Control of grid interactive AC microgrids

Wang, Xiongfei; Guerrero, Josep M. ; Chen, Zhe

Published in:
Proceedings of the IEEE International Symposium on Industrial Electronics, ISIE 2010

DOI (link to publication from Publisher):
10.1109/ISIE.2010.5637807

Publication date:
2010

Document Version
Early version, also known as pre-print

Citation for published version (APA):
Wang, X., Guerrero, J. M., & Chen, Z. (2010). Control of grid interactive AC microgrids. In *Proceedings of the IEEE International Symposium on Industrial Electronics, ISIE 2010* (pp. 2211-2216). IEEE Press. https://doi.org/10.1109/ISIE.2010.5637807

Control of Grid Interactive AC Microgrids

Xiongfei Wang[1], Josep M. Guerrero[2], Zhe Chen[1]
1. Institute of Energy Technology, Aalborg University, Denmark.
2. Technical University of Catalonia, Spain.
Email: xwa@iet.aau.dk

***Abstract*-Over the last decade, distributed energy resources (DER) technology has undergone a fast development. Increased penetration of DER units and wide spread use of renewable energy sources challenge the entire architecture of traditional power system. Microgrid, characterizing higher flexibility and reliability, becomes an attractive candidate for the configuration of future electrical power system. This paper gives a brief review of grid interactive ac microgrid configurations. Control methods for power electronics interfaced DER units in grid interactive ac microgrids are discussed. In addition, microgrid controls and power management strategies are presented. Future trends of microgrid are discussed pointing out how this concept can be a key to achieve a more intelligent and flexible AC grid.**

I. INTRODUCTION

Liberalized electricity market, environmental concerns with greenhouse gas emissions, energy efficiency, and diversified energy sources constitute the most important driving forces for the proliferation of distributed energy resource (DER) units in the electricity system. With the growing deployment of DER units, especially small-scale combined heat and power (CHP) plants and renewable energy sources (RES) based distributed generation (DG) units, distribution grids can no longer be considered as passive networks. The entire architecture of future electricity system must be redesigned to undertake increasingly complex operations. Three possible architectures are envisioned: Microgrids, Active Networks supported by ICT and the 'Internet' model [1].

Microgrids paradigm is becoming an increasingly attractive structure for the active distribution network. Microgrids connect multiple customers to multiple DER units including DG and distributed storage (DS) units as small distribution systems. Microgrids can operate in connection with the main grid and smoothly transfer to intentional or non-intentional islanding operation during grid disturbances such as grid faults and power quality events. To the utility a microgrid can be regarded as a controllable entity that operates as a single dispatchable load or generator, and provides power or ancillary services to meet the needs of upstream networks. To the customers microgrids provide both thermal and electricity needs and can meet their special demands, such as enhance local reliability, reduce feeder losses, improve power quality by supporting local voltage and reducing voltage sags, as well as offering uninterruptible power supply functions [2], [3]. Therefore, the microgrid concept presents a system approach to facilitate the integration of DER units at the distribution level and maximize their benefits to customers and utilities in a coordinated manner. The extensive research on microgrids and a number of worldwide demonstration projects, e.g. CERTS microgrid in USA, EU More microgrid in Europe, NEDO microgrid in Japan, and Hydro-Quebec microgrid in Canada, have shown problems and solutions in the microgrid field [4], [5].

In recent years, power electronics technology experiences a rapid development. The intensive use of power electronics systems not only furnishes cost-effective and flexible DER interfaces to the networks but also enables microgrids to properly control and manage the power and energy flows [6]. Moreover, by using Flexible AC Transmission Systems (FACTS) devices at lower voltage level, novel microgrid configurations and operations have been proposed for some specific applications [7].

This paper gives a brief review of grid interactive ac microgrids configurations. This is followed by a discussion of control schemes of power electronics interfaced DER units in a grid interactive ac microgrid. Then systematical analysis of line frequency ac microgrid controls and power management strategies are presented. Finally, future trends are discussed with the conclusion.

II. MICROGRID CONFIGURATIONS

A typical configuration of a grid interactive ac microgrid is illustrated in Fig. 1. Generally speaking, a microgrid consists of a static transfer switch (STS), single or multiple DG and DS units, distributed critical and noncritical loads, a power management system, and protection devices. Recent advances in power electronics and FACTS offer more options for microgrid architectures with different customer requirements. In terms of system frequency, grid interactive ac microgrids can be classified as high frequency ac (HFAC) microgrids [7] and line frequency ac (LFAC) microgrids [3].

A. HFAC Microgrids

From long time ago, there were well established distributed power buses for military and aircraft systems working in single-phase 400 Hz [8]. It is well known that by increasing the frequency, the size and weight of the power electronics equipment can be reduced. However, this High Frequency AC (HFAC) distributed power systems are limited to local areas, since the power losses and voltage drop increase with the line length and frequency in an HFAC system. Hence, this concept can be appropriate for small microgrids [35]. A paradigmatic example of an HFAC microgrid can be found in [7], which is made up of a single-phase 500 Hz High Frequency AC (HFAC) link, a unified power quality conditi-

978-1-4244-6392-3/10/$26.00 ©2010 IEEE

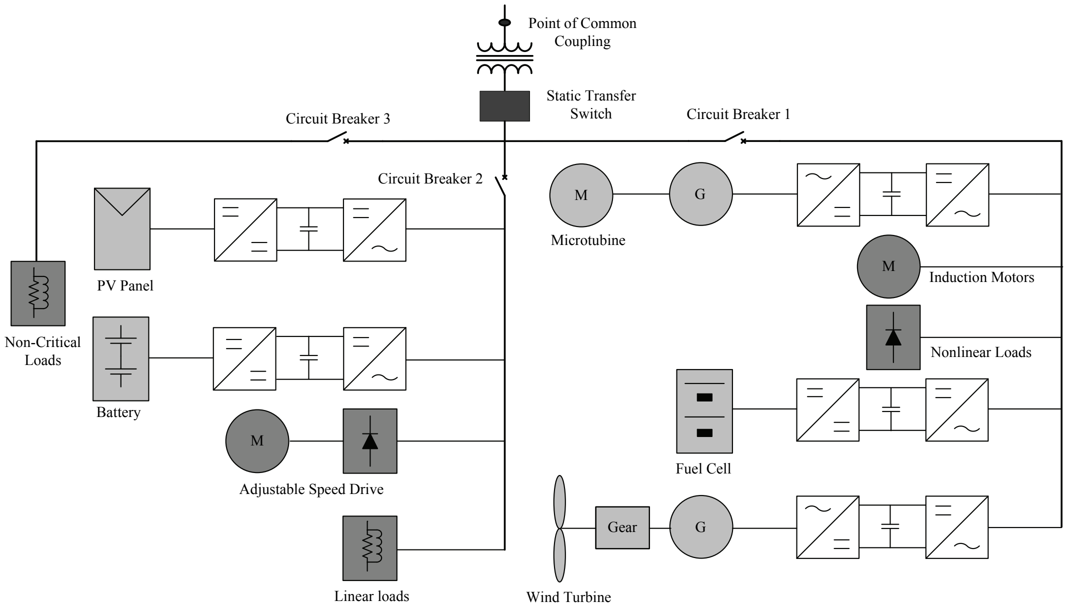

Fig. 1 The diagram of a typical ac microgrid.

oner (UPQC), and a universal active power line conditioner (UPLC). The UPQC is used to compensate for the voltage distortions caused by current harmonics injected by the nonlinear loads and the power electronics equipment. The UPLC, interconnecting the HFAC link to the main grid, is used to control the active and reactive power flow from/to the microgrid. It can be seen that the two-FACTS system constitutes the essential part of microgrid power flow control, thus making the microgrid operate at a high frequency for 400 Hz or 500 Hz applications.

B. LFAC Microgrids

Line Frequency AC (LFAC) microgrids have been the main research point since the microgrid concept was proposed. A wide variety of LFAC concepts and operation scenarios have been published previously in the literature. A systematically review on the control methods of DER units within a LFAC microgrid, and the microgrid control and power management strategies will be presented in the following sections.

III. Structures and Controls of DER Units

DER units in a microgrid can be distinguished by their interface characteristics as the conventional rotary DG units and electronically-coupled DER units [9]. Conventional DG units interface to the microgrid through generators, including fixed-speed wind turbines, reciprocating machines and small hydro engines. In contrast, the electronically-coupled DER units utilize power electronics converters to match their characteristics and the requirements of microgrid conditions. Electronically-coupled DER units mainly involve the DG units based on variable-speed wind turbines and other RES, microturbines, internal combustion engines (ICE), along with the DS units and plug-in vehicles.

A. Controls of Electronically-Coupled DER Units

As aforementioned in Section II, the paper is focused on grid-interactive ac microgrids. These microgrids can operate in grid-connected and intentional or non-intentional islanding modes, as well as smooth transitions between both modes are also desired. The complex dynamic behavior of such a microgrid challenges the control and power management strategies. However, power electronics interfaces introduce new control issues and possibilities for the DER units within the microgrid. Hence, two levels of controls for a grid-interactive ac microgrid are discussed following. The first level integrates the local control methods for electronically-coupled DER units, which include designing the inner current and voltage control loops and regulating the output voltage and current of each unit to follow the active and reactive power setpoints. The second control level involves the system controls of the microgrid and power management strategies, which will be addressed in Section V.

Control schemes for DER units within the microgrid are designed on the basis of the required functions and the possible operating conditions. In the microgrid, DER units can operate as grid-forming units, grid-feeding units and grid-supporting units. Table I shows the control methods for DR units in accordance with their different functions.

Grid-forming units regulate the system voltage and frequency through balancing the generation power and load demands when the microgrid operates in islanded mode [9], [10]. However, in grid-connected operation mode, as there are voltage and frequency references from the main grid, the grid-forming units are changed to function as grid-feeding units. Hence, the control methods for grid-forming units should be suitable for both microgrid operation modes, so as to ensure smooth transients during microgrid operation mode changes.

By using the conventional control method [11], there are two control modes: voltage-controlled mode and current-controlled mode, corresponding to islanded and grid-connected operations of the microgrid. The transitions between one and the other mode may bring voltage stability problems during the delay time caused by islanding detection, in case of non-intentional islanded mode. To cope with this problem, indirect current control algorithms [12], and ac voltage control loops have been widely implemented. Fig. 2 shows a diagram of the power control method through ac voltage regulation [13]. Moreover, in the case where two or more DER units operate as grid-forming units, the load demand sharing between them complicates more the control methods. In this sense, voltage and frequency droop-based method [14] and active current sharing control techniques [15] were developed, as will be discussed in Section V.

Grid-feeding units adjust the output active and reactive power (*P* and *Q*) based on the power dispatch strategies or the frequency and voltage variation of the load or the feeder. Grid-feeding units are operated by the current-controlled mode as normal grid-connected DER units. Many current control methods for grid-connected DER units have been presented [16]. In addition to the wide variety of current controllers, there are power control methods that can also be distinguished as voltage oriented control (VOC) and virtual flux oriented control. These control methods try to mimic the power electronic converter as a synchronous machine. Fig. 3 gives a general structure of VOC current control system. Three types of reference frame control strategies based on PI or proportional plus resonant (PR) controllers that can be used for VOC control purposes [16]. Instead of synchronizing with the grid voltage, virtual flux oriented control make the power control synchronized on the integral of voltage which can be viewed as a filtered grid voltage. In addition, the power control can also be performed together with the direct power control method [17]. Fig. 4 shows the structure of direct power control based on the virtual flux.

Furthermore, in order to maintain a stable power system with the high penetration of DER units, grid-connected DER units are required not only to comply with the grid requirements but also to ride through short grid disturbances [16]. On the other hand, in an islanded microgrid, switching of loads can also cause high voltage transients which require all DERs to support this disturbance [18]. To meet these requirements, the fault conditions in the utility gird and microgrid should be clarified. A detailed description about unbalanced grid faults is presented in [19]. The appearance of negative-sequence component in the grid voltage causes the second harmonic oscillation in the system of DER units. The control methods for DER units under grid fault conditions, in terms of requirements, are categorized as four groups in [16]. In such cases, the power calculation algorithm to generate the required current reference significantly influences the performance of control system. In this sense, several current reference generation methods for the real power control have been investigated in [20].

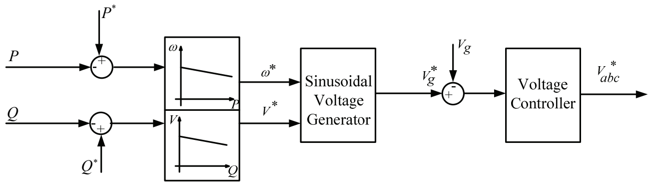

Fig. 2 Block diagram of the voltage and frequency droop based ac voltage controller.

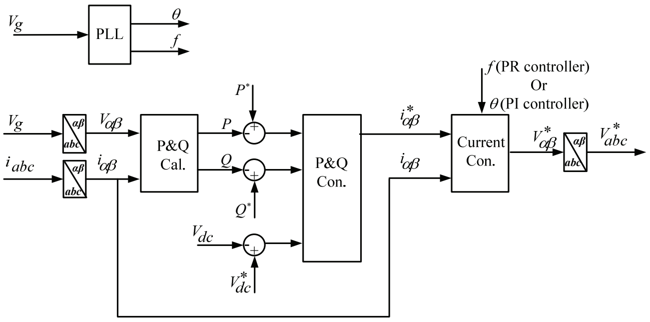

Fig. 3 A general scheme of VOC control system.

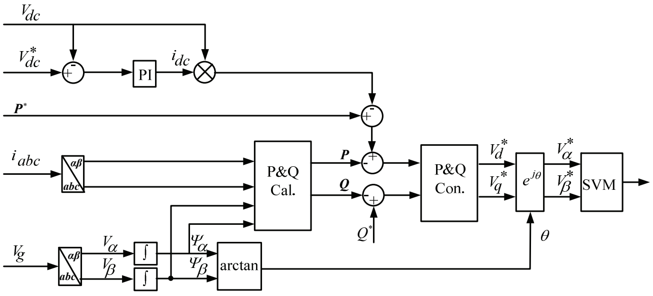

Fig. 4 Block diagram of direct power control based on the virtual flux.

TABLE I
CONTROL METHODS AND FUNCTIONS OF DER UNITS IN DIFFERENT OPERATING CONDITIONS

Operating Conditions	Functions	Control Methods
Grid-forming units	Voltage and frequency control	Hybrid ac voltage and current control, indirect current control, and ac voltage control
	Load demand sharing	Voltage and frequency droop method, active current sharing
Grid-feeding units	Power dispatch	Current control and ac voltage control, VOC and virtual flux, direct power control
	Real and reactive power support	Unity power factor control, positive sequence control, constant real and reactive power
Grid-Supporting units	Maximum real power output	MPPT
	Reactive power support	AC voltage control

Grid-supporting units here are different from grid parallel units defined in [10]. They are controlled to extract maximum real power from their primary energy source and the required reactive power to support grid voltage sags and local demands of reactive current. The control method for a small PV system with power quality conditioner has been reported recently in [21]. The ac voltage control method with a repetitive control loops to compensate selected harmonics was applied, along with a modified MPPT algorithm.

IV. MICROGRIDS CONTROL AND POWER MANAGEMENT

Grid interactive ac microgrids control involves significantly lot of issues somewhat different than in conventional distribution networks. A number of power electronics interfaces, inherently without inertias, and the intentional or non-intentional islanding operation modes challenge the control design of a microgrid and its power management system [22]. To ensure that a microgrid operates properly, several control tasks are imposed on the microgrid control and power management system. Generally, they are classified as short-term power balancing control and long-term energy management [9]. The short-term power balancing controller regulates the voltage and frequency of an ac microgrid, particularly during the transition between the operation modes. It is possessed of the following performances: instantaneous load following and sharing strategies, voltage and frequency restoration subsequent to transients, and resynchronization of the microgrid with the main grid. The long-term energy management dispatches the output power of DER units, controls the power exchanged between microgrid and main grid, and manages the load demands, so as to optimize the microgrid operation.

To perform these control tasks, a hierarchical control with four levels (level 0 to 3) is recently proposed in [23]. The control bandwidth is gradually decreased from level 0 to level 3. The primary control (level 1) and the secondary control (level 2) achieves the short-term power balancing control, while the tertiary control (level 3) performs the long-term energy management. The primary control provides the load following and load sharing strategies for the DER units during the transients. The secondary control restores frequency and voltage subsequent to transients, and the resynchronization with the main grid. Furthermore, in the case of islanded operation mode, load characteristics have large impact on the dynamic behavior of the microgrid [22]. To achieve the instantaneous load following requirements, the load controller integrated with load shedding strategy is essential to a microgrid without DS units. On the other hand, the load sharing strategies for different types of load is also important for the stabilization of frequency and voltage in a microgrid. In addition, the feeders with low X/R line impedance ratio are often used in low voltage distribution networks. This fact complicates the power sharing control, since the lines become mainly resistive and the active power injection cannot be achieved by increasing the power angle [24]. In view of this, possible short-term load sharing strategies and control architectures for long-term energy management system are discussed below.

A. Load Sharing Strategies in an AC Microgrid

Inertialess power electronics interfaces result in a challenge when pursuing load following capabilities for electronically-coupled DER units, but do offer the possibility of a more flexible control for load sharing. While many control strategies have been proposed for parallel operation of inverters, their applicability for load sharing between multiple electronically-coupled DER units should be further investigated [25]. With respect to the use of critical communication links, two main groups of strategies are available for load sharing between multiple DER units in an islanding ac microgrid, which include active load (current or power) sharing and droop control.

Active load (power/current) sharing methods involve the master-slave approach and the current limitation control [25]. In this kind of control strategies, a DER unit acting as the grid-forming (master) unit regulates the system voltage and frequency, whereas the rest of DER (slave) units receive the current references, through communication links, from either the master unit or the previous slave unit. Any DER unit in the microgrid can be the master. The most obvious drawback of this control method is that the limited communication bandwidth leads the master to take on most of nonlinear and unbalance loads in the microgrid [15].

Droop control is based on the well-known real power-frequency (P-ω) and reactive power-voltage (Q-V) droop characteristics of synchronous generators, as shown in Fig. 5 [14], [21]-[37]. Instead of using communication links, droop control enables DER unit in the microgrid to automatically share the total load through locally sensing its output voltage and current, thus achieving higher reliability and flexibility. In general, droop control can be further split into two types, i.e. single master control and multi-master control [22]. Single master control is the combination use of the master-slave method and droop control, which requires one DER unit to function as grid-forming unit (master), and the other units (slave) adjust the output real and reactive power based on the droop characteristics. Multi-master control is applied for the case that several DER units function as grid-forming units. Moreover droop control can be simply implemented by introducing the following P-ω and Q-V droop characteristics in the power controllers of DER units as shown in Fig. 2.

$$\omega = \omega^* - m(P - P^*) \tag{1}$$

$$V = V^* - n(Q - Q^*) \tag{2}$$

where $\omega^*$and V^* are the nominal system voltage frequency and amplitude, and m and n are the droop frequency and amplitude coefficients, respectively. P^* and Q^* are the real and reactive power setpoints whose values are generally determined by the energy management system. The controller gains m and n are chosen as a function of the P^* and Q^*, and the maximum allowed deviations in the system frequency and voltage amplitude.

However, due to the low X/R line impedance ratio of distribution feeders in low voltage microgrids, the P-ω and Q-V droop characteristics cannot be directly utilized for sharing loads between the directly coupled DER units. Then the droop control method in general form can be described as follows

$$\omega = \omega^* - m(P\sin\theta - Q\cos\theta) \tag{3}$$

$$V = V^* - n(P\cos\theta + Q\sin\theta) \tag{4}$$

where θ is the phase angle of the output impedance of the DER units, which determines the droop control law. Notice that this control law can be easily derived from the well-known Park transformation.

Hence, to decouple the real and reactive power flow (decoupling between P-ω and Q-V droop), interface inductors can be included between the DER units and the distribution feeder, but they are heavy and bulky [27]. Recently decoupled control of virtual real and reactive power through frame transformation is proposed, but it cannot share the actual real and reactive power between the DER units in the islanding operation mode [28]. There are some control methods that fix the output impedance of the units by emulating lossless resistors or reactors, which provides an alternative solution to decouple the control of real and reactive power flow [29] [30]. Nevertheless, while the power flow can be decoupled and the output impedance of the DER units can be well established, the line impedance is unknown, which can degrade the reactive power sharing. To solve this problem, injecting high-frequency signals through the power lines [31] or adding external data communication signals was developed [32]. Unfortunately, such communication among DER units increases complexity and reduces reliability.

It is important to note that the output impedance of DER unit can be altered by the feedback control. This provides a new control variable for the system dynamics of microgrids. Through the control of output impedance, adaptive output impedance method is proposed, which allows a good reactive power sharing with low sensitivity to the line-impedance [26]. Alternatively, an adaptive Q-V droop control algorithm based on a virtual inductance is presented to achieve accurate reactive power sharing [33].

Furthermore, due to the appearances of nonlinear and/or imbalance loads in ac microgrids, the harmonic and current sharing control is another challenging issue for the load sharing control. To cope with the nonlinear load sharing, in [34], a controller was proposed to share nonlinear loads by adjusting the output voltage bandwidth with the delivered harmonic power. But this method has two main constraints: the harmonic current sharing is achieved at the expense of reducing the stability of the system, and high-frequency signals injection limits the power rating of inverters. In another approach [35], every single term of the harmonic current is used to produce a proportional droop in the corresponding harmonic voltage term, which is added to the output-voltage reference. These control approaches have an inherent tradeoff between voltage regulation and power sharing. Nevertheless, the adjustable output impedance by adding virtual impedance provides several alternative methods [29] [30]. A parallel connected virtual resistive-impedance control method for harmonic current sharing is presented in [24]. Recently, a harmonic conductance and harmonic var droop is proposed based on the instantaneous power theory [36]. Moreover, for the imbalanced load situation, a secondary oscillation power and conductance droop is presented in [37]. However, these two methods are based on the assumption of balanced system voltage, which is not practical for the microgrid operating in the islanding mode.

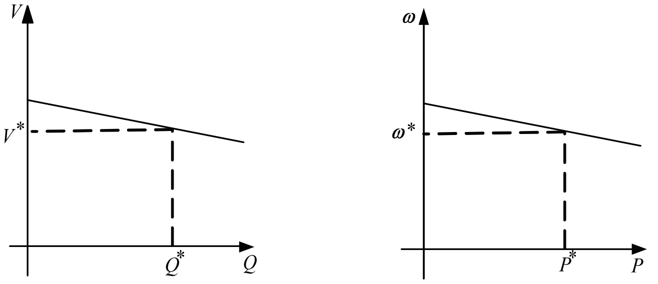

Fig. 5 Conventional Q-V and P-ω Droop characteristic.

B. Control Architectures for Energy Management

There are two types of supervisory control architectures (i.e. centralized or decentralized) for performing the microgrid energy management system. In the centralized control architecture, a microgrid central controller, on the basis of DER and load bids, security constraints and other factors, sends the control setpoints to the local controllers of gird-forming units and controllable load through the two-way communication links [38]. The disadvantage of centralized control is low reliability and redundancy. Also it requires the knowledge of all DER units and loads within it, and consequently reducing its scalability. Therefore, the decentralized control architecture is proposed to provide the plug-and-play feature. In the decentralized control, besides the power balancing control task, economic functions and power optimization algorithms are also imposed on the local controller of the DER units and controllable load. A multi-agent system (MAS) is developed for the decentralized control [39]. Those intelligent agents are a piece of software with autonomy, proactively, and social ability to co-operate with other agents by means of some communication language. The agent platform is a software environment in which software agents run. It consists of the machines, operating system, agent management system and the agents.

V. CONCLUSIONS

This paper gives an overview of grid interactive ac microgrids structures, controls, and energy managements. The locally control methods for DER units and microgrid controls as well as power management strategies were presented. It can be seen that the plug-and-play capability of DER units is essential to enable microgrid to meet the future smartgrid challenges. Furthermore, the discussions of AC microgrid configurations showed that the FACTS-aided microgrids provide an enhanced power quality.

Finally, the multilevel hierarchical control approach for modern microgrids points out that microgrid technologies are developing fast along with telecommunication infrastructures and information technologies.

REFERENCES

[1] European Commission – New ERA for electricity in Europe. Distributed Generation: Key Issues, Challenges and Proposed Solutions, EUR 20901, 2003, ISBN 92-894-6262-0.

[2] R. Lasseter, "Microgrids", in *Proc. IEEE PES Winter Meeting*, 2002, pp. 305-308.

[3] MICROGRIDS−Large scale integration of micro-generation to low voltage grids. (2002, May). EU Contract ENK5-CT-2002-00610, Tech. Annex [Online]. Available: http://microgrids.power.ece.ntua.gr.

[4] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power Energy Mag.*, vol. 6, no. 4, pp. 78-94, Jul./Aug., 2007.

[5] M. Barnes, J. Kondoh, H.Asano, J. Oyarzabal, G. Venkataramanan, R. Lasseter, N. Hatziargyriou, and T. Green, " Real-world MicroGrids-an overview," in *Proc. IEEE International Conference on System of Systems Engineering*, 2007, pp. 1-8.

[6] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron.*, vol. 19, pp. 1184-1194, Sept., 2004.

[7] S. Chakraborty, M. D. Weiss, and M. G. Simoes, "Distributed intelligent energy management system for a single-phase high-frequency ac microgrid," *IEEE Trans. Ind. Electron.,* vol. 54, no. 1, pp. 1-13, Feb., 2007.

[8] U. Borup, B. Nielsen, and F. Blaabjerg, "Compensation of cable voltage drop and automatic identification of cable parameters in 400 Hz ground power units," *IEEE Trans. Ind. Appl.,* vol. 40, no. 5, pp. 1281-1286, Sep./Oct., 2004.

[9] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," *IEEE Power and Energy Mag.,* vol. 6, no. 3, pp. 54 -65, May/Jun., 2008.

[10] P. Strauss and A. Engler, "AC coupled PV hybrid systems and microgrids-state of the art and future trends," in *Proc. World Conf. on Photovoltaic Energy Conversion*, 2001, pp.2129-2134.

[11] R. Tirumala, N. Mohan, and C. Henze, "Seamless transfer of grid-connected PWM inverters between utility-interactive and stand-alone modes," in *Proc. IEEE APEC*, 2002, pp.1081-1086.

[12] H. Kim, T. Yu, and S. Choi, "Indirection current control algorithm for utility interactive inverters in distributed generation systems," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp.1342-1347, May, 2008.

[13] Z. Chen and Y. Hu, "Control of power electronic converters for distributed generation units" in *Proc. IEEE IECON*, 2005, pp. 1317-1322.

[14] M. Chandokar, D. Divan, and R. Adapa, "Control of parallel connected inverters in standalone ac supply systems," *IEEE Trans. Ind. Appl.*, vol. 29, no. 1, pp. 136-143, Jan., 1993.

[15] T. Green and M. Prondanovic, "Control of inverter-based micro-grids," *Electric Power Systems Research*, vol. 77, no. 9, pp. 1204-1213, Jul., 2007.

[16] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. Timbus, "Overview of control and grid synchronization for distributed power generation system," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398-1409, Oct., 2006.

[17] M. Malinowski, M. Kazmierkowski, S. Hansen, and F. Blaabjerg, "Virtual-flux-based direct power control of three-phase PWM rectifiers," *IEEE Trans. Ind. Appl.*, vol. 37, no. 4, pp. 1019-1027, Jul./Aug., 2001.

[18] M. Prodanovic and T. Green, "High-quality power generation through distributed control of a power park microgrid," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1471-1482, Oct., 2006.

[19] A. Jouanne and B. Banerjee, "Assessment of voltage unbalance," *IEEE Trans. Power Del.*, vol. 16, no. 4, pp. 782-790, Oct., 2001.

[20] P. Rodriguez, A. Timbus, R. Teodorescu, M. Liserre, and F. Blaabjerg, "Flexible active power control of distributed power generation systems during grid faults," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2583-2592, Oct., 2007.

[21] J. C. Vasquez, R. Mastromauro, J. M. Guerrero, and M. Liserre, "Voltage support provided by a droop-controlled multifunctional inverter," *IEEE Trans. Ind. Electron.*, vol. 56, no. 11, pp. 4510-4519, Nov. 2009.

[22] J. Lopes, C. Moreira and A. Madureira, "Defining control strategies for MicoGrids islanded operation," *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 916-924, May, 2006.

[23] J. M. Guerrero, J. C. Vasquez and R. Teodorescu, "Hierarchical control of droop-controlled DC and AC microgrids−a general approach towards standardization," in *Proc. IEEE IECON*, 2009, pp. 4341-4346.

[24] J. M. Guerrero, J. Matas, L. G. Vicuna, M. Castilla, and J. Miret, "Decentralized control for parallel operation of distributed generation inverters using resistive output impedance," *IEEE Trans. Ind. Eelectron.*, vol. 54, no. 2, pp. 994-1004, Apr., 2007.

[25] J. M. Guerrero, L. Huang, and J. Uceda, "Control of distributed uninterruptible power supply systems," *IEEE Trans. Ind. Eelectron.*, vol. 55, no. 8, pp. 2845-2859, Agu., 2008.

[26] J. M. Guerrero, J. Matas, L. G. Vicuna, M. Castilla, and J. Miret, "Wireless-Control strategy for parallel operation of distributed-generation inverters," *IEEE Trans. Ind. Eelectron.*, vol. 53, no. 5, pp. 1461-1470, Oct., 2006.

[27] M. Chandorkar, D. Divan, Y. Hu and B. Barnajee, "Novel architectures and control for distributed UPS system," in *Proc. IEEE APEC,* 1994, pp. 683-689.

[28] K. Brabandere, B. Bolsens, J. Keybus, A. Woyte, J. Driesen, and R. Belmans, "A voltage and frequency droop control method for parallel inverters," *IEEE Trans. Ind. Eelectron.*, vol. 22, no. 4, pp. 1107-1115, Jul., 2007.

[29] S. Chiang, C. Yen, and K. Chang, "A multimodule prallelable series-connected PWM voltage regulator," *IEEE Trans. Ind. Eelectron.*, vol. 48, no. 3, pp. 506-516, Jun., 2001.

[30] A. Engler, "Control of parallel operating battery inverters," in *Proc. PV Hybrid Power Syst. Conf.,* 2000, CD-ROM.

[31] A. Tuladhar, H. Jin, T. Unger, and K. Mauch, "Control of parallel inverters in distributed ac power systems with consideration of line impedance," *IEEE Trans. Ind. Appl.*, vol. 36, no. 1, pp. 131-138, Jan./Feb., 2000.

[32] M. Marwali, J. Jung, and A. Keyhani, "Control of distributed generation systems−Part II: Load sharing control," *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp.1551-1561, Nov. 2004.

[33] Y. Li, and C. Kao, "An accurate power control strategy for power electronics interfaced distributed generation units operating in a low voltage multibus microgrid," *IEEE Trans. Power Electron.*, in press.

[34] A. Tuladhar, H. Jin, T. Unger, and K. Mauch, "Parallel operation of single phase inverter modules with no control interconnections," in *Proc. IEEE APEC*, 1997, pp. 94-100.

[35] U. Borup, F. Blaabjerg, and P. Enjeti, "Sharing of nonlinear load in parallel-connected three-phase converters," *IEEE Trans. Ind. Appl.*, vol. 37, no. 6, pp. 1817-1823, Nov./Dec., 2001.

[36] T. Lee, and P. Cheng, "Design of a new cooperative harmonic filtering strategy for distributed generation interface converters in an islanding network," *IEEE Trans. Power Electron.*, vol. 22, no. 5, pp. 1919-1927, Sep., 2007.

[37] P. Cheng, C. Chen, T. Lee, and S. Kuo, "A cooperative imbalance compensation method for distributed-generation interface converters," *IEEE Trans. Ind. Appl.*, vol. 45, no. 2, pp. 805-815, Mar./Apr., 2009.

[38] A. Tsikalakis and N. Hatziargyriou, "Centralized control for optimizing microgrids operation," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 241-248, Mar., 2008.

[39] L. Dimeas and N. Hatziargyriou, "Operation of a multiagent system for microgrid control," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1447-1455, Aug., 2005.