Distributed Voltage Control and Load Sharing for Inverter-Interfaced Microdrid with Resistive Lines

Mohammad S. Golsorkhi and D.D.C. Lu
School of Electrical and Information Engineering, the University of Sydney
Sydney, Australia
mgol15@yahoo.com; Dylan.lu@sydney.edu.au

Q. Shafiee
Department of Electrical and Computer Engineering, University of Kurdistan,
Sanandaj, Iran
q.shafiee@uok.ac.ir

Josep M. Guerrero
Department of Energy Technology, Aalborg University
Aalborg, Denmark
joz@et.aau.dk

***Abstract*— This paper proposes a new distributed control method for coordination of distributed energy resources (DERs) in low-voltage resistive microgrids. The proposed framework consists of two level structure; primary and secondary control. Unlike the existing distributed control methods, the proposed method is based upon the practical assumption of resistive network impedance. In this context, a V-I droop mechanism is adopted in the primary control level, where GPS timing is used to synchronize the control agents. A new distributed secondary control method based on consensus protocol is introduced to improve the voltage regulation and load sharing accuracy of the V-I droop method. In this method, the d-axis components of the voltage is altered so as to regulate the average microgrid voltage to the rated value while guarantying proper sharing of active power among the DERs. Additionally, the q-axis component of voltage is adjusted to perform proper current and, accordingly reactive power sharing. The proposed control methodology accounts for the distribution line impedances. It features a plug-and-play environment; prior system knowledge is not required, and an arbitrary DER can enter the microgrid without any need for additional synchronization mechanisms. An AC microgrid is prototyped to experimentally demonstrate the efficacy of the proposed method.**

keywords*— *Distributed control, dispersed generation, inverter, microgrid, secondary control.

I. Introduction

The increased penetration of distributed energy resources (DERs) gives rise to new challenges in control, performance and power quality of distribution networks. A systematic approach towards the coordination of DERs is to view the DERs and associated loads as a microgrid (MG) [1]. Over the recent years, several cooperative control strategies including decentralized [2], centralized [3], and distributed [4] control schemes have been proposed for MGs. In the decentralized approaches, individual DERs are controlled by local controllers, which are often coordinated by using droop characteristics. Despite simple implementation, decentralized control methods suffer from voltage and frequency deviations and poor load sharing [5].

To overcome limitation of the decentralized methods and improving their performance, communication-based control approaches are introduced. While centralized methods favor high flexibility and performance, they are considered less practical due to the requirement of an extensive and costly communication network and the fact that the single point-of-failure of the centralized controller affects the whole system [6]. Distributed control architectures have recently gained popularity since they can discharge duties of a central controller with less communication and computation costs, while being resilient to faults or unknown system parameters [4]. Distributed control schemes are composed of local control agents interconnected through a sparse communication network [7]. Each control agent includes primary and secondary control levels. At the primary level, droop control method is used to enable load sharing with a fast dynamic response. Using the information from other agents, the secondary controller eliminates the voltage and frequency deviations caused by load changes and improves power sharing [8].

The existing distributed control schemes are mostly developed based on the assumption of inductive network impedance [4], [9]. For inductive networks the active power and reactive power are decoupled and related with the frequency and voltage, respectively. Therefore, active power-frequency (P-f) and reactive power-voltage (Q-V) droop characteristics are adopted for the primary control level. Moreover, the secondary control methods are introduced to regulate the system frequency and voltage as well as to improve reactive power sharing among the DERs, tackling the limitation of droop control. However, the network impedance is mainly resistive in practice, especially in case of low voltage MGs. In such cases, the existing control methods for inductive systems cannot provide satisfactory performance. In [10], a distributed control method based on P-$\dot{V}$ and Q-f droop characteristics have been proposed for resistive MGs. However, that method suffers from poor dynamic response.

In this paper, building on our recently introduced V-I droop control method [2], [11]-[14], we introduce a new distributed secondary control framework which guarantees voltage regulation and load power sharing in low-voltage resistive MGs. In the primary level of the proposed framework, GPS timing technology is used to synchronize the control agents to a global reference time. By fixing the frequency at the rated value, all agents share an identical reference angle, which enables synchronizing the individual rotating reference frames to a global reference frame. In this context, v_d-i_d and v_q-i_q droop

978-1-5090-0737-0/16/$31.00 ©2016 IEEE

characteristics are used to share the active and reactive components of the load current among the DERs. The use of a resistive droop function not only improves the system damping but also makes the method appropriate for resistive networks. A distributed control scheme is proposed to improve the load sharing and voltage regulation of the V-I droop method. In this method, the d-axis voltage is adjusted so as to regulate the average MG voltage to the rated value while ensuring proper active power sharing. Moreover, the q-axis voltage is altered such that the load current and accordingly the reactive power are proportionally shared between the DERs.

The rest of the paper is organized as follows. The conventional and V-I droop control schemes are introduced in Section II. The proposed control method is detailed in Section III. Experimental results are presented in Section IV to verify the efficacy of the proposed method. The paper is concluded in Section V.

II. Background Concept

In order to maintain load/generation balance while regulating the voltage and frequency, droop control schemes are commonly used in practice. Assuming inductive network impedance, the active and reactive powers are proportional with the angle and magnitude of the voltage, respectively. This relation is used as the basis of the conventional droop method, in which the dispatchable DER units are coordinated according to P-f and Q-V droop characteristics. However, the aforementioned assumption is not practical for low voltage MGs, in which the R/X ratio is as large as 7 [15]. Additionally, the conventional droop suffers from slow dynamics and frequency fluctuations, which degrade the power quality.

To enhance the performance of the conventional droop method, several modified power-droop schemes including, P-V and Q-f droop [16], virtual impedance [17] and adaptive droop [18] schemes have been proposed in the literature. An alternative approach presented in [2] achieves a fast dynamic response by directly controlling the inverter voltage according to the output current. In this scheme, the d and q axis components of the voltage are controlled according to v_d-i_d and v_q-i_q droop characteristics, respectively. Furthermore, the dq reference frames of all DERs are synchronized with a global frame by means of GPS timing technology. This way, all DERs will operate at fixed frequency; hence the frequency fluctuations are eliminated.

In order to achieve proper sharing of load current among the DER units, the droop control law is defined as

$$\begin{bmatrix} v_{cd}^* \\ v_{cq}^* \end{bmatrix} = \overbrace{\begin{bmatrix} E_0 \\ 0 \end{bmatrix}}^{\text{no load voltage}} + \overbrace{\begin{bmatrix} R_{gs} & -X_{gs} \\ X_{gs} & R_{gs} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix}}^{\text{grid-side inductor drop compensation}} - \overbrace{\begin{bmatrix} r_d\, g(i_d) \\ r_q i_q \end{bmatrix}}^{\text{adaptive virtual resistance}} \quad (1)$$

where v_c^*, i, E_0, R_{gs}, X_{gs}, r_d, r_q are the reference voltage, output current, rated voltage, grid side inductor resistance and reactance, and d and q-axis droop coefficients, respectively. The droop function, $g(\cdot)$, is a monotonic peicewise linear function, which is introduced to improve the sharing accuracy at high loading conditions.

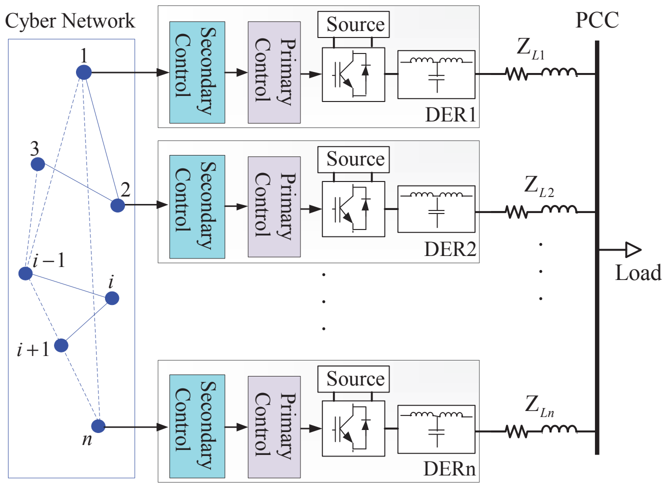


Fig. 1. Proposed control structure.

Equation (1) implies that the voltage phasor is almost aligned with the d-axis. So, considering the fact that the voltage variations are small throughout the MG, P and Q are proportional with i_d and i_q, respectively. Therefore, the active and reactive power can be proportionally shared among the DERs by selecting the droop coefficients as

$$r_{d1} P_1^{rated} = r_{d2} P_2^{rated} = \cdots = r_{dn} P_n^{rated} \quad (2)$$

$$r_{q1} Q_1^{rated} = r_{q2} Q_2^{rated} = \cdots = r_{qn} Q_n^{rated} \quad (3)$$

in which P_i^{rated} and Q_i^{rated} refer to the rated active and reactive power of DER unit i, respectively.

III. Proposed Control Method

The sharing accuracy of the droop-based schemes in general and the V-I droop method in particular, is dependent on the line impedances and the distribution of the load in the MG. Particularly, the DER units which have a smaller electrical distance with the load tend to have a larger power output compared to the farther units. On top of that, the voltage deviations caused by the droop characteristics degrades the voltage regulation across the MG. In order to improve the sharing accuracy and voltage regulation, a distributed secondary control method is proposed in this paper.

A. Control structure

The schematic diagram of the proposed control structure for a MG comprising of n DER units is illustrated in Fig. 1. Each DER includes an Energy source, an inverter and an LCL filter, which eliminates the switching harmonics from the output current. The DERs are connected to the point of common coupling (PCC) through line impedances.

Each DER is controlled by a local controller consisting of primary and secondary control layers. The primary control layer is composed of V-I droop controller and the inner control loops, which coordinate the DER units in a decentralized way. The distributed secondary control layer adjusts the offset of the droop characteristics so as to alleviate the effect of line voltage drops on the sharing accuracy and restore the voltage profile within a range of the nominal voltage. The secondary controller of each unit communicates with the neighbor units through a low bandwidth cyber network.

B. *Mechanism of operation*

The operation of the proposed control scheme is demonstrated based on Fig. 2. For simplicity, the number of DER units is limited to n=2 and the lines are assumed to be purely resistive. Furthermore, the resistance of line 1 is assumed to be larger than line 2. The v_q-i_q droop characteristics for the two DER units are depicted in Fig. 2 (a). In this figure, the droop characteristics before and after the activation of the secondary controller are shown by solid and broken lines, respectively. Prior to activating the secondary controller, both units have the same characteristics. However, due to the mismatch between the line impedances, the q-axis component of the local voltage of unit 1 (v_{q1}) is lower than unit 2 (v_{q2}). Therefore, unit 1 supplies a larger q-axis current compared to unit 2. In order to improve the i_q sharing accuracy, the secondary controller of unit 2 increases the secondary voltage, v_{sq2}. Consequently, the v_q-i_q droop characteristic of unit 2 is shifted up and the operating voltages are changed to v'_{q1} and v'_{q2} . As a result, the q-axis load current is equally shared among the units.

The v_d-i_d droop characteristics for the DERs are depicted in Fig. 2 (b). Prior to activating the secondary controller, the d-axis components of the local voltages drop to v_{d1} and v_{d2}. In order to improve the voltage regulation, the secondary controllers shift up the d-axis droop characteristics of both units until the d-axis voltages reach v'_{d1} and v'_{d2}. At this stage, the average value of the local voltages is restored to E_0. This way, the MG voltage profile is maintained within the permissible range. Furthermore, by applying a larger secondary voltage to unit 2, the adverse effect of line voltage drop on the sharing accuracy is eliminated. Therefore, i_d is equally shared among the units.

C. *Control scheme*

The schematic diagram of the proposed control method for agent i is illustrated in Fig. 3. The secondary control level is comprised of four blocks: calculation block, which obtains the terminal voltage, normalized active power and normalized q-axis current; distributed averaging block, which estimates the average value of DER terminal voltages; voltage control block, which improves the voltage regulation and active power sharing accuracy; and Q sharing block, which improves the current sharing accuracy. In the primary level, the inverter reference voltage is obtained by adding the droop and secondary control signals. The inner control loops, which consist of cascaded voltage and current controllers, track the reference voltage with a fast dynamic response. Accordingly, space-vector PWM module assigns appropriate switching signals to drive the inverter.

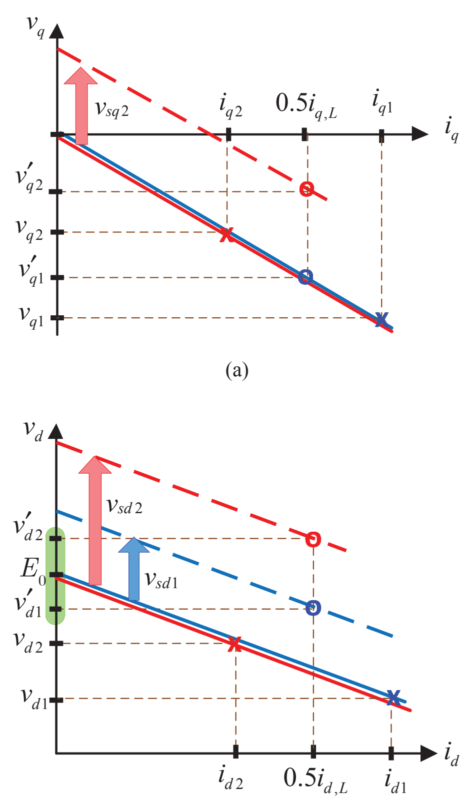


Fig. 2. Operation of the proposed controller in a) q-axis and b) b-axis.

The secondary control level is designed based on consensus concept. In this framework, an information state x_i is assigned to each control agent. The information states are shared between the agents, i.e., inverters through a sparse communication network. The state of each agent is updated based on the received information form the neighbors. If the distributed communication network contains minimum connectivity, all of the states will converge to a common value: $x_0 = x_1 = \ldots = x_n$ [19]. Here, three information state is a vector of three variables, including estimated average voltage, $\bar{v}_k$, normalized active power, P_k^{norm} and normalized q-axis current, i_{qk}^{norm}.

The average MG voltage is obtained by using the distributed averaging technique called dynamic consensus [20]. The average voltage estimator of agent i provides the estimation of average voltage magnitude, $\bar{v}_i$, using the information state received from agent j, $\bar{v}_j$, and the local terminal voltage, v_{ti}, as

$$\bar{v}_i(t) = v_{ti}(t) + k_{avg}\int_0^t \sum_{j\in\mathbb{N}_i} \left(\bar{v}_j(\tau) - \bar{v}_i(\tau)\right) d\tau, \qquad (4)$$

where k_{avg} is the integral gain, and $\mathbb{N}_i$ is the set of neighbors of agent i. Furthermore, the terminal voltage is obtained from capacitor voltage and output current, as following:

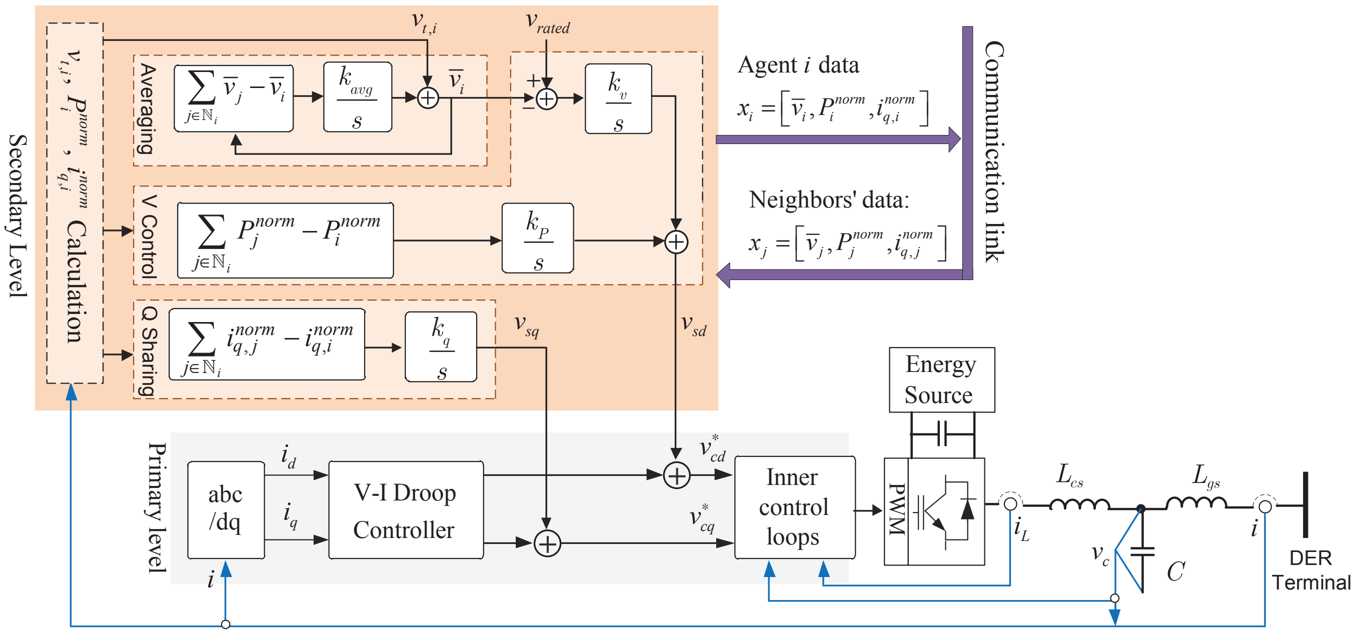


Fig. 3. Proposed control method for agent *i*.

$$\begin{bmatrix} v_{td} \\ v_{tq} \end{bmatrix} = \begin{bmatrix} v_{cd} \\ v_{cq} \end{bmatrix} + \begin{bmatrix} R_{gs} & -X_{gs} \\ X_{gs} & R_{gs} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{5}$$

$$v_t = \sqrt{v_{td}^2 + v_{tq}^2} \tag{6}$$

The normalized active power, P^{norm}, is defined as the ratio of the measured active power on the rated power:

$$P^{norm} = \frac{P}{P^{rated}} \tag{7}$$

If the load is shared proportionally among the DER units, the normalized active powers of all units will be equal. With the assumption of resistive network impedance, active power sharing is dependent on the voltage amplitude of individual DERs. In order to properly share the active power and also regulate the voltage within an acceptable range of the nominal value, the d-axis voltage correction term, v_{sd}, is obtained as

$$v_{sd,i} = k_v \int_0^t \left(V^{rated} - \bar{v}_i(\tau) \right) d\tau + k_P \int_0^t \sum_{j \in \mathbb{N}_i} \left(P_j^{norm}(\tau) - P_i^{norm}(\tau) \right) d\tau \tag{8}$$

Equation (8) implies that the control agents regulate the average voltage at the rated value while attempting to equalize their normalized active powers.

To ensure proper sharing of reactive power, another control module is implemented to provide appropriate q-axis voltage reference for the droop mechanism. Accordingly, the q-axis secondary controller at agent *i* update the voltage reference, v_{sq}, by comparing its normalized current, $i_{q,i}^{norm}$, with the normalized current of its neighbors' to find the loading mismatch

$$v_{sq,i} = k_q \int_0^t \sum_{j \in \mathbb{N}_i} a_{ij} \left(i_{q,j}^{norm}(\tau) - i_{q,i}^{norm}(\tau) \right) d\tau \tag{9}$$

where k_q is the integral gain. The normalized q axis current, i_q^{norm}, is defined as

$$i_q^{norm} = \frac{i_q}{I_q^{\max}} \tag{10}$$

The maximum q-axis current is dynamically updated based on the d-axis current

$$I_q^{\max} = \sqrt{I_{rated}^2 - i_d^2} \tag{11}$$

in which I_{rated} refers to the rated DER output current.

Equations (9)-(11) imply that the control agents attempt to perform reactive power sharing according to the rms current. It should be mentioned that the safe operating region of DERs is limited by their output current rather than a maximum reactive power. Therefore, the proposed approach is more practical compared to the conventional reactive power sharing, which aims at proportional sharing of load reactive power.

TABLE I. ELECTRICAL AND CONTROL PARAMETERS OF THE TEST MG

Parameter	Symbol	Value
Nominal phase voltage	E_0	220 Vrms
Nominal Frequency	f_{rated}	50 Hz
Inverter nominal power	P^{rated}	1500 W
LCL filter parameters	L_{cs}/ C / L_{gs}	8.6 mH / 4.5μF / 1.8mH
Line impedance	Z_{L1}	0.66+ j0.07
	Z_{L2}	0.5+ j0.07
	Z_{L3}	0.5+ j0.07
Load impedances (case 1)	Z_{Load1}/ Z_{Load2}	35Ω/ 35+j40 Ω
Load impedances (case 2)	Z_{Load1}/ Z_{Load2}	57Ω/ 34+j47 Ω
Communication Rate	f_{com}	100 samples/s
Communication delay	T_{dcom}	10 ms
DSC Parameters	k_{avg}	1.2 s^{-1}
	k_v	6 s^{-1}
	k_P	0.1 $W.s^{-1}$
	k_q	300 Ω $-s^{-1}$
Droop coefficients	r_d	5.5 Ω
	r_q	20 Ω

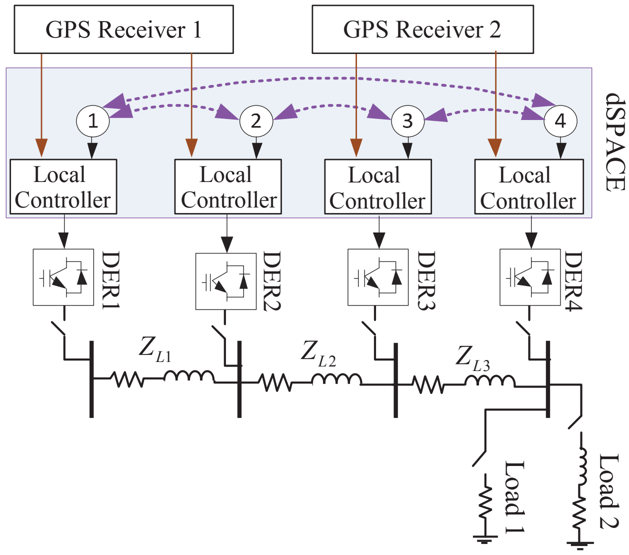
IV. EXPERIMENTAL RESULTS

The proposed method was implemented on a MG test bed, as shown in Fig. 4. The electrical and control parameters are listed in TABLE I. The test bed was prototyped in the Intelligent Microgrid Laboratory at Aalborg University [21]. The test setup is composed of four inverter-based DER units, which are supplied from a programmable DC supply.

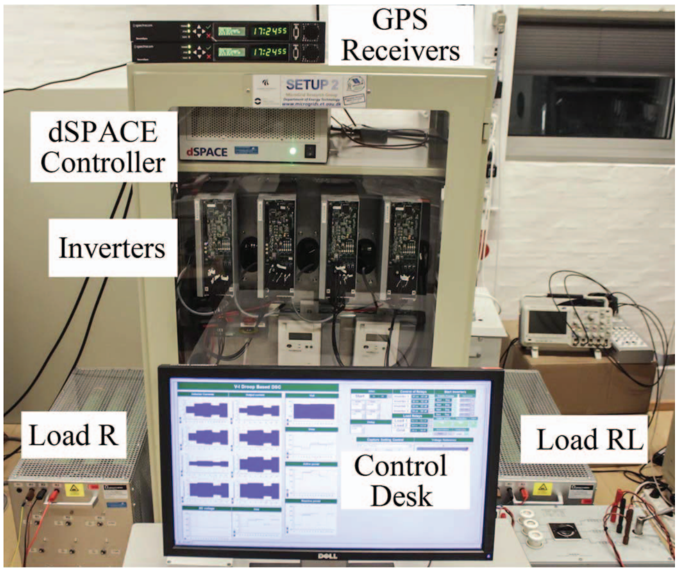
Each DER unit is controlled by a local controller. A ring-shaped communication network (shown as broken lines) is used to enable information exchange between the neighbor DER units. The proposed control routine is implemented in a dSPACE 1006 digital control system. In order to consider the communication constrains, each of the communication links is emulated in dSPACE as low bandwidth link with data rate of 100 samples per second and delay of 10ms. Two Spectracom ® GPS synchronization systems [22] are used to synchronize the local controllers with the UTC.

The DER units are interconnected through a resistive model with R/X ratio of around 7. The MG loads are modeled by a combination of resistive and inductive loads. To consider the worst case scenario, all loads are accumulated at the downstream bus.

In order to validate the efficacy of the proposed method, two case studies are presented; performance assessment, and plug'n'play capability. The experimental results are captured using dSPACE Control Desk program and plotted in MATLAB. The experimental results for the first study are shown in Fig. 5. Initially, load 1 is turned on and the distributed secondary controller (DSC) is disabled. As shown in Fig. 5 (a), the sharing of active power between the DERs, provided by the V-I droop mechanism, is affected by the line impedances. Specifically, DER4 provides the largest share (P4) due to its electrical closeness with the load. At $t = 3s$, Load 2 is turned on. It is observed that the load sharing accuracy is improved at higher loading conditions thanks to



(a)



(b)

Fig. 4. Experimental setup: a) Schematic diagram and b) Hardware prototype.

the adaptive droop function. Nevertheless, a considerable error is observed in both active and reactive power sharing. Additionally, the voltage of DER4 (V4) falls to 207V (see Fig. 5(c)), which is out of the permissible range (0.95pu-1.05pu). Subsequent to activation of the DSC at $t = 6s$, the load active power is proportionally shared between the DERs and the voltages are regulated within an acceptable range of the rated voltage. Additionally, the reactive power is properly shared between the DERs according to the available reactive current capacity. Load 2 is turned off and on at $t = 9$ s and 12 s, respectively. It is observed that the power sharing has an acceptable accuracy and the rms voltages remain within the permissible range during the transients.

In the second case study, plug'n'play capability of the proposed control method is examined. To that end, the

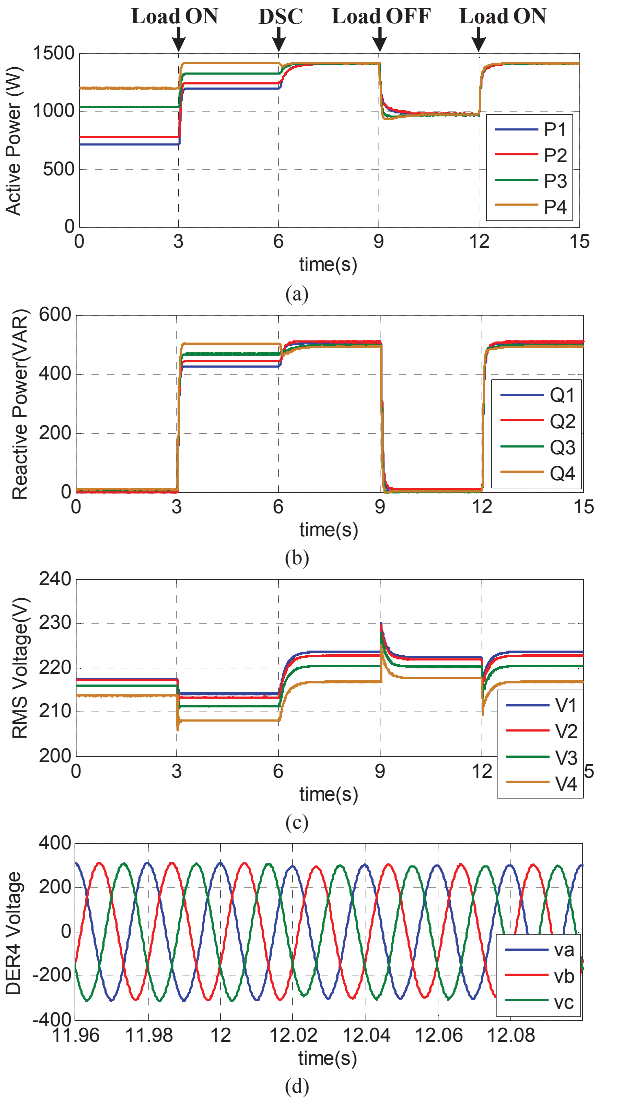


Fig. 5. Performance of the proposed method for the first scenario: a) active powers, b) reactive powers, c) rms voltages and d) DER4 voltage.

electrical connection of DER4 and accordingly all related communication links are disconnected at $t = 2s$. As illustrated in Fig. 6, the active and reactive power generations of DER1-3 are smoothly increased to compensate for the disconnection of DER4. Moreover, the voltages are maintained within an acceptable range of the rated value. The DER4 is reconnected at $t = 4s$. Following, the powers and voltages are smoothly changed back to their initial value. It should be pointed out that unlike the conventional droop method, the proposed method does not require any additional synchronization mechanisms e.g., PLL prior to reconnection of DER4.

V. Conclusions

In this paper, a new distributed control framework comprising of primary and secondary control levels is proposed for islanded MGs with resistive line impedances. In the primary level, V-I droop method is adopted as a decentralized control mechanism for fast sharing of load

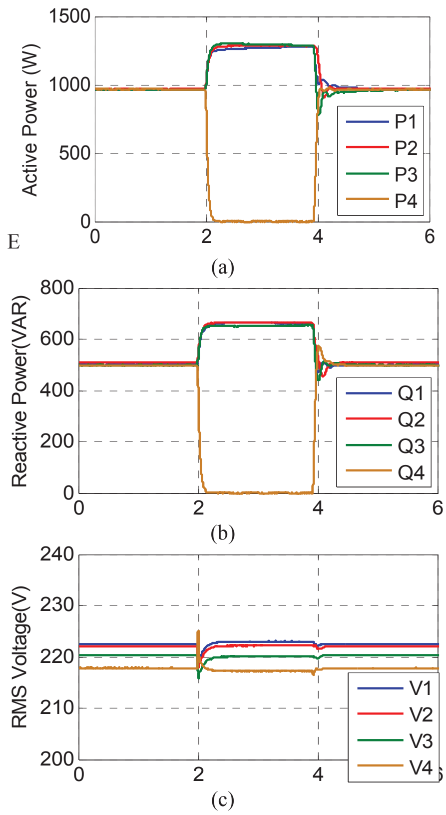


Fig. 6. Plug and play capability: a) active powers, b) reactive powers, c) rms voltages.

current. For the secondary level, a novel distributed control method is proposed. In this method, each of the control agents alters the d and q axis voltages according to the information received from neighbor agents so as to improve the voltage regulation and ensure proper sharing of active and reactive power. Since the proposed framework uses GPS timing to synchronize the control agents, it has an essential feature that no additional synchronization mechanisms are required while entering a new DER. Experimental results demonstrate the effectiveness of the proposed method in satisfying the control objectives.

VI. References

[1] A. Purvins, H. Wilkening, G. Fulli, E. Tzimas, G. Celli, S. Mocci, *et al.*, "A European supergrid for renewable energy: local impacts and far-reaching challenges," *Journal of Cleaner Production,* vol. 19, pp. 1909-1916, Nov. 2011.

[2] M. S. Golsorkhi and D. D. C. Lu, "A Control Method for Inverter-Based Islanded Microgrids Based on V-I Droop Characteristics," *IEEE Trans. Power Del.,* vol. 30, pp. 1196-1204, Jun. 2015.

[3] K. T. Tan, X. Y. Peng, P. L. So, Y. C. Chu, and M. Z. Q. Chen, "Centralized Control for Parallel Operation of Distributed Generation Inverters in Microgrids," *IEEE Trans. Smart Grid,* vol. 3, pp. 1977-1987, Dec. 2012.

[4] Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, "Distributed Secondary Control for Islanded Microgrids-A Novel Approach," *IEEE Trans. Power Electron.,* , vol. 29, pp. 1018-1031, Feb. 2014.

[5] A. Bidram and A. Davoudi, "Hierarchical Structure of Microgrids Control System," *IEEE Trans. Smart Grid,* vol. 3, pp. 1963-1976, May 2012.

[6] J. M. Guerrero, M. Chandorkar, T. Lee, and P. C. Loh, "Advanced Control Architectures for Intelligent Microgrids ; Part I: Decentralized and Hierarchical Control," *IEEE Trans. Ind. Electron.,* vol. 60, pp. 1254-1262, Apr. 2013.
[7] A. Bidram, A. Davoudi, and F. L. Lewis, "A Multiobjective Distributed Control Framework for Islanded AC Microgrids," *IEEE Trans. Ind. Informat.,* vol. 10, pp. 1785-1798, Aug. 2014.
[8] C. W. F. Guo, J. Mao and Y.-D. Song, "Distributed Secondary Voltage and Frequency Restoration Control of Droop-Controlled Inverter-Based Microgrids," *IEEE Trans. Ind. Electron.,* vol. vol. 62, no. 7, pp. 4355–4364, Jul. 2015.
[9] J. W. Simpson-Porco, Q. Shafiee, F. Dorfler, J. C. Vasquez, J. M. Guerrero, and F. Bullo, "Secondary Frequency and Voltage Control of Islanded Microgrids via Distributed Averaging," *IEEE Trans. Ind. Electron.,* vol. 62, pp. 7025-7038, Nov. 2015.
[10] L. Lin-Yu and C. Chia-Chi, "Consensus-Based Droop Control Synthesis for Multiple DICs in Isolated Micro-Grids," *IEEE Trans. Power Syst.,* vol. 30, pp. 2243-2256, Sept. 2015.
[11] M. S. Golsorkhi and D. D. C. Lu, "A Decentralized Control Method for Islanded Microgrids Under Unbalanced Conditions," *IEEE Trans. Power Del.,* vol. 31, pp. 1112-1121, Jun. 2016.
[12] M. S. Golsorkhi and D. D. C. Lu, "A decentralized negative sequence compensation method for islanded mirogrids," in *Proc. International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2015, pp. 1-7.
[13] M. Golsorkhi, D.D.C. Lu, and J. Guerrero, "A GPS-Based Decentralized Control Method for Islanded Microgrids," *IEEE Trans. Power Electron.,* Apr. 2016.
[14] M. S. Golsorkhi and D. D. C. Lu, "A decentralized power flow control method for islanded microgrids using V-I droop," in *Proc. Iranian Conference on Electrical Engineering (ICEE)*, 2014, pp. 604-609.
[15] A. Engler and N. Soultanis, "Droop control in LV-grids," in *Future Power Systems, 2005 International Conference on*, 2005, pp. 6 pp.-6.
[16] J. M. Guerrero, J. Matas, V. Luis Garcia de, M. Castilla, and J. Miret, "Decentralized Control for Parallel Operation of Distributed Generation Inverters Using Resistive Output Impedance," *IEEE Trans. Ind. Electron.,* vol. 54, pp. 994-1004, Apr. 2007.
[17] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, "Secondary Control for Voltage Quality Enhancement in Microgrids," *IEEE Trans. Smart Grid,* vol. 3, pp. 1893-1902, Jul. 2012.
[18] Y. A. R. I. Mohamed and E. F. El-Saadany, "Adaptive Decentralized Droop Controller to Preserve Power Sharing Stability of Paralleled Inverters in Distributed Generation Microgrids," *IEEE Trans. Power Electron.,* vol. 23, pp. 2806-2816, Nov. 2008.
[19] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and Cooperation in Networked Multi-Agent Systems," in *Proceedings of the IEEE,* vol. 95, pp. 215-233, Jan. 2007.
[20] J. Schiffer, T. Seel, J. Raisch, and T. Sezi, "Voltage Stability and Reactive Power Sharing in Inverter-Based Microgrids With Consensus-Based Distributed Voltage Control," *IEEE Trans. Control Syst. Technol.,* vol. 24, pp. 96-109, Jan. 2016.
[21] Microgrid Research programme", URL: www.microgrids.et.aau.dk.
[22] http://spectracom.com. *SecureSync Time & Frequency Reference System*. Available: http://spectracom.com/products-services/precision-timing/securesync-time-and-frequency-reference-system