROPOSED CONTROLLER REACTIVE OUTPUT POWER

Traditional Droop control			
Load Case	Inverter 1 output (VAR)	Inverter 2 output (VAR)	Error %
Low	532	473	5.9%
Medium	5210	4725	4.9%
High	9350	8550	4.5%

Proposed Controller				
Load Case		Inverter 1 output (VAR)	Inverter 2 output (VAR)	Error %
During algorithm execution (Current load)	After algorithm execution (New load)			
Low	High	9770	9540	1.2%
Medium	High	11880	11880	0.0%
High	Low	952	878	4.0%
High	Medium	8725	8628	0.56%

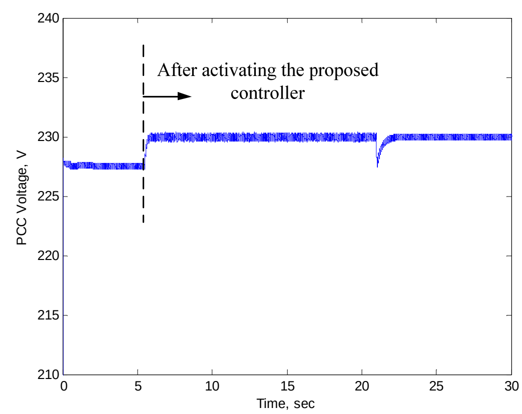


Fig. 9. PCC voltage before and after activating the proposed controller (in all cases).

reactive power sharing due to the proposed controller when compared with the performance of the traditional control under different load conditions. It is noted that the total reactive power is different before and after activating the proposed controller. This is due to the change of V_{PCC} as it increases due to the action of the voltage drop compensation in stage 1 as seen in Fig. 9.

Fig. 10 depicts the risk of a potential communication loss for controllers that rely on continuous measurements of the PCC voltage, such as the one reported in [17], if a wireless link is used between the PCC and the inverters. Initially, the two inverters are supplying load 1 and adopting the traditional droop control until the moment t=5.5sec when the algorithm reported in [17] is activated and accurate reactive power sharing is achieved. One of the two inverters lose the PCC voltage measurements at t=20sec for 100ms. As can be seen, the output voltages of both inverters exceed the limit which causes the inverter to trip.

The load might change during Stage 1. Therefore, the

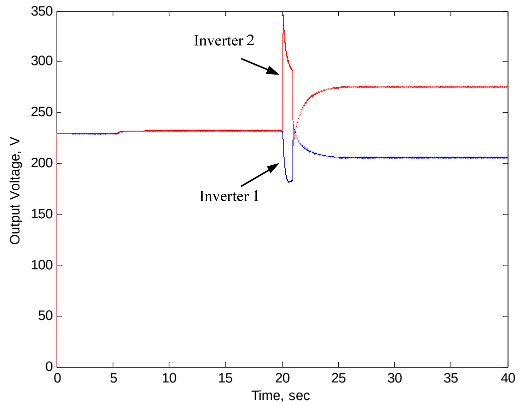


Fig. 10. Output voltages when PCC voltage is lost at t=20 sec for 100ms.

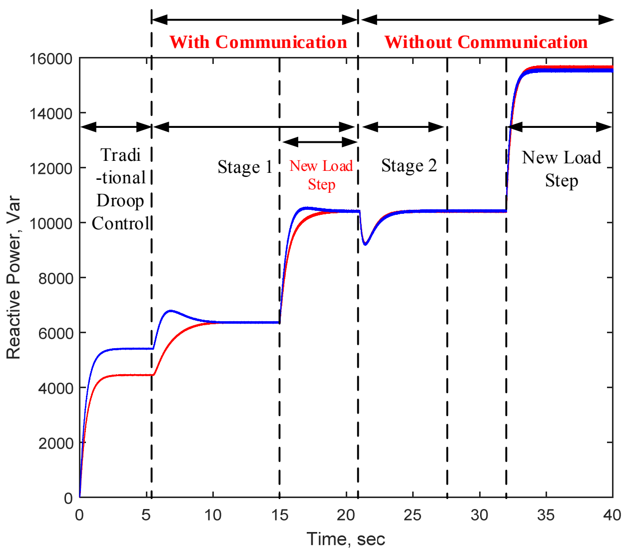


Fig. 11. Load change during Stage 1.

controller will not proceed to Stage 2 until the steady state input of the integrator reaches zero. This action is depicted in Fig. 11 where a new load is connected at t=15sec. The controller is transferred to Stage 2 only after the steady state is reached at t=20sec.

The proposed strategy is based on the assumption that the network is predominantly inductive as shown in Equ. (15). Therefore, the accuracy of the proposed controller is degraded if the network is predominantly resistive. In this case, the virtual impedance plays an important role in improving the accuracy of the controller. A larger resistive output impedance ($X/R = 0.3$) for both of the inverters is used with feeder resistance of $R = 0.15\Omega$. The simulation results in Fig. 12 show the controller performance without [Fig 12(a)] and with [Fig 12(b)] the inductive virtual impedance. The controller is activated at t=5sec and new loads are connected at t=32sec. The results reveal that the accuracy of the proposed controller decreases with a more resistive network. Nevertheless, adopting an inductive virtual impedance provides more accurate steady state values.

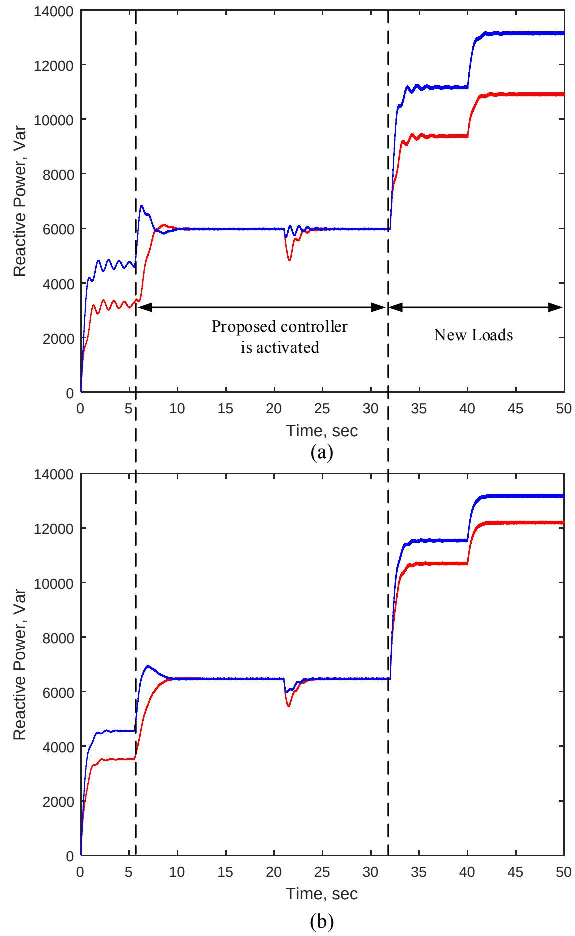


Fig. 12. The proposed controller performance (a) without and (b) with the virtual impedance in resistive network.

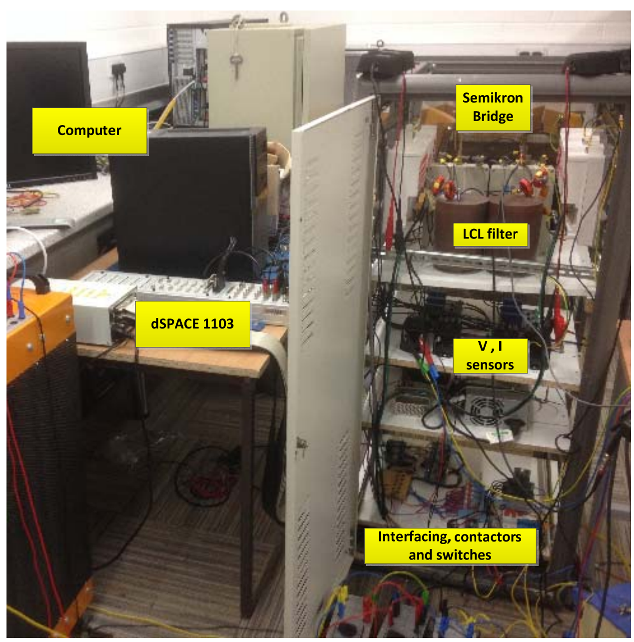


Fig. 13. View of the laboratory setup.

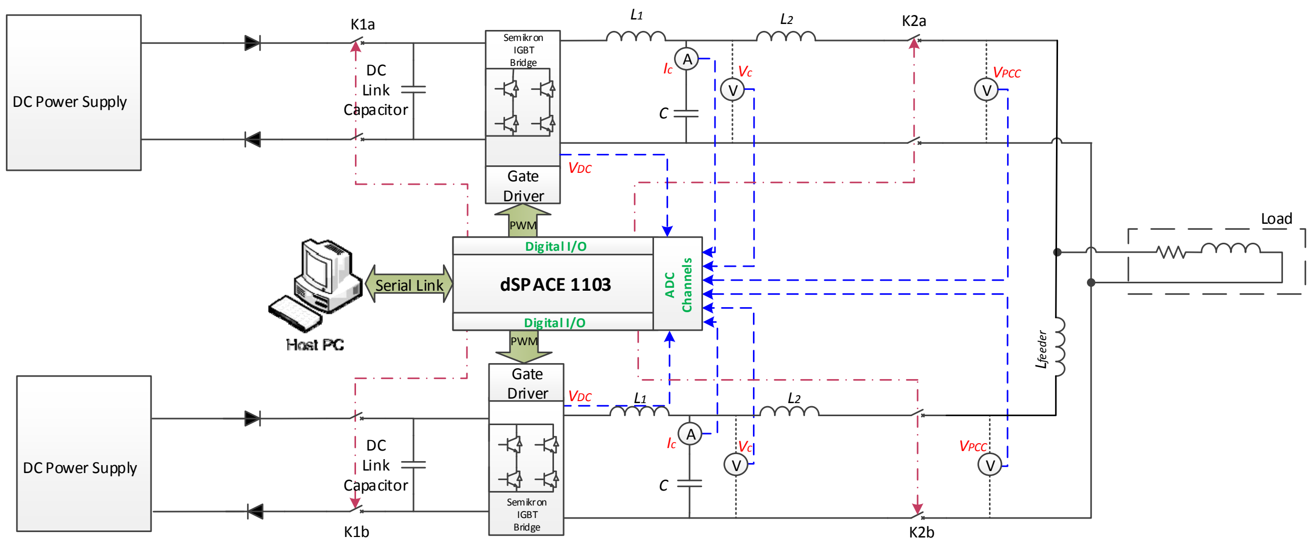


Fig. 14. Experimental setup diagram.

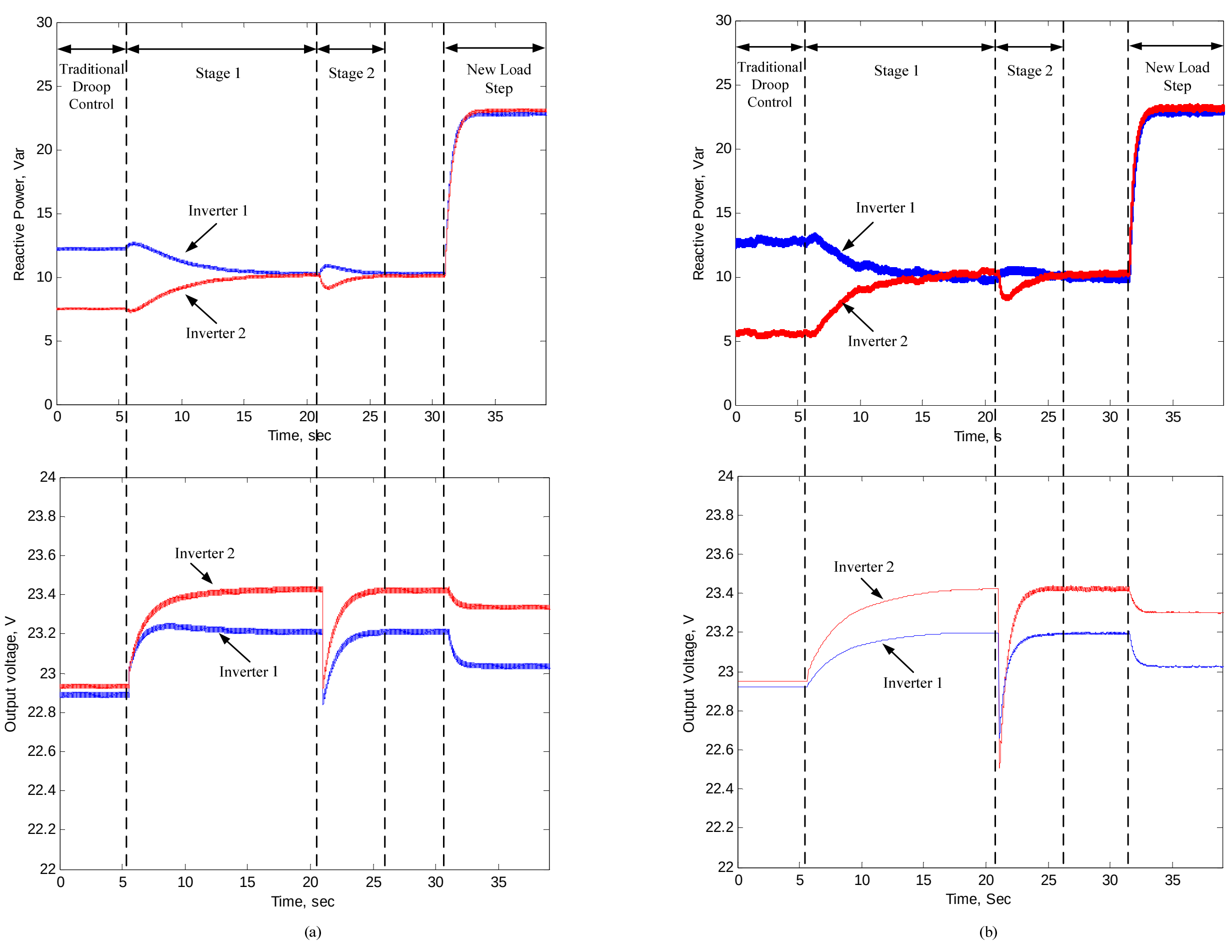


Fig. 15. Reactive output power and output voltages results of the proposed controller: (a) simulation (b) experimental.

TABLE III
EXPERIMENTAL PARAMETER VALUES

Symbol	Description	Value
L_1	Inverter-side filter inductor	1400μH
C	Filter capacitor	240μF
L_2	Grid-side filter inductor	300μH
C_{DC}	DC link capacitor	2000μF
f_s	Sampling frequency	20kHz
f_{sw}	Switching frequency	10kHz
X_f	Feeder line impedance	500μH
m	Frequency droop gain	0.01
n	Voltage droop gain	0.01
V_o	Voltage set point	23 Vrms
Load 1	Load 1 active and reactive power	80W,15Var
Load 2	Load 2 active and reactive power	27Var

V. EXPERIMENTAL RESULTS

A laboratory-scale microgrid was built to validate the proposed controller. It consists of two inverters connected in parallel. Each inverter consists of a Semikron single phase H-bridge and an output LCL filter. The experimental setup diagram is shown in Fig. 14. A dSPACE 1103 control unit is used to implement and realize the proposed control scheme in real time. The dSPACE interfacing board is equipped with eight analog to digital channels (ADC) to interface the measured signals. The software code is generated by the Real-Time-Workshop under the Matlab/Simulink environment. The experimental setup parameters are listed in Table III. A picture of the experimental setup is shown in Fig. 13. A detailed simulation model of the experimental setup was also built using Matlab SimPowerSystem. The two inverters have identical parameters. However, an extra impedance is inserted between inverter 2 and the PCC to model the impedance of a long feeder.

Fig. 15 shows that the reactive power flows from the two inverters during the entire process. The initial PCC load was Load 1 as defined in Table III. The microgrid was initially operating using the traditional droop method. The inverters do not share reactive power equally due to a mismatch in the feeder impedances. Stage 1 began at t=5.5sec and at t=20sec the Q sharing was achieved thanks to the integral controller using V_{PCC}. By the end of stage 1, the new droop gain and the voltage offset were calculated to be used in the next stage. Stage 2 began at t=20.5sec and the controller switched to the traditional droop method using the new calculated droop gain and the integral controllers using V_{PCC} were stopped. At the beginning of stage 2, the voltage offset is added gradually using a ramp function and the whole process finished at t=26sec. At t=32sec, a step load was applied by connecting Load 2 at the PCC and the two inverters shared it equally. The figure also shows the inverters' output voltage responses during the whole process. The experimental results show good agreement with the simulation results and confirm the reliability of the proposed controller against load changing.

VI. CONCLUSION

In this paper, a novel power-sharing algorithm was proposed to enhance the reactive power sharing between parallel inverters in the island mode of microgrids. The proposed strategy uses an intermittent measurement of the PCC voltage to accomplish accurate reactive power sharing. Under this condition it is possible to estimate the value of the output impedance of the inverters (which is assumed to be dominantly inductive), including that of the cables. The new estimated impedance values are then used to calculate a new value for the gain of the traditional droop controller. This takes over the control of the reactive power sharing when the PCC voltage measurement is not available. The new droop configuration improves the reactive power sharing without needing to measure the PCC voltage continuously – intermittent measurements can be repeated and transmitted to the inverters over a slow communication link to handle any changes in the network. This increases the reliability of the system against communication link loss. Since the proposed controller assumes a predominantly inductive output impedance, there might be a decrease in the sharing accuracy when it has significantly resistive value. In addition, discrete measurements of the PCC voltage are managed according to the changes in the structure of the microgrid (loads, cables length and number of inverters). Finally, simulation and experimental results are presented to validate the performance and effectiveness of the proposed controller.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support from EPSRC-DST funded Reliable and Efficient System for Community Energy Solution - RESCUES project (EP/K03619X/1).

REFERENCES

[1] Y. Pei, G. Jiang, X. Yang, and Z. Wang, "Auto-master-slave control technique of parallel inverters in distributed AC power systems and UPS," in *IEEE 35th Annual Conference of Power Electronics Specialists*, pp. 2050-2053, 2004.

[2] W. C. Lee, T.-K. Lee, S.-H. Lee, K.-H. Kim, D.-S. Hyun, and I.-Y. Suh, "A master and slave control strategy for parallel operation of three-phase UPS systems with different ratings," in *the Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition*, Vol. 1, pp. 456-462, 2004.

[3] Y. J. Cheng and E. K. K. Sng, "A novel communication strategy for decentralized control of paralleled multi-inverter systems," *IEEE Trans. Power Electron.,* Vol.

21, No. 1, pp. 148-156, Jan 2006.

[4] T. Iwade, S. Komiyama, Y. Tanimura, M. Yamanaka, M. Sakane, and K. Hirachi, "A novel small-scale UPS using a parallel redundant operation system," in *The 25th International Telecommunications Energy Conference* Japan, pp. 480-484, 2003.

[5] J. Tan, H. Lin, J. Zhang, and J. Ying, "A novel load sharing control technique for paralleled inverters," in *IEEE 34th Annual Power Electronics Specialist Conference*, pp. 1432-1437, 2003.

[6] T.-F. Wu, Y.-K. Chen, and Y.-H. Huang, "3C strategy for inverters in parallel operation achieving an equal current distribution," *IEEE Trans. Ind. Electron.,* Vol. 47, No. 2, pp. 273-281, Apr. 2000.

[7] M. Abusara, J. M. Guerrero, and S. Sharkh, "Line interactive UPS for microgrids," *IEEE Trans. Ind. Electron.,*Vol. 61, No. 3, pp. 1-8, Mar. 2013.

[8] J. M. Guerrero, L. G. De Vicuna, J. Matas, M. Castilla, and J. Miret, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," *IEEE Trans. Power Electron.,* Vol. 19, No. 5, pp. 1205-1213, Sep. 2004.

[9] W. Yao, M. Chen, M. Gao, and Z. Qian, "A wireless load sharing controller to improve the performance of parallel-connected inverters," in *Twenty-Third Annual IEEE in Applied Power Electronics Conference and Exposition*, pp. 1628-1631, 2008.

[10] E. A. A. Coelho, P. C. Cortizo, and P. F. D. Garcia, "Small-signal stability for parallel-connected inverters in stand-alone AC supply systems," *IEEE Trans. Ind. Appl.,* Vol. 38, No. 2, pp. 533-542, Apr. 2002.

[11] J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodríguez, and R. Teodorescu, "Adaptive droop control applied to voltage-source inverters operating in grid-connected and islanded modes," *IEEE Trans. Ind. Electron.,* Vol. 56, No. 10, pp. 4088-4096, Oct. 2009.

[12] H. J. Avelar, W. A. Parreira, J. B. Vieira, L. C. G. de Freitas, and E. A. A. Coelho, "a state equation model of a single-phase grid-connected inverter using a droop control scheme with extra phase shift control action," *IEEE Trans. Ind. Electron.,* Vol. 59, No. 3, pp. 1527-1537, Mar. 2012.

[13] A. Tuladhar, H. Jin, T. Unger, and K. Mauch, "Control of parallel inverters in distributed AC power systems with consideration of line impedance effect," *IEEE Trans. Ind. Appl.,* Vol. 36, No. 1, pp. 131-138, Feb. 2000.

[14] C.-T. Lee, C. C. Chu, and P.-T. Cheng, "A new droop control method for the autonomous operation of distributed energy resource interface converters," in *Proc. of the 2010 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 702-709, 2010.

[15] A. Micallef, M. Apap, C. S. Staines, and J. M. Guerrero Zapata, "Secondary control for reactive power sharing and voltage amplitude restoration in droop-controlled islanded microgrids," in *3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, pp. 492-498, 2012.

[16] Y. W. Li and C. N. Kao, "An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus microgrid," *IEEE Trans. Power Electron.,* Vol. 24, No. 12, pp. 2977-2988, Dec. 2009.

[17] Q.-C. Zhong, "Robust droop controller for accurate proportional load sharing among inverters operated in parallel," *IEEE Trans. Ind. Electron.,* Vol. 60, No. 4, pp. 1281-1290, Apr. 2013.

[18] J. He and Y. W. Li, "An enhanced microgrid load demand sharing strategy," *IEEE Trans. Power Electron.,* Vol. 27, No. 9, pp. 3984-3995, Sep. 2012.

[19] J. He, Y. W. Li, J. M. Guerrero, J. C. Vasquez, and F. Blaabjerg, "An islanding microgrid reactive power sharing scheme enhanced by programmed virtual impedances," in *3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG),* pp. 229-235, 2012.

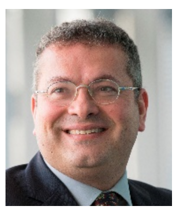
[20] J. He, Y. W. Li, J. M. Guerrero, F. Blaabjerg, and J. C. Vasquez, "An islanding microgrid power sharing approach using enhanced virtual impedance control scheme," *IEEE Trans. Power Electron.,* Vol. 28, No. 11, pp. 5272-5282, Nov. 2013.

[21] W. Issa, M. Abusara, and S. Sharkh, "Control of transient power during unintentional islanding of microgrids," *IEEE Trans. Power Electron.,* Vol. 30, No. 8, pp. 4573-4584, Aug. 2014.

[22] B. M. Eid, N. A. Rahim, J. Selvaraj, and A. H. El Khateb, "Control methods and objectives for electronically coupled distributed energy resources in microgrids: A review," *IEEE Systems Journal*, Jan. 2014.

[23] J. M. Guerrero, L. G. de Vicuna, J. Matas, M. Castilla, and J. Miret, "Output impedance design of parallel-connected UPS inverters with wireless load-sharing control," *IEEE Trans. Ind. Electron.,* Vol. 52, No. 4, pp. 1126-1135, Aug. 2005.

Walid Issa received his B.S. and M.S. degrees in Electrical Engineering from the Islamic University of Gaza (IUG), Palestine, in 2007 and 2011, respectively; and his PhD in Renewable Energy from the University of Exeter, Exeter, England, UK, in 2015. He worked as a Teaching Assistant at IUG, from 2007 to 2010. In addition, he was a Lecturer at University College of Applied Science (UCAS), Palestine, from 2009 to 2011. His current research interests include power electronics, digital control, DC/AC and DC/DC converters, and microgrids.



Suleiman Sharkh obtained his B.S. and Ph.D. degrees in Electrical Engineering from the University of Southampton, Southampton, England, UK, in 1990 and 1994, respectively. He is presently working as a Professor of Power Electronics, Machines and Drives and as the Head of the Electro-Mechanical Research Group at the University of Southampton. He is also the Managing Director of HiT Systems Ltd., UK and a Director of HiT Power Ltd., UK. He has published over 140 papers in academic journals and conference proceedings. Professor Sharkh is a Member of the IEEE and the IET. He is also a Chartered Engineer. He was the 2008 winner of The Engineer Energy Innovation Award for his work on rim driven thrusters and marine turbine generators.

Tapas Mallick (M'15) received his Ph.D. degree from Ulster University, Coleraine, Northern Ireland, UK, in 2003. From 2007 to 2012, he was a Lecturer at Heriot-Watt University, Edinburgh, Scotland, UK. He is Presently working as a Professor of Renewable Energy and a Chair of Clean Technologies in the Environment and

Sustainability Institute of the University of Exeter, Penryn Campus, Cornwall, England, UK. His current research interests include renewable energies, concentrating photovoltaics, building integrated photovoltaics, the integration of renewables, heat transfer, optics, and electrical modeling.

Mohammad Abusara received his B.S. degree from Birzeit University, Palestine, in 2000; and his Ph.D. degree from the University of Southampton, Southampton, England, UK, in 2004, both in Electrical Engineering. He is presently working as a Senior Lecturer in Renewable Energy at the University of Exeter, Exeter, UK. He has over ten years of industrial experience with the Bowman Power Group, Southampton, UK, in the research and development of the digital control of power electronics. During his years in industry, he has designed and prototyped a number of commercial products that include grid and parallel connected inverters, microgrids, DC/DC converters for hybrid vehicles, and sensorless drives for high speed permanent magnet machines.