Advanced Control Architectures for Intelligent MicroGrids – Part I: Decentralized and Hierarchical Control

Josep M. Guerrero, *Senior Member, IEEE,* Mukul Chandorkar, *Member, IEEE,* Tzung-Lin Lee, *Member, IEEE,* and Poh Chiang Loh, *Senior Member, IEEE*

***Abstract*— This paper presents a review of advanced control techniques for microgrids. The paper covers decentralized, distributed, and hierarchical control of grid connected and islanded microgrids. At first, decentralized control techniques for microgrids are reviewed. Then, the recent developments in the stability analysis of decentralized controlled microgrids are discussed. Finally, hierarchical control for microgrids that mimic the behavior of the mains grid is reviewed.**

***Index Terms*—Microgrids, Hierarchical Control, Distributed Control, Electrical Distribution Networks, Droop Method.**

I. INTRODUCTION

THE promise of the smart grid is round the corner. However, research and society cannot wait for the approval of many standards and grid codes, especially when these codes can restrict more the independence of the electricity users from the suppliers. In this sense, the demand side management can be satisfied by using local energy storage and generation systems, thus performing small grids or microgrids. Microgrids should able to locally solve energy problems, hence increase flexibility and flexibility. Power electronics plays an important role to achieve this revolutionary technology. We can imagine the future grid as a number of interconnected microgrids in which every user is responsible for the generation and storage part of the energy that is consumed, and to share the energy with the neighbors [1].

Hence, microgrids are key elements to integrate renewable and distributed energy resources as well as distributed energy storage systems. In this sense, new power electronic equipment will dominate the electrical grid in the next decades. The trend of this new grid is to become more and more distributed, and hence the energy generation and consumption areas cannot be conceived separately [5]-[7]. Nowadays electrical and energy engineers have to face a new scenario in which small distributed power generators and dispersed energy storage devices have to be integrated together into the grid. The new electrical grid, also named smart-grid (SG), will deliver electricity from suppliers to consumers using digital technology to control appliances at consumer's homes to save energy, reducing cost and increase reliability and transparency. In this sense, the expected whole energy system will be more interactive, intelligent, and distributed. The use of distributed generation (DG) makes no sense without using distributed storage (DS) systems to cope with the energy balances.

Microgrids, also named minigrids, are becoming an important concept to integrate DG and DS systems. The concept has been developed to cope with the penetration of renewable energy systems, which can be realistic if the final user is able to generate, store, control, and manage part of the energy that will consume. This change of paradigm, allows the final user be not only a consumer but also a part of the grid.

Islanded microgrids have been used in applications like avionic, automotive, marine, or rural areas [2]-[8]. The interfaces between the prime movers and the microgrids are often based on power electronics converters acting as voltage sources (voltage source inverters, VSI, in case of AC-microgrids) [9], [10]. These power electronics converters are parallel connected through the microgrid. In order to avoid circulating currents among the converters without the use of any critical communication between them, the droop control method is often applied [11]-[15].

In case of paralleling inverters, the droop method consist of subtracting proportional parts of the output average active and reactive powers to the frequency and amplitude of each module to emulate virtual inertias. These control loops, also called *P–f* and *Q–E* droops, have been applied to parallel-connected uninterruptible power systems (UPS) in order to avoid mutual control wires while obtaining good power sharing [16]-[20]. However, although this technique achieves high reliability and flexibility, it has several drawbacks that limit its application.

For instance, the conventional droop method is not suitable when the paralleled-system must share nonlinear loads, because the control units should take into account harmonic currents, and, at the same time, to balance active and reactive power. Thus, harmonic current sharing techniques have been proposed to avoid the circulating distortion power when sharing

---

Manuscript received May 27, 2011.

J. M. Guerrero is with the Department of Energy Technology, Aalborg Univeristy, 9220 Aalborg East, Denmark (Tel: +45 2037 8262; Fax: +45 9815 1411; e-mail: joz@et.aau.dk).

M. Chandorkar is with the Indian Institute of Technology, Bombay, India.

T.-L. Lee is with the department of electrical engineering, National Sun Yat-sen University, Kaohsiung, Taiwan.

P. C. Loh is with the Nanyang Technological University, Singapore.

nonlinear loads. All of them consist in distorting the voltage to enhance the harmonic current sharing accuracy, resulting in a trade-off. Recently, novel control loops that adjust the output impedance of the units by adding output virtual reactors [17] or resistors [16] have been included into the droop method, with the purpose of sharing the harmonic current content properly. Further, by using the droop method, the power sharing is affected by the output impedance of the units and the line impedances. Hence, those virtual output impedance loops can solve this problem. In this sense, the output impedance can be seen as another control variable.

Besides, another important disadvantage of the droop method is its load-dependent frequency and amplitude deviations. In order to solve this problem, a secondary controller implemented in the microgrid central control can restore the frequency and amplitude in the microgrid.

In this paper, a review of advanced control techniques for microgrids is provided. The paper is organized as follows. In Section II decentralized control techniques for microgrid are reviewed. In Section III recent developments in the stability analysis of decentralized controlled microgrids are discussed. Section IV presents the hierarchical control architecture for microgrids. Finally, Section V presents the conclusions of the paper.

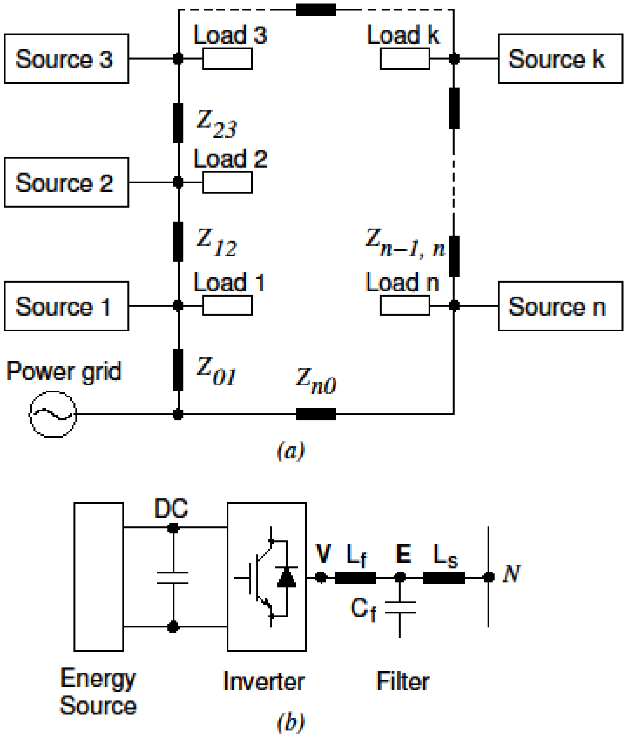


Fig. 1. Microgrid with distributed sources and loads

II. REVIEW OF MICROGRID DECENTRALIZED CONTROL METHODS

The aim of this Section is to review recent work in microgrid decentralized control. The emphasis is on control affecting microgrid dynamic behavior on a relatively fast time scale, while the issue of load planning and scheduling has been left out of this review.

A key feature of microgrids with distributed energy sources is that the sources are dispersed over a wide area. These sources are interconnected to each other and to loads by a distribution network. Further, the distributed microgrid may be connected to the main power grid at some point as well. Fig. 1(a) shows a distributed microgrid structure connected to the main grid. The figure also shows the microgrid line impedances ($Z_{01}, Z_{12}, \ldots Z_{n-1,n}$). The source is connected to the microgrid distribution network by an inverter interface through a filter, e.g. an *LCL* filter, shown in Fig. 1(b).

The control of the inverter+filter interfaces is crucial to the operation of the microgrid. Because of the distributed nature of the system, these interfaces need to be controlled on the basis of local measurements only; it is not desirable to use data communication. The decentralized control of the individual interfaces should address the following basic issues.

- The interfaces should share the total load (linear or nonlinear) in a desired way.
- The decentralized control based on local measurement should guarantee stability on a global scale.
- The inverter control should prevent any dc voltage offsets on the microgrid.
- The inverter control should actively damp oscillations between the output filters.

From the viewpoint of decentralized control, it is convenient to classify distributed generation architectures into three classes with respect to the interconnecting impedances Z_{01} etc., shown in Fig. 1(a). In highly dispersed networks, the impedances are predominantly inductive and the voltage magnitude and phase angle at different source interconnects can be very different. In networks spread over a smaller area, the impedances are still inductive but also have a significant resistive component. The voltage magnitude does not differ much, but the phase angles can be different for different sources. In very small networks, the impedance is small and predominantly resistive. Neither magnitude nor phase angle differences are significant at any point. In all cases, the main common quantity is the steady-state frequency which must be the same for all sources. In the grid-connected mode, the microgrid frequency is decided by the grid. In the islanded mode, the frequency is decided by the microgrid control.

In each of these classes, if every source is connected to at most two other sources as shown in Fig. 1(a), then the microgrid is *radial*. Otherwise, it is *meshed*. If there is a line connecting Source 1 with Source *k* in Fig. 1(a), then it is a meshed microgrid. By far the largest body of research work done in decentralized microgrid control has been for radial architectures of the type described in [1].

Early work on decentralized parallel inverter control concepts suitable for microgrid operation was reported in [2]. This work assumed that the impedance connecting sources was predominantly inductive; resistance was neglected. Based on the decentralized control used in conventional power systems, the use of droops is introduced in the generators, hence adjusting the frequency set-point according to the output active power, and voltage magnitude set-point depending on the output reactive power. It was shown that the distributed system could be operated without the use of phase-locked loops

(PLLs), and that total load real- and reactive-power could be shared based on the converter ratings.

Subsequent work [3], [4] extended the droop concept to ensure sharing of harmonic currents of non-linear loads. This was done by extending the droop concept by making the sources inject control signals into the network at a frequency which droops as the shared quantity increases. PLLs in remote units extract this information and adjust their output. Although interesting, this approach has not yet been investigated fully to study the issues of voltage distortion and noise immunity.

In further investigation of the droop concept, some researchers [5]-[7] have proposed power-*angle* droop control, in which the phase angle of the distributed source voltage, relative to a system-wide common timing reference, is set according to a droop law. One possible source for the common timing reference is the Global Positioning System (GPS). The GPS provides a 1-pulse-per-second (1PPS) signal [8], the rising edge of which is simultaneous globally to within 1 µs. The 1PPS signal can be used to synchronize local clocks in the distributed sources. The local clock is used to generate the timing reference with which the output voltage phase is measured. An alternative, in the near future, to the GPS clock signal may be an implementation of the Precision Time Protocol (PTP), defined in IEEE Standard 1588-2008 [9]. Angle control has the advantage that power sharing can be achieved without a change in the system frequency during islanded operation. No communication is needed between sources. However, those issues of system stability, loss of the global synchronizing signal at a few units, fallback to power-frequency droop operation, and grid-interactive operation need to be explored further.

Droop-based control methods have a drawback: in the islanded mode, the voltage and frequency of the microgrid change with change in load. Steeper droops ensure better load sharing, but also result in larger frequency and voltage deviations. If it is intended that microgrid sources conform to IEEE Standard 1547-2003 [10], then there should be a mechanism to restore the system frequency and voltage to nominal values following a load change [11], [12]. Following the term used in electric power system control, this restoration mechanism is termed as *secondary control* of voltage and frequency, and takes place over a longer time scale. In this regard, in addition to decentralized control, several researchers have considered the use of low-bandwidth communication channels between source controllers for the secondary control functions of restoration, load sharing and management [13]-[15].

Researchers have also recognized that the conventional frequency- and voltage-droop methods proposed in earlier work have limitations when the microgrid interconnecting impedances have a significant resistive component [16]-[23]. In this situation, the active power vs. frequency droop (*P–f* droop) and the reactive power vs. voltage droop (*Q–E* droop), taken from conventional power system control practice, are not valid. Thus, the real power is affected more by voltage magnitude and the reactive power is affected more by phase angle difference [16], [17]. The droop controller is modified accordingly for resistive impedance, obtaining *P–E* and *Q–f* droops.

There are two main approaches to addressing the effect of the interconnecting line impedance on droop based control. The first approach decouples the voltage and frequency droop controls by analyzing and compensating for the effect of the line impedance on active and reactive power flows. The second approach introduces virtual impedance at the converter output through closed loop converter control.

The authors of [20] adopt the first approach. They report the way in which frequency and voltage influence active and reactive power for different inductance to resistance ratios of the interconnecting line. They propose a way to decouple the frequency and voltage control droops by the use of a reference frame transformation that depends on knowledge of the line reactance to resistance ratio.

The second approach to addressing the line impedance issue is presented in [16], in which virtual resistive output impedance is introduced by modifying the output voltage reference based on output current feedback. With resistive impedance, the voltage and frequency droop controllers are decoupled.

The use of inductive virtual impedance at the converter output is reported in [22]. Output current feedback is used to implement a controller that presents a virtual inductor at the converter output. The frequency and voltage droops are decoupled with a virtual inductor at the output, and the conventional droop schemes can be used.

The virtual impedance method has the advantage over the decoupling method in that it is insensitive to the nature of the line impedance [16]. Thus, an overall decentralized control strategy could include virtual impedance control in conjunction with droops, and secondary control to restore the system frequency and voltage [19].

It is worth noting that the majority of work done on microgrid decentralized control has been for radial microgrid topologies. The decentralized control of interfaces in meshed topologies is an area that needs further research.

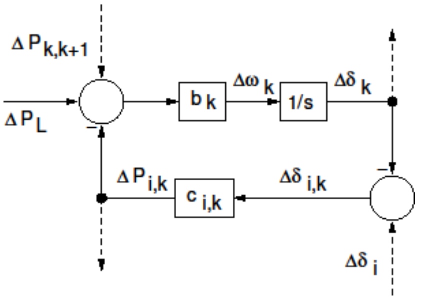


Fig. 2. Radial microgrid power-frequency droop control: small-signal behavior

III. STABILITY ANALYSIS OF DECENTRALIZED CONTROLLED MICROGRIDS

Stability is a critical issue in a microgrid in which the source power electronic interfaces are controlled in a decentralized way. Each interface is controlled based only on local measurement, and so it is important to analyze how the individual control systems interact to ensure overall stability. In this regard, if a steady state can be reached in which the fundamental components of all voltages in the microgrid have constant amplitudes and constant relative phase angle differences, then the system is stable. In this section we review results of microgrid stability analysis, and also present recent results in the testing of decentralized controllers.

By far the largest body of work done in microgrid stability analysis is for radial microgrids. Stability studies for meshed microgrids have still not been reported significantly in the literature, and are an open research area.

Stability analysis studies typically assume that frequency deviations are small even transiently, so that all impedances in the network can be assumed constant. This assumption results in a significant simplification in the analytical formulation of microgrid stability.

Early work towards a generalized approach for analyzing the small-signal stability of interconnected inverter systems was reported in [24]. This was reported for a radial architecture with inductive line impedances, inverters controlled by power-frequency droops, constant output voltage amplitude, and fast response of the inner voltage control loop. It was shown that such a system is always small-signal stable regardless of the number of interfaces, and has only non-oscillatory response to load changes. The control interconnections for such a system are shown in Fig. 2. In this figure, i and k are indices for the parallel inverters in the radial system. The constant b is the droop value, and the constant c depends on the voltage magnitude and line impedance. $\Delta\delta$ is a small change in the voltage phase angle from its nominal value, and ΔP is a small change in power flow from its nominal value. It was also shown that large values of the power-frequency droops violate the condition on the inner voltage control loop, and the network becomes unstable.

This result was extended in [25] with the inclusion of reactive power-voltage magnitude droops for the interface inverters. While the inner voltage control loop dynamics were ignored, a frequency restoration controller was included in the small-signal stability analysis. The authors showed that a radial microgrid with inductive interconnects is small-signal stable in the presence of both, frequency and voltage droops. The studies of [24] and [25] show that a radial microgrid with inductive interconnecting impedances, having fast voltage control loops, and controlled by frequency and voltage droops, will always be small-signal stable for reasonable values of droop gains, regardless of the microgrid size.

Recognizing that the nominal operating point used for small-signal analysis changes with change in frequency and voltage in a microgrid, the authors of [26] investigate the dependence of the small-signal stability on the operating point. The authors propose a method, based on the operating point, to set droop gains adaptively. However, the analysis is limited to a system with three sources.

Further investigation of the effect of droop gains on microgrid stability margin is carried out in [27]. Rather than changing the droop gains constantly depending on the operating point, the authors suggest the use of limit cases to set limits on the values of the droop gains. The limit cases are constructed off-line, based on knowledge of the microgrid structure. The authors present cases that achieve acceptable transient behavior with acceptable stability margins. A radial microgrid structure is assumed.

An interesting case study of small-signal modeling of a microgrid that is supplied by both, a synchronous generator and an inverter-interfaced energy source, is presented in [28]. The generator electromechanical model and the excitation system model are linearized about an operating point. The inverter and its control are similarly modeled and linearized. The combined linearized model can be used for small-signal stability studies. However, while the study is limited to two distributed sources, it is not clear how the approach can be scaled to address small-signal stability of larger systems.

A computational approach to determining microgrid stability, scalable to large systems, is presented in [29]. The approach considers the overall stability as affected by the droop control gains. Scalability is achieved by model order reduction. Using a three-inverter radial microgrid as a test case, the authors show that high values of frequency droop gains compromise the stability of the overall microgrid, but voltage droop gains do not have a significant effect on stability. Another scalable, computational approach to microgrid modeling is given in [29] and [30]. This approach uses the Automated State Model Generation algorithm proposed in [31] to develop the microgrid transient model systematically. The model can then be used either as part of a transient simulation program to study large-signal behavior, or as part of a computational program to study small-signal stability. While most stability studies have considered radial microgrid topologies, we feel that computational approaches such as in [30] may be very suitable for the stability studies of meshed topologies.

An important aspect of proving microgrid stability in specific cases is to have the ability to test microgrid controllers in real-time hardware-in-loop (HIL) simulation. An example of this testing is provided in [23] and [32] in which the microgrid dynamics are simulated on a real-time digital simulator, and the controller is interfaced to the simulator. Both [23] and [32] report the use of a commercial real-time simulator to implement the microgrid model.

IV. HIERARCHICAL CONTROL OF MICROGRIDS

Microgrids are now in the cutting edge of the state of the art [1]. However, the control and management of such a systems needs still further investigation. Microgrids for standalone and grid-connected applications have been considered in the past as separated approaches. Nevertheless, nowadays is necessary to conceive flexible microgrids able to operate in both grid-connected and islanded modes [19]. Thus, the study of topologies, architectures, planning, and configurations of microgrids are necessary. This is a great challenge due to the need of integrating different technologies of power electronics, telecommunications, generation and storage energy systems, among others. In addition, islanding detection algorithms for microgrids are necessary for ensuring a smooth transition between grid-connected and islanded modes. Furthermore, security issues such as fault monitoring, predictive maintenance, or protection are very important regarding microgrids feasibility.

This section deals with the hierarchical control of microgrids, consisted in three control levels. UCTE (Union for the Co-ordination of Transmission of Electricity, Continental Europe) have defined a hierarchical control for large power systems, as shown in Fig. 3. In such a kind of systems, it is supposed to operate over large synchronous machines with high inertias and inductive networks. However, in power electronic based microgrids there are no inertias and the nature of the networks is mainly resistive, as discussed in Section II. Consequently there are important differences between both systems that we have to take into account when designing their control schemes. This three-level hierarchical control is organized as follows [48]. The primary control deals with the inner control of the DG units by adding virtual inertias and controlling their output impedances. The secondary control is conceived to restore the frequency and amplitude deviations produced by the virtual inertias and output virtual impedances. The tertiary control regulates the power flows between the grid and the microgrid at the point of common coupling (PCC).

A. Inner control loops

The use of intelligent power interfaces between the electrical generation sources and the microgrid is mandatory. These interfaces have a final stage consisting of dc/ac inverters, which can be classified in current-source inverters (CSIs), consisted of an inner current loop and a PLL to continuously stay synchronized with the grid, and voltage-source inverters (VSIs), consisted of an inner current loop and an external voltage loop. In order to inject current to the grid, CSIs are commonly used, while in island or autonomous operation, VSIs are needed to keep the voltage stable.

VSIs are very interesting for microgrid applications since they do not need any external reference to stay synchronized. Furthermore, VSIs are convenient since they can provide to distributed power generation systems performances like ride-through capability and power quality enhancement. When these inverters are required to operate in grid-connected mode, they often change its behavior from voltage to current sources. Nevertheless, to achieve flexible microgrid, i.e., able to operate in both grid-connected and islanded modes, VSIs are required to control the exported or imported power to the mains grid and to stabilize the microgrid [19].

VSIs and CSIs can cooperate together in a microgrid. The VSIs are often connected to energy storage devices, fixing the frequency and voltage inside the microgrid. The CSIs are often connected to photovoltaic (PV) or small wind-turbines (WT) that require for maximum power point tracking (MPPT) algorithms, although those DG inverters could also work as VSIs if necessary. Thus, we can have a number of VSIs and CSIs, or only VSIs, connected in parallel forming a microgrid.

B. Primary control

When connecting two or more VSIs in parallel, circulating active and reactive power can appear. This control level adjusts the frequency and amplitude of voltage reference provided to the inner current and voltage control loops. The main idea of this control level is to mimic the behavior of a synchronous generator, which reduces the frequency when the active power increases. This principle can be integrated in VSIs by using the well known *P/Q* droop method [2]:

$$f = f^* - G_P(s)\cdot\left(P - P^*\right) \qquad (1)$$

$$E = E^* - G_Q(s)\cdot\left(Q - Q^*\right) \qquad (2)$$

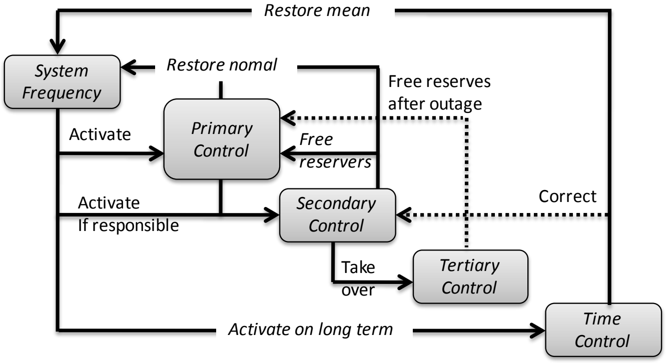


Fig. 3. Frame for the multilevel control of a power system, defined by UCTE.

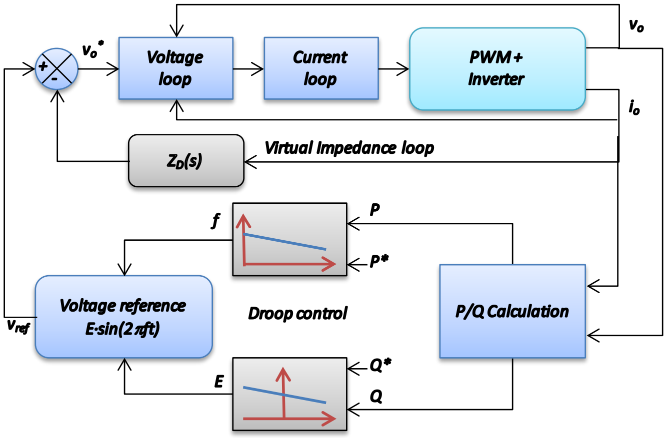


Fig. 4. Primary control: Droop control with virtual impedance, and inner control loops applied to an inverter.

being *f* and *E* the frequency and amplitude of the output voltage reference, f^* and E^* their references, *P* and *Q* the active and reactive power, P^* and Q^* their references, and $G_P(s)$ and $G_Q(s)$ their corresponding transfer functions, which are typically proportional droop terms, i.e. $G_P(s) = m$ and $G_Q(s) = n$. Note that the use of pure integrators is not allowed when the microgrid is in island mode, since the total load will not coincide with the total injected power, but they can be useful in grid connected mode to have a good accuracy of the injected *P* and *Q*. Nevertheless, this control objective will be achieved by the tertiary control level.

The design of $G_P(s)$ and $G_Q(s)$ compensators can be done by using different control synthesis techniques. However, the DC gain of such a compensators (named *m* and *n*) provide for the static $\Delta P/\Delta f$ and $\Delta Q/\Delta V$ deviations, which are necessary to keep the system synchronized and inside the voltage stability limits. Those parameters can be designed as follows:

$$m = \Delta f \;/ P_{max} \qquad (3)$$

$$n = \Delta V \,/\, 2Q_{max} \qquad (4)$$

being Δf and ΔV the maximum frequency and voltage allowed, and P_{max} and Q_{max} the maximum active and reactive power delivered by the inverter. If the inverter can absorb active power, since it is able to charge batteries like a line-interactive UPS, then $m = \Delta f \,/\, 2\,P_{max}$.

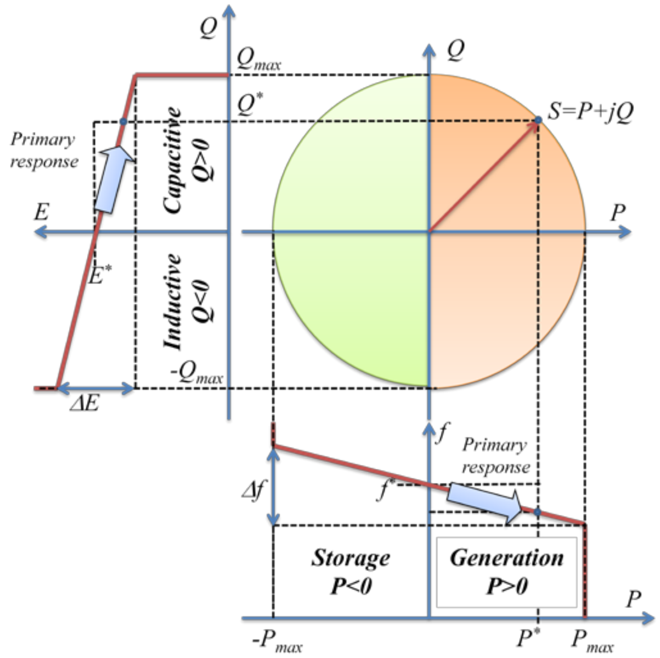


Fig. 5. *P-Q* circle and *P-f* and *Q-E* droop primary control relationship..

Fig. 5 shows the relationship between the *P-Q* circle of a DG unit and *P-f* and *Q-E* droops. Notice that in that case, the DG is able to generate active power ($P>0$) and to store energy ($P<0$), and, at the same time, is able to supply reactive power ($Q>0$, acting like a capacitor) or to absorb reactive power ($Q<0$, acting like an inductor).

In the conventional droop method used by large power systems, it is supposed that the output impedance of synchronous generators as well as the line impedance is mainly inductive. However, when using power electronics the output impedance will depend on the control strategy used by the inner control loops. Further, the line impedance in low voltage applications is near to be pure resistive. Thus the control droops (1) and (2) can be modified according to the park transformation determined by the impedance angle θ [18]:

$$f = f^* - G_P(s)\left[\left(P-P^*\right)\sin\theta - \left(Q-Q^*\right)\cos\theta\right] \tag{5}$$

$$E = E^* - G_Q(s)\left[\left(P-P^*\right)\cos\theta + \left(Q-Q^*\right)\sin\theta\right] \tag{6}$$

The primary control level can also include the virtual output impedance loop, in which the output voltage can be expressed as [16]:

$$v_o^* = v_{ref} - Z_D(s)\cdot i_o \tag{7}$$

where v_{ref} is the voltage reference generated by equations (5)-(6) being $v_{ref} = E\ sin(2\pi f\ t)$, and $Z_D(s)$ is the virtual output impedance transfer function, which normally ensures inductive behavior at the line-frequency. Fig. 4 depicts the virtual impedance loop in relation with the other control loops: inner current and voltage loops, and the droop control. Usually the virtual impedance Z_D is designed to be bigger than the output impedance of the inverter plus the line impedance, this way the total equivalent output impedance is mainly dominated by Z_D [16]. The virtual output impedance Z_D is equivalent to the series impedance of a synchronous generator. However, although the series impedance of a synchronous generator is mainly inductive, the virtual impedance can be chosen arbitrarily. In contrast with a physical impedance, this virtual output impedance has no power losses, thus it is possible to implement resistance without efficiency losses.

Notice that by using the virtual impedance control loop, the inverter output impedance becomes a new control variable. Thus, we can adjust the phase angle of equations (6)-(7) according to the expected *X/R* ratio of the line impedance, $\theta = tan^{-1}X/R$, and the angle of the output impedance at the line frequency. Furthermore, the virtual output impedance can provide additional features to the inverter, such as hot-swap operation and harmonic current sharing [17]-[18]. These control loops allows the parallel operation of the inverters. However, those have an inherent trade of between *P*/*Q* sharing and frequency/amplitude regulation [16]-[19].

A. Secondary control

In order to compensate for the frequency and amplitude deviations, a secondary control can be used. The secondary control ensures that the frequency and voltage deviations are regulated towards zero after every change of load or generation inside the microgrid. The frequency and amplitude levels in the microgrid f_{MG} and E_{MG} are sensed and compared with the references f^*_{MG} and E^*_{MG} the errors processed through compensators (δf and δE) are send to all the units to restore the output voltage frequency and amplitude.

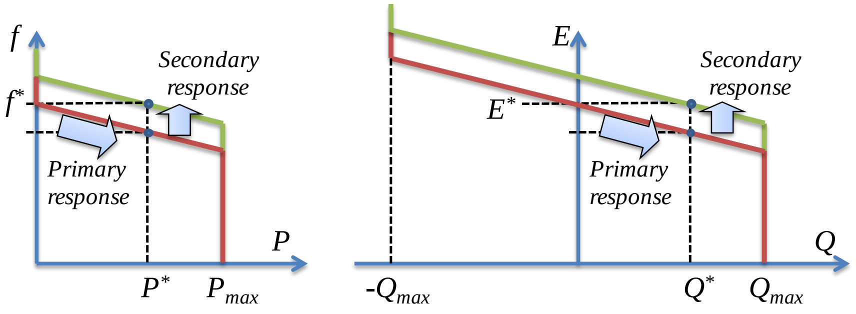


Fig. 6. *P-f* and *Q-E* primary and secondary control actions.

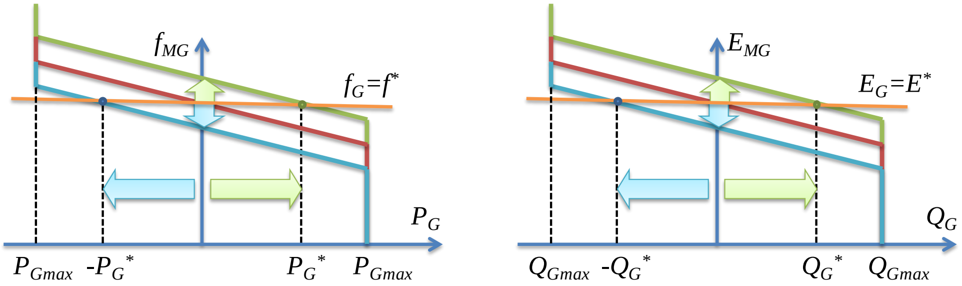


Fig. 7. *f* – *P* and *E* –*Q* tertiary control actions.

The secondary control is used in power systems correct the grid frequency deviation within allowable limit, e.g. ±0.1 Hz in Nordel (North of Europe) or ±0.2Hz in UCTE (Union for the Co-ordination of Transmission of Electricity, Continental Europe). It consists of a PI-type controller, also called Load-Frequency Control (LFC) in Europe or Automatic Gain Controller (AGC) in USA. In case of an AC-microgrid, the frequency and amplitude restoration controllers, G_f and G_E, can be obtained similarly as follows:

$$\delta f = k_{pf}\left(f_{MG}^{*}-f_{MG}\right)+k_{if}\int\left(f_{MG}^{*}-f_{MG}\right)dt+\Delta f_S \quad (8)$$

$$\delta E = k_{pE}\left(E_{MG}^{*}-E_{MG}\right)+k_{iE}\int\left(E_{MG}^{*}-E_{MG}\right)dt \quad (9)$$

being k_{pf}, k_{if}, k_{pE}, and k_{iE} the control parameters of the secondary control compensator, and Δf_S is a synchronization term which remains equal to zero when the grid is not present. In this case, δf and δE must be limited in order to do not exceed the maximum allowed frequency and amplitude deviations.

Fig. 6 depicts the primary and secondary control action over the *P*-*f* and *Q*-*E* characteristics. This way, the frequency and amplitude restoration process is done by the secondary control in a droop controlled microgrid when increasing the *P* and *Q* demanded. Notice that without this action, both frequency and amplitude of the microgrid are load-dependent.

B. *Tertiary control*

When the microgrid is operating in grid-connected mode, the power flow can be controlled by adjusting the frequency (changing the phase in steady state) and amplitude of the voltage inside the microgrid [19]. By measuring the *P/Q* at the PCC, P_G and Q_G, they can be compared with the desired P^*_G and Q^*_G, and controlled as following:

$$f_{MG}^{*} = k_{pP}\left(P_G^{*}-P_G\right)+k_{iP}\int\left(P_G^{*}-P_G\right)dt \quad (10)$$

$$E_{MG}^{*} = k_{pQ}\left(Q_G^{*}-Q_G\right)+k_{iQ}\int\left(Q_G^{*}-Q_G\right)dt \quad (11)$$

being k_{pP}, k_{iP}, k_{pQ}, and k_{iQ} the control parameters of the tertiary control compensator. Here, f_{MG}^* and E_{MG}^* are also saturated in case of being outside of the allowed limits. This variables are inner generated in island mode ($f_{MG}^* = f_i^*$ and $E_{MG}^*=E_{MG}^*$), by the secondary control. When the grid is present, the synchronization process can start, and f_{MG}^* and E_{MG}^* can be equal of those measured in the grid. Thus, the frequency and amplitude references of the microgrid will be the frequency and amplitude of the mains grid. After the synchronization, these signals can be given by the tertiary control (10)-(11).

Notice that, depending on the sign of P_G^* and Q_G^*, the active and reactive power flows can be exported or imported independently. Fig. 7 shows the tertiary control action, which is responsible of interchange *P* and *Q* at the PCC, the power flow bidirectionality of the microgrid can be observed. The grid have constant frequency and amplitudes ($f_G=f^*$ and $E_G=E^*$), so that it is represented by horizontal lines. Thus, the amount of *P* and *Q* exchanged between the microgrid and the grid (P_G and Q_G) are determined by the intersection of the droop characteristics of the microgrid and the horizontal lines of the grid. Consequently, P_G can be controlled by adjusting the microgrid reference frequency f_{MG}^* as follows. If $f_{MG}^*>f_G$ then $P_G>0$, and the microgrid injects *P* to the grid; while if $f_{MG}^*<f_G$ then $P_G<0$ thus the microgrid absorbs *P* from the grid. The frequency of the microgrid will be determined by the grid, so that this action will result in a change of the power angle. Similar analysis can be done for the reactive power Q_G.

Furthermore, in (8) and (9), by making k_{iP} and k_{iQ} equal to zero, the tertiary control will act as a primary control of the microgrid, thus allowing the interconnection of multiple microgrid, forming a cluster. Hence, this control loop also can be used to improve the power quality at the *PC*C. In order to achieve voltage dips ride-through, the microgrid must inject reactive power to the grid, thus achieving inner voltage stability. Particularly, if we set $k_{iQ} = 0$, the microgrid will inject automatically *Q* when there is a voltage sag or absorb reactive power when there is a swell in the grid. This can endow to the microgrid low-voltage ride-through (LVRT) capability. In Part II of this paper will be introduced the implementation of this capability by means of a dedicated power converter [33].

Islanding detection is also necessary to disconnect the microgrid from the grid and disconnect both the tertiary control references as well as the integral terms of the reactive power PI controllers, to avoid voltage instabilities. When a non-planned islanding scenario occurs, the tertiary control tries to absorb *P* from the grid, so that as the grid is not present, the frequency will start to decrease. When it goes out from the expected values, the microgrid is disconnected from the grid for safety and the tertiary control is disabled.

V. CONCLUSIONS

We have reviewed the current status of microgrid decentralized control and methods to analyze and assess microgrid stability. We have also considered the issue of in-situ decentralized testing of microgrid controllers.

Time-synchronization techniques such as the GPS timing signal and the PTP are very likely to play a significant role in both, microgrid control and controller testing. Similarly, advances in numerical techniques that assess conventional power system stability are also likely to play a role in microgrids as well.

The future trends in hierarchical control for microgrids are essentially related to energy management systems (EMS), giving references from and to the tertiary control in order to optimize the efficiency of the microgrid. Another important issue will be the clusters of microgrids, which are expected to be developed in near future by interconnecting intelligent microgrids. Each microgrid will have a number of Energy Services, such as active/reactive power demand/generation, storage capability, and so on, which could be of mutual interest among microgrids. Thus multi-agents could negotiate the interchange of energy between microgrids or microgrid clusters. Being multi-agents and hierarchical control a clear trend of research in microgrids, technologies like communication systems are becoming important to make feasible these applications.

Finally, more industrial applications will push the research in this area after the recent final approval of the Standard IEEE 1547.4, which allows microgrids to operate in island under certain conditions [32]. This Standard constitutes a clear breakthrough toward new codes and industrial equipment that will need for extra functionalities required by the microgrid operations.

REFERENCES

[1] R.H. Lasseter, “Microgrids”, in *Proc. IEEE PES Winter Meeting 2002*, pp. 305-308.

[2] M. Chandorkar, 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./Feb. 1993.

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

[4] 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, Jan./Feb. 2000.

[5] R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, “Angle droop versus frequency droop in a voltage source converter based autonomous microgrid”, in *Proc. IEEE PES General Meeting* 2009.

[6] R. Majumder, B. Chaudhuri, A. Ghosh, R. Majumder, G. Ledwich, and F. Zare, “Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop”, *IEEE Trans. Power Systems*, vol. 25, no. 2, pp. 796-808, May 2010.

[7] R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, “Load sharing and power quality enhanced operation of a distributed microgrid”, *IET Renew. Power Gener.*, vol. 3, no. 2, pp. 109-119, 2009.

[8] G. J. Geier, T.M. King, H.L. Kennedy, R.D. Thomas, and B.R. McNamara, “Prediction of the time accuracy and integrity of GPS timing”, in *Proc. IEEE International Frequency Control Symposium*, 1995, pp. 266-274.

[9] *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*, IEEE Standard 1588-2008.

[10] *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*, IEEE Standard 1574-2003.

[11] M.C. Chandorkar and D.M. Divan, “Decentralized Operation of Distributed UPS Systems”, in *Proc. IEEE PEDES 1996*, pp. 565-571.

[12] F. Katiraei and M.R. Iravani, “Power management strategies for a microgrid with multiple distributed generation units”, *IEEE Trans. Power Systems*, vol. 21, no. 4, pp. 1821-1831, Nov. 2006.

[13] M. Prodanovic and T.C. Green, “High-quality power generation through distributed control of a power park microgrid”, *IEEE Trans. Ind. Electron.*, vo. 53, no.5, pp. 1471-1482, October 2006.

[14] M. N. Marwali, J.-W. 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.

[15] A. Mehrizi-Sani and R. Iravani, “Potential function based control of a microgrid in islanded and grid-connected modes”, *IEEE Trans. Power System*, vo. 25, no.4, pp. 1883-1891, Nov. 2010.

[16] J.M. Guerrero, J. Matas, L.G. de Vicuña, M. Castilla, and J. Miret, “Decentralized control for parallel operation of distributed generation inverters using resistive output impedance”, *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 994-1004, April 2007.

[17] J.M. Guerrero, J. Matas, L.G. de Vicuña, 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, August 2005.

[18] J.M. Guerrero, J. Matas, L.G. de Vicuña, M. Castilla, and J. Miret, “Wireless-control strategy for parallel operation of distributed-generation inverters”, *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1461-1470, October 2006.

[19] J.M. Guerrero, J.C. Vásquez, J. Matas, M. Castilla, and L.G. de Vicuña, “Control Strategy for flexible microgrids based on parallel line-interactive UPS systems”, *IEEE Trans. Ind. Electron.*, vol. 56, no. 3, pp. 726-735, August 2009.

[20] K. D. Brabandere, B. Bolsens, J. V. D. Keybus, A. Woyte, J. Driesen, and R. Belmans, “A voltage and frequency droop control method for parallel inverters,” *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp. 1107–1115, Jul. 2007.

[21] C.-T. Lee, C.-C. Chuang, C.-C. Chu, and P.-T. Cheng, “Control strategies for distributed energy resources interface converters in low voltage microgrid”, in *Proc. IEEE ECCE 2009*, pp. 2022-2029.

[22] Y. W. Lee, 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, December 2009.

[23] X. Yu, A.M. Khambadkone, H. Wang, and S.T.S. Terence, “Control of parallel-connected power converters for low-voltage microgrid – Part I: a hybrid control architecture”, *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 2962-2970, December 2010.

[24] M.C. Chandorkar, *Distributed uninterruptible power supply systems*, Ph.D. dissertation, University of Wisconsin-Madison, 1995.

[25] G. Venkataramanan and M. Illindala, “Small signal dynamics of inverter interfaced distributed generation in a chain-microgrid”, in *Proc. IEEE PES General Meeting*, 2007.

[26] Y. 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, no. 6, pp. 2806-2816, Nov. 2008.

[27] E. Barklund, N. Pogaku, M. Prodanovic, C. Hernandez-Aramburo, and T.C. Green, “Energy management in autonomous microgrid using stability-constrained droop control of inverters”, *IEEE Trans. Power Electron.*, vol. 23, no. 5, pp. 2346-2352, Sep. 2008.

[28] F. Katiraei, M.R. Iravani, and P.W. Lehn, “Small-signal dynamic model of a micro-grid including conventional and electronically interfaced distributed resources”, *IET Gener. Transm. Distrib.*, vol. 1, no. 3, pp. 369-378, May 2007.

[29] S.V. Iyer, M.N. Belur, and M.C. Chandorkar, “A generalized computational method to determine stability of a multi-inverter microgrid”, *IEEE Trans. Power Electron.*, vol. 25, no. 9, pp. 2420-2432, Sept. 2010.

[30] B.B. Johnson, A. Davoudi, P.L. Chapman, and P. Sauer, “Microgrid dynamics characterization using the Automated State Model Generation Algorithm”, in *Proc. IEEE Circuits and Systems (ISCAS) 2010*, pp. 2758-2761.

[31] O. Wasynczuk, S.D. Sudhoff, “Automated state model generation algorithm for power circuits and systems”, *IEEE Trans. Power Systems*, vol. 11, no. 4, pp. 1951-1956.

[32] IEEE Guide for Design, Integration, and Operation of Distributed Resource Island Systems with Electric Power Systems, IEEE Standard 1547.4.2011, 2011.

Josep M. Guerrero (S'01–M'03–SM'08) was born in Barcelona, Spain, in 1973. He received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, Spain, in 1997, 2000 and 2003, respectively. He has been an Associate Professor with the Department of Automatic Control Systems and Computer Engineering, Technical University of Catalonia, Barcelona, teaching courses on digital signal processing, FPGAs, microprocessors, and control of renewable energy. Since 2004, he has been responsible for the Renewable Energy Laboratory, Escola Industrial de Barcelona. He has been a visiting Professor at Zhejiang University, China, and University of Cergy-Pontoise, France. From 2011, he became a Full Professor at the Department of Energy Technology, Aalborg University, Denmark, where he is the responsible of the Microgrids research program. His research interests is oriented to different Microgrids aspects, including power electronics, distributed energy storage systems, hierarchical and cooperative control, energy management systems and optimization of microgrids and islanded minigrids.

Prof. Guerrero is an Associate Editor for the IEEE Transactions on Power Electronics, IEEE Transactions on Industrial Electronics, and IEEE Industrial Electronics Magazine. He has been Guest Editor of the IEEE Transactions on Power Electronics Special Issues: Power Electrics for Wind Energy Conversion and Power Electronics for Microgrids; and the IEEE Transactions on Industrial Electronics Special Sections: Uninterruptible Power Supplies (UPS) systems, Renewable Energy Systems, Distributed Generation and Microgrids, and Industrial Applications and Implementation Issues of the Kalman Filter. He currently chairs the Renewable Energy Systems Technical Committee of IEEE IES.

Mukul Chandorkar (M'84) is a professor in the Department of Electrical Engineering at the Indian Institute of Technology, Bombay, India. He received the B. Tech. degree from the Indian Institute of Technology - Bombay, the M. Tech. degree from the Indian Institute of Technology - Madras, and the Ph.D. Degree from the University of Wisconsin-Madison, in 1984, 1987 and 1995 respectively, all in electrical engineering. He has several years of experience in the power electronics industry in India, Europe and the USA. His technical interests include microgrid decentralized operation, and he has authored several papers on the subject. His interests also include power quality compensation, power system wide-area measurements, real-time simulation and load emulation.

Tzung-Lin Lee (S'04–M'08) received the B.S. degree in electrical engineering from Chung Yuan Christian University, Taoyuan, TAIWAN, in 1993, the M.S. degree in electrical engineering from National Chung Cheng University, Chiayi, TAIWAN, in 1995, and the Ph.D. degree in electrical engineering from National Tsing Hua University, Hsinchu, TAIWAN, in 2007.

From 1997 to 2001, he worked at the Microwave Department in Electronics Research & Service Organization (ERSO), Industrial Technology Research Institute (ITRI), Hsinchu, TAIWAN. He began his teaching career in Chang Gung University, Taoyuan, TAIWAN, in Sep. 2007. Since Aug. 2008, he joined the department of electrical engineering, National Sun Yat-sen University, Kaohsiung, TAIWAN, where he is currently an Assistant Professor. His research interests are in utility applications of power electronics, such as active power filters and Microgrids.

Poh Chiang Loh (S'01-M'04-SM'12) received his B.Eng (Hons) and M.Eng from the National University of Singapore in 1998 and 2000 respectively, and his Ph.D from Monash University, Australia, in 2002, all in electrical engineering.

During the summer of 2001, he was a visiting scholar with the Wisconsin Electric Machine and Power Electronics Consortium, University of Wisconsin-Madison, USA, where he worked on the synchronized implementation of cascaded multilevel inverters, and reduced common mode control strategies for multilevel inverters. From 2002 to 2003, he was a project engineer with the Defence Science and Technology Agency, Singapore, managing defence infrastructure projects and exploring technology for defence applications. From 2003 to 2009, he was an assistant professor with the Nanyang Technological University, Singapore, and since 2009, he is an associate professor at the same university. In 2005, he has been a visiting staff first at the University of Hong Kong, and then at Aalborg University, Denmark. In 2007 and 2009, he again returned to Aalborg University first as a visiting staff working on matrix converters and the control of grid-interfaced inverters, and then as a guest member of the Vestas Power Program.

In total, Dr. Loh has received two third paper prizes from the IEEE-IAS IPCC committee in 2003 and 2006, and he is now serving as an associate editor of the IEEE Transactions on Power Electronics.

Advanced Control Architectures for Intelligent Microgrids – Part II: Power Quality, Energy Storage, and AC/DC MicroGrids

Josep M. Guerrero, *Senior Member*, *IEEE*, Poh Chiang Loh, *Senior Member, IEEE*, Tzung-Lin Lee, *Member, IEEE*, and Mukul Chandorkar, *Member, IEEE*

Abstract— This paper summarizes the main problems and solutions of power quality in Microgrids, distributed energy storage systems, and AC/DC hybrid Microgrids. First, power quality enhancement of grid-interactive Microgrids is presented. Then, cooperative control for enhance voltage harmonics and unbalances in Microgrids is reviewed. After, the use of static synchronous compensator (STATCOM) in grid-connected Microgrids is introduced in order to improve voltage sags/swells and unbalances. Finally, the coordinated control of distributed storage systems and AC/DC hybrid microgrids is explained.

***Index Terms*—Microgrids, distributed energy storage, power quality, STATCOM.**

I. Introduction

A microgrid is a local grid consisting of Distributed Generators (DGs), energy storage systems, and dispersed loads, which may operate in both grid-connected or islanded modes [1], [2]. DGs are often connected to the microgrid through a power electronic interface converter. The main role of an interface converter is to control the power injection. In addition, compensation of power quality problems, such as voltage harmonics can be achieved through proper control strategies [3]. The voltage harmonic compensation approaches are based on making the DG unit to emulate a resistance at harmonic frequencies in order to compensate those harmonics [4]-[10].

Voltage unbalances could appear when connecting single-phase loads to the microgrid. Compensation of voltage unbalances is usually done by using series active power filter through injection of negative sequence voltage in series with the power distribution line [4]. However, there are also works based on using shunt active power filter for voltage unbalance compensation [6]. In these works, voltage unbalances caused by unbalanced loads are compensated by injecting negative sequence currents. In addition, when the voltage is highly unbalanced and distorted, a big amount current is needed, thus DGs must be oversized or this compensation would interfere with the active and reactive power supply by the DG. In such a case, the use of static synchronous compensators (STATCOMs) in microgrids can be well justified.

Furthermore, DC- and AC-microgrids have been proposed for different applications, and hybrid solutions have been developed Microgrids can be conceived to use DC or AC voltage in the local grid [11]. Also, there are AC sources or microgrids interconnected by means of power electronic interfaces to a DC microgrid. Thus hybrid DC-AC microgrids are often implemented, being necessary to control the power flow between DC and AC parts. In this sense, it seems reasonable that the DC-microgrid area can be connected to storage energy systems like batteries, supercapcitors or hydrogen-based fuelcells. Although DC transmission and distribution systems for high voltage applications are well established, and there is a notable increase of DC microgrid projects, we cannot find so many studies about the overall control of these systems.

This paper is summarized as follows. In Section II power quality of microgrids and interactivity with the grid is presented. In Section III cooperative control is applied to microgrids to enhance power quality. Section IV introduces the control of distributed storage systems in microgrids. Section V presents AC and DC microgrids coordinated control. Conclusions and future trends are pointed out in Section VI.

II. Power Quality Enhancement between Utility and Microgrids

Microgrids should preferably tie to the utility grid so that any surplus energy generated within them can be channeled to the utility. Similarly, any shortfall can be replenished from the utility, which preferably should only be occasional, since microgrids should mostly be designed as self-sustainable, if

Manuscript received May 27, 2011.

J. M. Guerrero is with the Department of Energy Technology, Aalborg Univeristy, 9220 Aalborg East, Denmark (Tel: +45 2037 8262; Fax: +45 9815 1411; e-mail: joz@et.aau.dk).
M. Chandorkar is with the Indian Institute of Technology, Bombay, India.
T.-L. Lee is with the department of electrical engineering, National Sun Yat-sen University, Kaohsiung, Taiwan.
P. C. Loh is with the Nanyang Technological University, Singapore.

frequent load shedding is not intended [12]. Having an inter-tie would also expose the microgrids and utility grid to their respective inner disturbances, like harmonics, unbalance and other power quality “noises”. To better isolate the grids from their respective “noises”, a power quality conditioner is recommended between each microgrid and the utility grid, as demonstrated in Fig. 1. This power conditioner should ideally have a shunt converter and a series converter, in order to achieve full voltage and current compensation. Indeed, such configuration would appear similar to a unified power quality conditioner (UPQC) [13]-[15] or a unified power flow controller (UPFC) [16], which certainly is the case when judging on their power stages. Their control schemes are however different, as can be seen when comparing the requirements of a microgrid power quality conditioner (MPQC) with those of an example UPQC.

For the former, there is a general incline towards controlling the shunt converter to provide a regulated voltage within the microgrid, whose parameters are properly tuned for power dispatch or sharing purposes [17], [18]. A firm voltage would definitely help with the interfacing of other localized sources, and the avoidance of sensitive load tripping within the microgrid. This is especially important in the islanded mode, during which the utility grid is not available for stabilizing the network voltage. A firm voltage imposed by the shunt converter would however cause large unbalanced current to flow along the interconnecting feeder, if the utility voltage is unbalanced, and the series converter is not in operation. The problem would prevail even for a small amount of unbalanced voltage, because the feeder impedance is usually small. Harmonic voltages, if present in the utility grid, would likewise lead to harmonic currents along the feeder. They however are of a lesser concern, since their values progressively contract, as the feeder impedance increases with harmonic order.

To nonetheless remove these non-idealities from the current, one probably obvious method is to control the series converter to inject voltages that correspond directly to the unbalanced and harmonic voltages detected in the utility grid. None of the distorted and unbalanced voltages now appears across the feeder, inferring that no corresponding current components will flow. The main difficulty encountered here would be the impossibility of detecting the non-idealities in the utility grid, which is usually far away. Indirect determination is therefore needed, and can be done by first filtering out the line current non-idealities using notch filters or filters in the relevant synchronous frames [19]. These current components can then be forced to zero by passing them through controllers with large gains, ideally infinite, at the frequencies of interest. The outputs of the controllers would then ensure that the series converter injects the right amount of unbalanced and harmonic voltages, so that the feeder carries only balanced sinusoidal current, which also flows through the series converter. Noting further that the series converter produces only unbalanced and harmonic voltages, while carrying only positive-sequence balanced current, its active and reactive powers injected to the grid are zero.

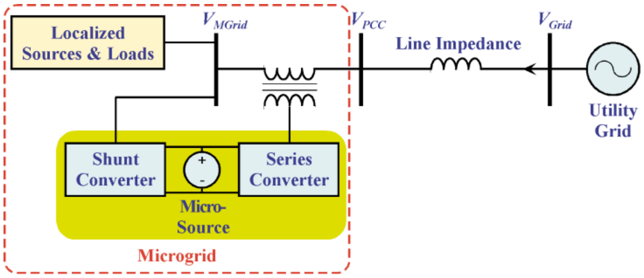


Fig. 1. Illustration of network with distributed sources and storages.

The same principles would apply during utility voltage sag, during which the feeder current will again be large. To reduce this current, the series converter can be controlled to introduce a large impedance along the feeder, so that the large voltage difference caused by the sag appears mostly across it, and not the feeder. Current flow through the feeder is then reduced accordingly. The main concerns here would be to sense the instants of sag initiation and recovery, but cannot be done by measuring the grid voltage, which is usually faraway, and therefore not readily accessible. The former can however be detected by sensing the initial current surge along the feeder, while the latter can be detected by sensing the voltage at the point of common coupling (PCC), which would roughly be equal to the grid voltage during the sag [15], [16].

For convenience of referencing, the main requirements discussed above for MPQC can neatly be summarized as:

- Controlling its shunt converter in voltage mode, so as to produce a well regulated voltage in the microgrid.
- Controlling its series converter in current mode, so as to produce balanced sinusoidal line current.
- Controlling its series converter as a large impedance for limiting the line current during utility voltage sag.

These requirements can be realized by various basic voltage and control-mode control schemes with any number of inner control loops. Regardless of the final implementation adopted, the control objectives here are undeniably different from those of UPQC, listed as follows [11]-[13]:

- Controlling its shunt converter in current mode, so as to shape the grid current as balanced sinusoid (unbalanced and harmonic load current compensation).
- Controlling its series converter in voltage mode, so as to balance the load terminal voltage (unbalanced and harmonic grid voltage compensation).
- Controlling its series converter in voltage mode, so as to improve the downstream load voltage quality during upstream utility voltage sag (series voltage injection).

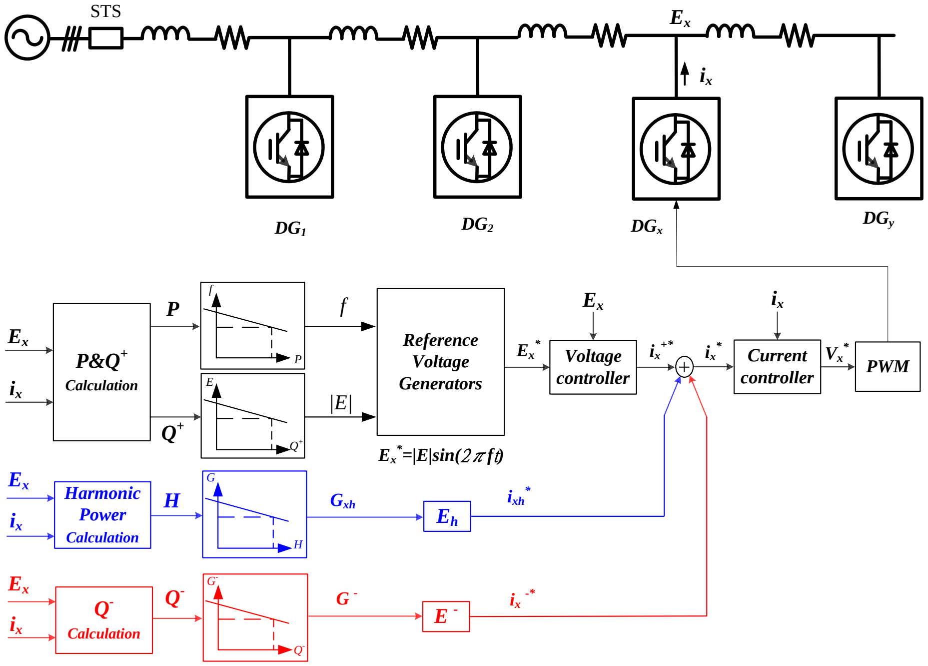


Fig. 2. Control algorithms of cooperative voltage harmonic and unbalance compensation.

III. COOPERATIVE CONTROL FOR POWER QUALITY ENHANCEMENT IN MICROGRIDS

Deep penetration of renewable energy sources (RESs) leads to severe voltage distortion and voltage fluctuation [20]. Various international standards have included limitations of power quality to assure proper operation of microgrids [21]. In the grid-connected operation, the utility needs to balance power flow between sources and loads, and to maintain voltage quality. In contrast, inverter-based DGs must coordinate power requirements in the islanding networks. In order to maintain decent power quality as well as collect more energy from RESs, power conditioning equipment is definitely required, for example active power filters and STATCOMs [22]-[24]. Here, we will exclusively focus on cooperative solutions to voltage quality in the islanding microgrids, followed by the STATCOM to suppress voltage fluctuation in the grid-connected operation.

A. Distributed compensation

Compared with the grid-connected mode, voltage distortion and voltage unbalance in islanding networks are severe due to high line impedance and uneven distribution of single-phase DGs/loads [25], [26]. Instead of installing power conditioning equipment, a preferable solution is to provide power-quality services by inverter-based DGs. That means, in addition to transferring fundamental power, the inverter needs to provide harmonic filtering as well as unbalanced suppression. In order for multiple DGs to work cooperatively, a coordinating or supervisory algorithm is definitely needed, for example the droop control and low-bandwidth communication systems [27], [28]. Here, we will review various cooperative compensations developed for distributed DGs.

In [29], Tuladhar *et Al.* presented a harmonic power vs. voltage loop bandwidth droop to share the harmonic current among multiple inverters when sharing nonlinear loads. However, since this approach is based on increasing the gain of the voltage loop to reduce the bandwidth when the distortion increases, it can affect to the closed-loop system stability. In addition, high frequency signals with small magnitude are generated and injected by the converter over the voltage waveform. Then, the response is sensed back in order to achieve good reactive power sharing in spite of the asymmetrical power lines. Thus, high PWM frequency with fine resolution is required to successfully implement this control algorithm.

In [30], Borup *et Al.* proposed a virtual inductor that operates at certain harmonic frequencies, in order to share between the inverters the harmonic current produced by nonlinear loads. This method would be effective as the converters are installed at the same location. Voltage detection active filters with droop-controlled harmonic conductance were presented to reduce voltage distortion in the power system [31].

In order to cooperatively compensate voltage harmonics by using multiple DGs, a power-harmonic conductance droop ($H-G_h$ droop) was proposed in [32]. This way the harmonic conductance command value G_{xh} can be obtained and multiplied by the harmonic distortion E_{xh}, hence generating the harmonic current reference i_{xh}^* as follows:

$$i_{xh}^* = G_{xh} \cdot E_{xh} \tag{1}$$

This harmonic current reference is added to the fundamental current reference, which is often generated by the voltage control loop.

Fig. 2 shows the control block diagram of the cooperative compensation controller. The designed $H-G_h$ droop (blue line) can be integrated together with the active power vs. frequency droop ($P-f$) and the positive-sequence reactive power vs. voltage (Q^+-E) droop. Notice that only Q^+ is used to adjust the voltage amplitude, since the negative-sequence reactive power Q- will be used for unbalance voltage compensation. The *H* – *G_h* droop equation for DG$_x$ is defined by

$$G_x = G_0 - b_x \cdot (H_{x0} - H_x) \tag{2}$$

where b_x is the droop coefficient, H_{0x} is the rated harmonic power, and G_0 is the rated conductance. If the droop coefficient is designed in inverse proportion to the rated harmonic power, the total harmonic power will be evenly shared among DGs in proportion to their rated capacity:

$$\begin{gathered} b_1H_{10} = b_2H_{20} = \cdots = b_xH_{x0} = b_yH_{y0} = b_zH_{z0} \\ \frac{H_1}{H_{10}} = \frac{H_2}{H_{20}} = \cdots = \frac{H_x}{H_{x0}} = \frac{H_y}{H_{y0}} = \frac{H_z}{H_{z0}} \end{gathered} \tag{3}$$

Accordingly, multiple DGs can cooperatively without using communications can share the harmonic current injected to reduce the harmonic voltage. This approach is suitable for microgrid DGs supplying nonlinear loads.

On the other hand, a shunt or series converter could be controlled to inject negative-sequence current in order to reduce unbalanced voltage [33], [34]. As can be seen from Fig. 2, the negative-sequence conductance G_x^- was introduced in the DGs control for this purpose [34]. Thus, the negative-sequence current can be expressed as follows:

$$i_x^- = G_x^- \cdot E_x^- \tag{4}$$

where G_x^- is the conductance (proportional gain) that regulates the amount of negative-sequence current (i_x^-) to be injected tp compensate the amount of negative-sequence voltage (E_x^-).

Additionally, a $Q^- – G^-$ droop (red line) was established based on the negative-sequence reactive power Q_x^- with respect to the negative-sequence conductance G_x^- in order to allow DGs to cooperatively share the unbalance compensation, i.e. share the amount of Q^- to be injected to the reduce E^-.

The definition of the $Q^- – G^-$ droop equation is given as follows:

$$G_x^- = G_0^- - u_x \cdot (Q_{x0}^- - Q_x^-) \tag{5}$$

where u_x is the $Q^- – G^-$ droop coefficient.

Notice that if E^- increases due to the voltage unbalance, Q^- will be naturally increased. In this situation, the $Q^- – G^-$ droop will increase G^-, and the amount of i_x^- will increase accordingly, thus decreasing E^-, which is the main control objective. That means that all the DGs will reach a steady-state point, and they can share the amount of Q^- according to the u_x selection. Consequently, Q^- could be evenly distributed among DGs based on each DG rated power capacity, bearing in mind that the droop coefficient u_x is inversely proportional to the rated power of DG_x, according to:

$$\begin{gathered} u_1Q_{10}^- = u_2Q_{20}^- = \cdots = u_xQ_{x0}^- = u_yQ_{y0}^- = u_zQ_{z0}^- \\ \frac{Q_1^-}{Q_{10}^-} = \frac{Q_2^-}{Q_{20}^-} = \cdots = \frac{Q_x^-}{Q_{x0}^-} = \frac{Q_y^-}{Q_{y0}^-} = \frac{Q_z^-}{Q_{z0}^-} \end{gathered} \tag{6}$$

B. STATCOM for Microgrid applications

Voltage regulation in the distributed power system is conventionally realized by using on-load tap changer (OLTC), static VAR compensator, step voltage regulator or switched capacitor [35], [36]. In contrast, STATCOM could flexibly compensate reactive power and also its response time is superior to the other methods. Recent applications of STATCOM to improve power quality in microgrids have been presented recently in the literature [37]-[40].

In [37], Fujita *et Al.* presented an active power filter to suppress voltage distortion and fluctuations. This work illustrated voltage swell, due to DGs, could be mitigated by drawing lagging fundamental current from the grid. The use of a STATCOM to restore positive-sequence voltage and to reduce voltage unbalance has received much attention [38]-[40]. In [40], a STATCOM operating with a positive-sequence admittance and a negative-sequence conductance was proposed. Thus, the reference current i^* can be expressed as:

$$i^* = Y_p^* \cdot E_{f}^{+'} + G_n^* \cdot E_{f}^- \tag{7}$$

being Y_P^* the positive sequence conductance, G_n^* the negative-sequence admittance, and E^+_f’ and E^-_f the quadrature positive-sequence and negative-sequence fundamental voltages.

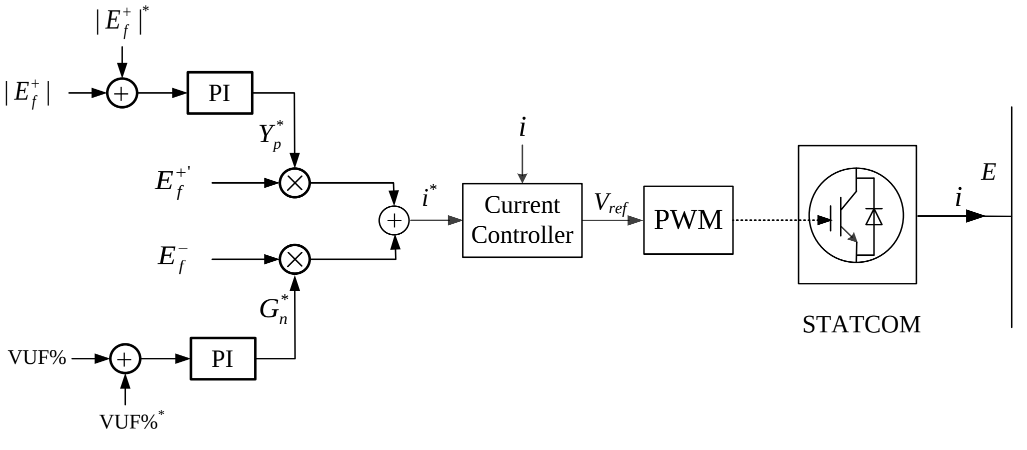


Fig. 3. STATCOM positive-sequence conductance and negative-sequence control diagram.

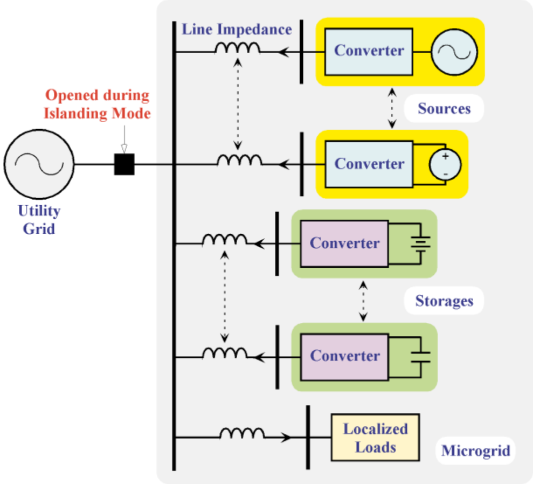


Fig. 4. Illustration of network with distributed sources and storages.

IV. AUTONOMOUS CONTROL OF DISTRIBUTED STORAGES IN MICROGRIDS

Most discussions on microgrids or related topics have focused on source power sharing without much consideration about distributed storages, and are therefore not yet rightfully autonomous. Certainly, storages can be found within each source with their combination usually treated as a single entity with smoother power flow [41], [42]. Such arrangement might not be the best option at times, since the storages would occupy prime spaces that can otherwise be used for energy generation. An example is solar generation, where vast amount of spaces is needed for installing photovoltaic panels. In the defense industry, it is also sensible to locate the storages at more secure places, rather than place them near to the exposed solar generators. The idea of distributed storages (DSs) that are distanced from the sources might therefore be an attractive alternative for consideration, like drawn in Fig. 4.

In principles, DSs can be controlled like sources based on the same active and reactive droop characteristics reviewed in Section II [43], [44]. That means their terminal voltages and currents should be measured for calculating the active and reactive powers drawn from them by the loads. These power values are fed to their appropriate droop characteristics to determine the reference voltage magnitude and frequency to be tracked by a classical double-loop control scheme with an outer voltage and an inner current loop. The controlled DSs therefore appear as voltage sources with their power flows not internally defined, but decided by the external loads. That certainly is fine, but would not be satisfactory, if the general purposes of the DSs are to provide energy for smoothening any detected source or load changes, and ride-through enhancement to the overall microgrids [45].

For these functions, the DSs must autonomously sense for the existing system conditions, and request for maximum charging energy only when excess generation capacity is available [45]. As generation capacity drops or demand increases, energy drawn by the storages should decrease spontaneously, until full source capacity is near. At which point, the storages release their stored energy for meeting the extra load demand. A droop characteristic that will meet the above charging and discharging patterns is shown in Fig. 5 with its expressions for realization written as:

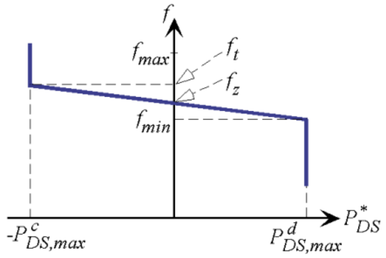


Fig. 5. DS control using frequency versus active power.

$$P^*_{DS} = \begin{cases} -P^c_{DS,max}, & f \geq f_t \\ \gamma'(f - f_z), & f_{min} \leq f < f_t \\ P^d_{DS,max}, & f < f_{min} \end{cases}$$

$$\gamma' = \frac{P^c_{DS,max} + P^d_{DS,max}}{f_{min} - f_t}$$

$$f_z = \frac{P^c_{DS,max} f_{min} + P^d_{DS,max} f_t}{P^c_{DS,max} + P^d_{DS,max}} \qquad (8)$$

where γ' is the droop coefficient, f_t and f_z are the frequencies at which charging first decreases and falls to zero, f_{max} and f_{min} are the maximum and minimum frequencies permitted in the microgrid for realizing source droop power sharing, P^*_{DS}, $P^c_{DS,max}$ and $P^d_{DS,max}$ are the active power reference, maximum charging and discharging powers permitted by each DS.

Fig. 5 clearly shows the DS droop having both positive discharging and negative charging active power values. At any instant, the appropriate power to track is determined by sensing the network frequency, which in effect, represents the excess generation capacity of the network. Upon tracked, the DSs will share the charging and discharging active power based on their ratings, as explained in [45].

Works on DS control are quite recent, and areas of possible extension are plentiful like to incorporate them to the hierarchical structure reviewed in Section IV. Further, using of different source characteristics to the control structure is also an interesting issue that needs further exploration.

V. COORDINATED CONTROL OF AC AND DC MICROGRIDS

Traditional utility grids have always been ac due to its relative ease of transmission, distribution, protection and transformation. This preference for ac networks has to a great extent migrated to microgrid development, but the incentives for a full ac microgrid might not be as strong now. Some obvious reasons are the lower power level found in a microgrid, shorter distance of distribution, and a higher portion of sources and storages that are dc by nature. The main contributing dc sources would undeniably be solar energy and fuel cells, and for storages, it would be different types of batteries and capacitive storage mediums. Like for an ac microgrid, the thought of grouping these dc entities together to form a dc microgrid for powering localized dc (mostly electronic) loads

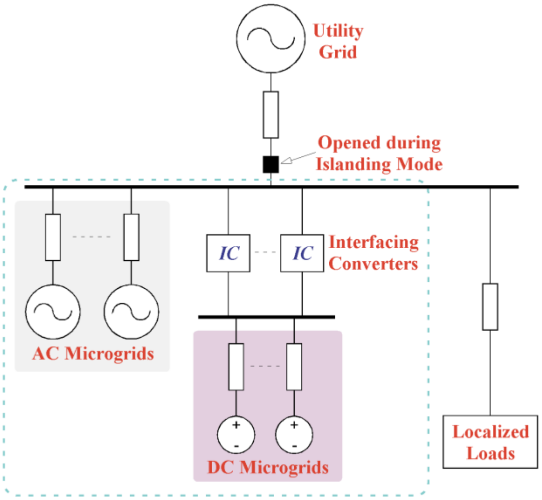


Fig. 6. Example layout of ac and dc microgrids tied by interfacing converter.

might equally be feasible with a significant reduction in power conversion stages expected [46]. Co-existence of an ac and a dc microgrid with an interfacing converter, like in Fig. 6, is therefore likely, inferring that methods for coordinating them should be discussed.

Probably, the simplest approach is to treat each microgrid as an independent network with either dc sources supplying only dc loads, or ac sources supplying ac loads. That certainly defeats the purpose of linking the two microgrids, and would require much higher source ratings, in order to always meet supply and demand within each microgrid. To better coordinate the microgrids, and hence lowering the source ratings, some forms of energy sharing between them must be introduced with preferably no or only slow communication link [7]. That would certainly require some means of droop control, where Section II has already reviewed, but more for sharing power among the sources in the ac microgrid. Extension to the dc microgrid is possible, and would simply involve replacing the active power vs. frequency droop ($P - f$) droop for the ac microgrid by the acive power vs. dc voltage droop ($P - V_{dc}$) for the dc microgrid [47]. Upon implemented, power sharing among sources in the dc microgrid would be realized with some minor errors expected. This slight sharing inaccuracy is no different from that experienced by reactive power sharing in the ac microgrid, as discussed in Section II.

The next concern is to introduce power sharing between the ac and dc microgrids, treated as two separate entities. Droop representation of each entity can rightfully be determined by summing the individual source characteristics in each microgrid, leading to an overall P–f droop for the ac microgrid and an overall P–V_{dc} droop for the dc microgrid. Information from these two droop characteristics should properly be merged, before using it to decide on the amount of power to transfer across the interfacing converter. For that, the recommendation written in the following equation is to normalize the frequency in the ac microgrid and voltage in the dc microgrid, so that their respective ranges of variation commonly span from -1 to 1 [67]:

$$f_{pu} = \frac{f-0.5(f_{max}+f_{min})}{0.5(f_{max}-f_{min})}$$
$$V_{dc,pu} = \frac{V_{dc}-0.5(V_{dc,max}+V_{dc,min})}{0.5(V_{dc,max}-V_{dc,min})} \qquad (9)$$

where subscripts *max* and *min* represent the respective maximum and minimum limits of f and V_{dc}, and subscript *pu* represents their normalized per-unit values. These normalized variables should next be forced equal by feeding their error to a PI controller, followed by an inner current controller [49]. Upon equalized, the two microgrids would share active power based on their respective overall ratings [48]. This thought is no different from enforcing a common frequency in the popularly discussed ac microgrid, upon which the ac sources would share power proportionally based on their respective ratings.

One simple method to keep f_{pu} and $V_{dc,pu}$ equal is to feed their error $(f_{pu} - V_{dc,pu})$ to a PI controller, whose output is the active power reference P_{Ik}^{*} that must be transferred from the dc to ac microgrid through the interfacing converter when positive, and vice versus. The determined P_{Ik}^{*}, upon converted to a current command, can be tracked by any forms of closed-loop current control ranging from classical PI control in the synchronous frame, state feedback control and repetitive control, to name only a few [48]. The commanded current can also include a reactive component for the ac microgrid, whose value is determined by first measuring the ac terminal voltage of the interfacing converter. The sensed voltage value, upon passed through the same reactive droop characteristic discussed in Section II, would give the reactive power and hence reactive current references that the interfacing converter should inject.

Certainly, the power sharing principle reviewed here is only a possible method of control. Other management principles with different objectives could be defined for future investigation.

VI. CONCLUSIONS AND FUTURE TRENDS

Voltage unbalance and harmonic compensation control strategies for microgrids have been reviewed. In islanding operation, the $Q^{-} - G^{-}$ droop (unbalanced reactive power vs. negative-sequence conductance) the $H - G_h$ droop (harmonic power vs. harmonic conductance) were described. These control lops can be implemented together with $P - f$ and $Q - E$ droops, so that multiple interface converters of DGs can cooperatively share all workloads in distorted and/or unbalanced networks. On the other hand, voltage regulation of grid-connected microgrid can be accomplished by STATCOM, so as to allow more DGs operating on-line with an acceptable level of voltage rise.

A power quality conditioner with a shunt and a series inverter has been presented for interfacing microgrids to the utility grid. The shunt inverter is responsible for keeping a set of balanced, distortion-free voltages within the micro-grid, while the series inverter is controlled to inject unbalanced voltages in series along the feeder to balance the line currents with no real and reactive power generated. During utility voltage sags, the series inverter can also be controlled to limit the flow of large fault currents. Collectively, the conditioner has already been shown to raise the quality of power within the micro-grid, and the quality of currents flowing between the micro-grid and utility.

A control scheme for coordinating DSs in microgrids, where DGs and localized loads, was reviewed. An alternative set of droop characteristics and technique for determining control references, that are different from those of DGs, are formulated for DS control. Earlier results have already verified that the presented DS control can autonomously sense for excess generation capacity or supply-demand unbalance, before deciding on the appropriate amount and direction of active power flow.

Further, a control scheme for regulating power flows in a hybrid ac-dc microgrid interlinked by power converters was explained. Through proper sensing of the network information from localized quantities and normalization, results show that the converters are capable of enforcing rated proportional active power sharing among all sources. This sharing is achieved with no dependence on the source natures (ac or dc) and their physical placements within the hybrid microgrid.

Future work is also expected in terms of cooperative control for power quality enhancement in microgrids, for instance in the area of electrical vehicles. In these applications, huge charging current of electrical vehicle may deteriorate power quality. In this case, cooperative control can be integrated into the vehicle charger to assist improving voltage fluctuations and voltage harmonics in the low-voltage distributed system.

Another important issue is that PV or WT power converters, could used additional capacity power rating not only to inject or absorb reactive power, but also to improve the power quality in microgrids.

REFERENCES

[1] J. M. Guerrero, P. C. Loh, M. Chandorkar, T.-L. Lee, “Advanced Control Architectures for Intelligent MicroGrids – Part I: Decentralized and Hierarchical Control,” *IEEE Trans. Ind. Electron.*, 2012.

[2] J. C. Vasquez, J. M. Guerrero, J. Miret, M. Castilla, L. G. de Vicuña, “Hierarchical Control of Intelligent Microgrids,” IEEE Industrial Electronics Magazine, vol.4, no.4, pp.23-29, Dec. 2010

[3] J. C. Vasquez, J. M. Guerrero, J.M., M. Savaghebi, R. Teodorescu, “Modeling, analysis, and design of stationary reference frame droop controlled parallel three-phase voltage source inverters,” in Proc. IEEE ECCE Asia (ICPE & ECCE), 2011, pp.272-279.

[4] S. Chakraborty, M. D. Weiss, M. G. Simoes, "Distributed Intelligent Energy Management System for a Single-Phase High-Frequency AC Microgrid," IEEE Trans. Industrial Electronics, vol.54, no.1, pp.97-109, Feb. 2007.

[5] M. Savaghebi, A. Jalilian, J. C Vasquez, J. M. Guerrero, T.-L. Lee, “Voltage harmonic compensation of a microgrid operating in islanded and grid-connected modes,” Proc. in ICEE, 2011.

[6] M. Savaghebi, J. M. Guerrero, A. Jalilian, J. C. Vasquez, “Experimental evaluation of voltage unbalance compensation in an islanded microgrid,” in Proc. IEEE ISIE, pp.1453-1458, 2011.

[7] M. Prodanovic, T. C. 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.

[8] J. C: Vasquez, R. A. Mastromauro, J. M. Guerrero, M. Liserre, "Voltage Support Provided by a Droop-Controlled Multifunctional Inverter," IEEE Trans. Ind. Electron., vol.56, no.11, pp.4510-4519, Nov. 2009.

[9] K. Borisov, H. L. Ginn, “Multifunctional VSC Based on a Novel Fortescue Reference Signal Generator,” IEEE Trans. Ind. Electron., vol.57, no.3, pp.1002-1007, March 2010.

[10] J. Dannehl, M. Liserre, F. W. Fuchs, "Filter-Based Active Damping of Voltage Source Converters With LCL Filter," IEEE Trans. Ind. Electron., vol.58, no.8, pp.3623-3633, Aug. 2011.

[11] Z. Jiang and X. Yu, “Hybrid DC- and AC-Linked Microgrids: Towards Integration of Distributed Energy Resources,” IEEE Energy 2030 Conference, 2008.

[12] J.-H. Jeon, J.-Y. Kim, H.-M. Kim, S.-K. Kim, C. Cho, J.-M. Kim, J.-B. Ahn, and K.-Y. Nam, “Development of Hardware In-the-Loop Simulation for Testing Operation and Control Functions of Microgrid”, *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 2919-2929, December 2010.

[13] H. Fujita and H. Akagi, “The unified power quality conditioner: the integration of series- and shunt-active filters,” *IEEE Trans. Power Electron.*, vol. 13, no. 2, pp. 315-322, Mar. 1998.

[14] B. Han, B. Bae, H. Kim, and S. Baek, “Combined operation of unified power-quality conditioner with distributed generation,” *IEEE Trans. Power Delivery*, vol. 21, no. 1, pp. 330-338, Jan. 2006.

[15] V. Khadkikar and A. Chandra, “A new control philosophy for a unified power quality conditioner (UPQC) to coordinate load-reactive power demand between shunt and series inverters,” *IEEE Trans. Power Delivery*, vol. 23, no. 4, pp. 2522-2534, Oct. 2008.

[16] L. Gyugyi, C. D. Schauder, S. L. Williams, T. R. Rietman, D. R. Torgerson and A. Edris, “The unified power flow controller: a new approach to power transmission control”, *IEEE Trans. Power Delivery*, vol. 10, no. 2, pp. 1085-1093, Apr. 1995.

[17] Y. W. Li, D. M. Vilathgamuwa and P. C. Loh, “A grid-interfacing power quality compensator for three-phase three-wire microgrid applications”, *IEEE Trans. Power Electron.*, vol. 21, no. 4, pp. 1021-1031, Jul. 2006.

[18] Y. W. Li, D. M. Vilathgamuwa and P. C. Loh, “Microgrid power quality enhancement using a three-phase four-wire grid-interfacing compensator”, *IEEE Trans. Ind. Applicat.*, vol. 41, no. 6, pp. 1707-1719, Nov/Dec. 2005.

[19] R. Teodorescu, F. Blaabjerg, M. Liserre and P. C. Loh, “Proportional-resonant controllers and filters for grid-connected voltage-source converters”, *IEE Proc. Electric Power Applicat.*, vol. 153, no. 5, pp. 750-762, Sep. 2006.

[20] (2010) Department of the new energy and industrial technology development organization (NEDO), JAPAN. [Online]. Available: http://www.nedo.go.jp/english/index.html

[21] *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*, IEEE Std. 1547.2-2008, 2008

[22] L. Gyugyi, “A unified power flow control concept for flexible ac transmission systems,” *Proc. Inst. Elect. Eng.*, vol. 139, no. 4, pp. 323–331, Jul. 1992.

[23] H. Akagi, “Active harmonic filters,” *Proc. IEEE*, vol. 93, no. 12, pp. 2128–2141, Dec. 2005

[24] A. Bhattacharya, C. Chakraborty, and S. Bhattacharya, “Shunt compensation,” *IEEE Ind. Electron. Mag.*, pp. 38–49, Sept. 2009

[25] J. H. R. Enslin and P. J. M. Heskes, “Harmonic interaction between a large number of distributed power inverters and the distribution network,” *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1586–1593, Nov. 2004.

[26] A. V. Jouanne and B. Banerjee, “Assessment of voltage unbalance,” *IEEE Trans. Power Del.*, vol. 16, no. 4, pp. 782–790, Oct. 2001.

[27] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, “Microgrids management,” *IEEE Power and Energy Magazine*, vol. 6, no. 3, pp. 54–65, May/June 2008

[28] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, “Hierarchical control of droop-controlled AC and DC microgrids – a general approach toward standardization,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, Jan. 2011

[29] 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. 131–137, Jan./Feb. 2000.

[30] U. Borup, F. Blaabjerg, and P. N. 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

[31] T.-L. Lee and P.-T. Cheng, “Design of a new cooperative harmonic filtering strategy for distributed generation interface converters in

an islanding network," *IEEE Trans. Power Electron.*, vol. 42, no. 5, pp. 1301–1309, Sept. 2007.

[32] K. Wada, H. Fujita, and H. Akagi, "Considerations of a shunt active filter based on voltage detection for installation on a long distribution feeder," *IEEE Trans. Ind. Appl.*, vol. 38, no. 4, pp. 1123–1130, Jul./Aug. 2002.

[33] Y.-R. Mohamed and E. El-Saadany, "A control scheme for pwm voltage source distributed-generation inverters for fast load-voltage regulation and effective mitigation of unbalanced voltage disturbances," *IEEE Trans. Ind. Electron.*, vol. 55, no. 5, pp. 2072–2084, May 2008.

[34] P.-T. Cheng, C.-A. Chen, T.-L. Lee, and S.-Y. 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.

[35] T. Senjyu, Y. Miyazato, A. Yona, N. Urasaki, and T. Funabashi, "Optimal distribution voltage control and coordination with distributed generation," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 1236–1242, Apr. 2008.

[36] D. Westermann and M. Kratz, "A real-time development platform for the next generation of power system control functions," *IEEE Trans. Ind. Electron.*, vol. 57, no. 4, pp. 1159–1166, Apr. 2010.

[37] H. Fujita and H. Akagi, "Voltage-regulation performance of a shunt active filter intended for installation on a power distribution system," *IEEE Trans. Power Electron.*, vol. 22, no. 3, pp. 1046–1053, May 2007.

[38] C. Hochgraf and R. H. Lasseter, "STATCOM controls for operation with unbalanced voltages," *IEEE Trans. Power Del.*, vol. 13, no. 2, pp. 538–544, Apr. 1998.

[39] E. Twining, M. J. Newman, P. C. Loh, and D. G. Holmes, "Voltage compensation in weak distribution networks using a D-STATCOM," in *IEEE Power Electronics and Drive Systems (PEDS)*, 2003, pp. 178–183.

[40] T.-L. Lee, S.-H. Hu, and Y.-H. Chan, "D-STATCOM with Positive-Sequence Admittance and Negative-Sequence Conductance to Mitigate Voltage Fluctuations in High-Level Penetration of Distributed Generation Systems," *IEEE Trans. Ind. Electron., 2011, Early Access*.

[41] T. Kinjo, T. Senjyu, N. Urasaki, and H. Fujita, "Output leveling of renewable energy by electric double-layer capacitor applied for energy storage system," *IEEE Trans. Energy Convers.*, vol. 21, no. 1, pp. 221-227, Mar. 2006.

[42] R. Wanger, "Large lead/acid batteries for frequency regulation, load leveling and solar power applications," J. Power Sources, vol. 67, pp. 163-172, 1997.

[43] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids: An overview of ongoing research, development, and demonstration projects," *IEEE Power & Energy Mag.*, pp. 78-94, Jul/Aug. 2007.

[44] M. Barnes, A. Dimeas, A. Engler, C. Fitzer, N. Hatziargyriou, C. Jones, S. Papathanassiou, and M. Vandenbergh, "MicroGrid laboratory facilities", in *Proc. Int. Conf. Future Power Systems,* 2005, pp. 1-6.

[45] P. C. Loh and F. Blaabjerg, "Autonomous control of distributed storages in microgrids," in *Proc. IEEE-ICPE*, 2011, pp. 536-542.

[46] X. Liu, P. Wang, and P. C. Loh, "A hybrid ac/dc microgrid and its coordination control", *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 278-286, Jun. 2011.

[47] B. K. Johnson, R. H. Lasseter, F. L. Alvarado, and R. Adapa, "Expandable multiterminal dc systems based on voltage droop," *IEEE Trans. Power Delivery*, vol. 8, no. 4, pp. 1926-1932, Oct. 1993.

[48] C. Jin, P. C. Loh, P. Wang, Y. Mi, and F. Blaabjerg, "Autonomous operation of hybrid ac-dc microgrids," in *Proc. IEEE-ICSET*, 2010, pp. 1-7.

[49] M. P. Kazmierkowski and L. Malesani, "Current control techniques for three-phase voltage-source PWM converters: a survey," *IEEE Trans. Ind. Electron.*, vol. 45, no. 5, pp. 691-703, Oct. 1998.

Josep M. Guerrero (S'01–M'03–SM'08) was born in Barcelona, Spain, in 1973. He received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, Spain, in 1997, 2000 and 2003, respectively. He has been an Associate Professor with the Department of Automatic Control Systems and Computer Engineering, Technical University of Catalonia, Barcelona, teaching courses on digital signal processing, FPGAs, microprocessors, and control of renewable energy. Since 2004, he has been responsible for the Renewable Energy Laboratory, Escola Industrial de Barcelona. He has been a visiting Professor at Zhejiang University, China, and University of Cergy-Pontoise, France. From 2011, he became a Full Professor at the Department of Energy Technology, Aalborg University, Denmark, where he is the responsible of the Microgrids research program. His research interests is oriented to different Microgrids aspects, including power electronics, distributed energy storage systems, hierarchical and cooperative control, energy management systems and optimization of microgrids and islanded minigrids.

Prof. Guerrero is an Associate Editor for the IEEE Transactions on Power Electronics, IEEE Transactions on Industrial Electronics, and IEEE Industrial Electronics Magazine. He has been Guest Editor of the IEEE Transactions on Power Electronics Special Issues: Power Electrics for Wind Energy Conversion and Power Electronics for Microgrids; and the IEEE Transactions on Industrial Electronics Special Sections: Uninterruptible Power Supplies (UPS) systems, Renewable Energy Systems, Distributed Generation and Microgrids, and Industrial Applications and Implementation Issues of the Kalman Filter. He currently chairs the Renewable Energy Systems Technical Committee of IEEE IES.

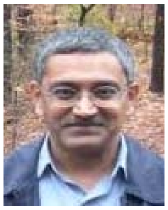
Poh Chiang Loh (S'01-M'04-SM'12) received his B.Eng (Hons) and M.Eng from the National University of Singapore in 1998 and 2000 respectively, and his Ph.D from Monash University, Australia, in 2002, all in electrical engineering.

During the summer of 2001, he was a visiting scholar with the Wisconsin Electric Machine and Power Electronics Consortium, University of Wisconsin-Madison, USA, where he worked on the synchronized implementation of cascaded multilevel inverters, and reduced common mode control strategies for multilevel inverters. From 2002 to 2003, he was a project engineer with the Defence Science and Technology Agency, Singapore, managing defence infrastructure projects and exploring technology for defence applications. From 2003 to 2009, he was an assistant professor with the Nanyang Technological University, Singapore, and since 2009, he is an associate professor at the same university. In 2005, he has been a visiting staff first at the University of Hong Kong, and then at Aalborg University, Denmark. In 2007 and 2009, he again returned to Aalborg University first as a visiting staff working on matrix converters and the control of grid-interfaced inverters, and then as a guest member of the Vestas Power Program.

In total, Dr. Loh has received two third paper prizes from the IEEE-IAS IPCC committee in 2003 and 2006, and he is now serving as an associate editor of the IEEE Transactions on Power Electronics.

Tzung-Lin Lee (S'04–M'08) received the B.S. degree in electrical engineering from Chung Yuan Christian University, Taoyuan, TAIWAN, in 1993, the M.S. degree in electrical engineering from National Chung Cheng University, Chiayi, TAIWAN, in 1995, and the Ph.D. degree in electrical engineering from National Tsing Hua University, Hsinchu, TAIWAN, in 2007.

From 1997 to 2001, he worked at the Microwave Department in Electronics Research & Service Organization (ERSO), Industrial Technology Research Institute (ITRI), Hsinchu, TAIWAN. He began his teaching career in Chang Gung University, Taoyuan, TAIWAN, in Sep. 2007. Since Aug. 2008, he joined the department of electrical engineering, National Sun Yat-sen University, Kaohsiung, TAIWAN, where he is currently an Assistant Professor. His research interests are in utility applications of power electronics, such as active power filters and Microgrids.



Mukul Chandorkar (M'84) is a professor in the Department of Electrical Engineering at the Indian Institute of Technology, Bombay, India. He received the B. Tech. degree from the Indian Institute of Technology - Bombay, the M. Tech. degree from the Indian Institute of Technology - Madras, and the Ph.D. Degree from the University of Wisconsin-Madison, in 1984, 1987 and 1995 respectively, all in electrical engineering. He has several years of experience in the power electronics industry in India, Europe and the USA. His technical interests include microgrid decentralized operation, and he has authored several papers on the subject. His interests also include power quality compensation, power system wide-area measurements, real-time simulation and load emulation.