Review of Primary Voltage and Frequency Control Methods for Inverter-Based Islanded Microgrids with Distributed Generation

Ebrahim Rokrok[a], Miadreza Shafie-khah[a], João P. S. Catalão[a,b,c,*]

[a]*C-MAST, University of Beira Interior, Covilhã 6201-001, Portugal*
[b]*INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465, Portugal*
[c]*INESC-ID, Instituto Superior Técnico, University of Lisbon, Lisbon 1049-001, Portugal*

Abstract

Microgrid (MG) is a relatively new concept for the integration of distributed generation (DG) along with the loads in a distribution system. Islanded microgrid can be considered as a weak grid that has less inertia compared with the conventional power system. This reality makes the microgrid vulnerable to contingencies. Towards a flexible, safe and secure operation of an islanded MG, researchers have introduced a hierarchical control structure comprising tertiary, secondary and primary control. The primary control plays an important role in maintaining the voltage and frequency stability by sharing the loads among the DGs. This paper reviews and categorizes various primary control methods that have been introduced to control the voltage and frequency of inverter-based microgrids. Moreover, the reviewed methods in terms of their potential advantages and disadvantages are compared. Finally, the future trends are presented.

Keywords: Distributed Generation; Droop Control; Hierarchical control; Microgrid; Primary control.

Nomenclature

DG	Distributed Generation
LC	Load Controller
LV	Low Voltage
MG	MicroGrid
MC	Microsource Controller
MGCC	MicroGrid Central Controller
MV	Medium Voltage

---

[*] Corresponding author at INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465, Portugal.
E-mail address: catalao@ubi.pt.

1. Introduction

The environmental issues besides the increasing concern for traditional energy resources lead to increasing concentrations on distributed generation based on renewables. Integration of the parallel DGs with a cluster of loads in the power system makes a novel concept “microgrid”. MGs are located in the distribution systems in both medium voltage (MV) and low voltage (LV) levels [1]. At first, the concept of microgrid introduced in [2,3]. An LV microgrid can operate in two different operating modes:

a) Connected Mode: in this case, the MG is connected to the main MV network and it is able to either inject power into the MV network or absorb the power from it.

b) Islanded Mode: when disconnection from upstream network occurs, the MG forms an island and according to a power management plan will supply the loads inside the island [4].

The islanded microgrids in comparison with the conventional power systems are weaker grids and with a smaller equivalent inertia. This reality makes MGs sensitive to the system contingencies and vulnerable to voltage and frequency deviation, especially when the penetration of intermittent renewable generation is high [5]. Safe, economic and stable operation of the MG in both operation condition depends on existence of a proper control system [6–9]. To enhance the controllability, flexibility and security of the distribution system, MG is controlled in a hierarchical approach[8]. The hierarchical control of MG has three level including: 1- primary control (first level) 2- secondary control (second level) 3- tertiary control (third level)[8–12]. These control levels differ in terms of time response and communication requirements [12].

Primary control of an inverter-based islanded microgrid can be divided into two general classification comprising: a) communication based methods b) without communication methods or droop-based methods[13]. The communication based methods include centralized control [14–16], distributed control [17,18], master-slave control[19–21], angle droop control [22,23].

Because of reliability issues and restriction on physical location of the DG units, it is preferred that there is no communication link between the DG units in microgrid [6]. So, researchers proposed the primary control without communication methods including P-F/Q-U droop control and its variants [24–30], , P-U/Q-F droop control [31–33], virtual frame transformation [34–38].

Recently, some valuable reviews are carried out on different types of microgrid control methods with different objectives, especially hierarchical control of the microgrid [39–44]. Reference [39] provides the main control techniques proposed in the literature along with the information of research projects and experimental microgrids all around the world. Reference [40] states that the next generation of microgrids might adopt the distributed techniques due to dividing the control tasks among the DG units. The extensive integrated communication infrastructures can be a challenge for the distributed control techniques. In [41], a new family of control and management system for microgrids based on play and plug concept and frequency dynamics is presented. In [42], the control techniques and their corresponding objectives from the point of frequency and voltage stability are discussed and the factors that affect the proper load sharing are presented. Reference [43], in addition to surveying the operation of MG in islanded mode, is investigated the possible control schemes of the MG in grid connected mode.

This paper aims to provide a more comprehensive classification, challenges and solutions of the primary control methods in an islanded MG. To this end, first the microgrid control structure in terms of hierarchical control system is briefly surveyed. Then, the primary control methods are introduced and the advantage and disadvantage of the methods are discussed and compared. Finally, the future trends are presented.

The rest of the paper is organized as follows. In section 2, the hierarchical control structure of the microgrids is briefly explained. In section 3, the primary control methods for an islanded MG are introduced and categorized. After that, the communication-based methods and the droop-based methods are discussed in section 4 and section 5, respectively. Section 6 gives the comparison of reviewed methods in terms of their potential advantages and disadvantages. Likewise, the future trends in control strategies for microgrids are stated in this section. Finally, section 7 concludes the paper.

2. Microgrid control structure

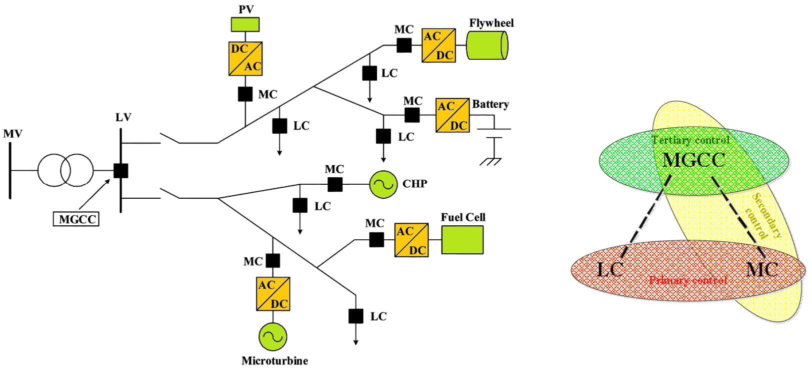
Fig. 1 shows the structure of a typical low voltage MG along with the relation among MG controllers [4]. Generally, the MG comprises LV feeders, loads, microsources (like photovoltaic (PV), wind energy conversion system (WECS), fuel cell, microturbine,…) and storage devices (like battery energy storage system (BESS) and flywheel). The MicroGrid Central Controller (MGCC) that is installed at the LV side of MV/LV substation controls MG centrally. Load Controller (LC) and Microsource Controller (MC) are local controllers to control the loads and microsources, respectively and exchange the required information (like set-points, load/consumption situation,…) with the MGCC through a communication link. LC is used to control loads through the local load shedding schemes in emergency conditions and MC controls the active and reactive power of microsources [4].

Primary control or local control is the first level of hierarchical control system that has the fastest response and is used to stabilize the voltage and frequency of MG through the proper load sharing among the DG units [45–48]. MCs and LCs are responsible for the primary control in MG. Secondary control performs corrective action to remove the frequency and voltage deviations that exists in primary level. According to [4,49–51], secondary control may be employed in both centralized and decentralized approach (i.e. either MGCC can carry out the secondary control centrally or MCs do this locally).

Tertiary control manages the flow of power between the MG and the grid in the normal connected mode. Also, it has key function such as economic managing function and control functionalities that provides optimal scheduling of DG units [8].

3. Primary control methods for an islanded microgrid

There are two general classifications for primary control including communication-based methods and without communication methods. The communication-based methods have some advantages such as accurate power sharing, high power quality, good transient response and circulating current elimination. However, these methods have more cost and complexity and require to high-bandwidth communication link control loops. Without communication methods are based on droop control that uses the local measurement to control the DG units. These methods have many desirable features such as flexibility, expandability, redundancy, simple implementation [10,52]. However, droop-based methods have some drawbacks such as inaccurate power sharing, slow transient response and circulating current among inverters. To overcome these drawbacks, some variations on the conventional droop characteristics have been presented. Fig. 2 shows the classification of the primary control categories for an islanded MG. Primary control schemes are discussed in the following sections.



(a) (b)

Fig. 1. a) typical low voltage MG [4], b) relation among the MG controllers.

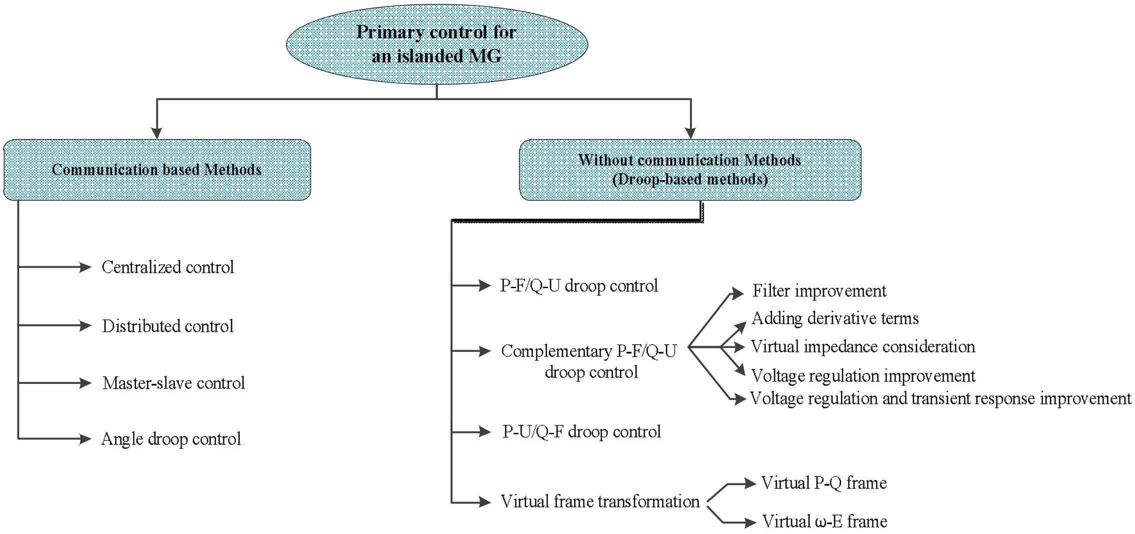


Fig. 2. Classification of primary control for an islanded MG.

4. Communication-based primary control methods

Communication-based primary control methods give an excellent voltage regulation and appropriate power sharing. Moreover, in contrast to droop-based methods, which will be discussed in detail later, the output voltage and frequency are close to their nominal values without using a secondary control [53]. However, these control techniques require communication lines among the inverters which in turn, increase the cost of the system. Likewise, the long distance communication lines reduce the system reliability and expandability. Several typical communication-based primary control methods are reviewed in the following subsections.

4.1. Centralized control

The centralized control method is presented in [14–16]. As shown in Figure 3, this control method requires the current sharing modules and the synchronization signals. The phase locked loop (PLL) of each DG unit, establishes the consistency among the phase of the output voltage, the frequency and the synchronization signal. The current sharing module detects the total load and defines the reference value for the current of each DG unit. The current reference i_{ref} depends on the capacity of each DG unit and it is a fraction of load current i_L. For N equal inverter-based DG units, $i_{\mathrm{ref}} = i_L /N$. The advantage of this method is the proper current sharing in both steady-state and transient. However, this control technique requires a centralized controller which reduces the system redundancy and makes it difficult to expand the system. Moreover, the synchronization pulses and reference currents have to be sent to the inverters through the high-bandwidth communication links. So, this method is high-cost and presents a high dependency on communication system which may be compromised with single-point failures and reduce the reliability.

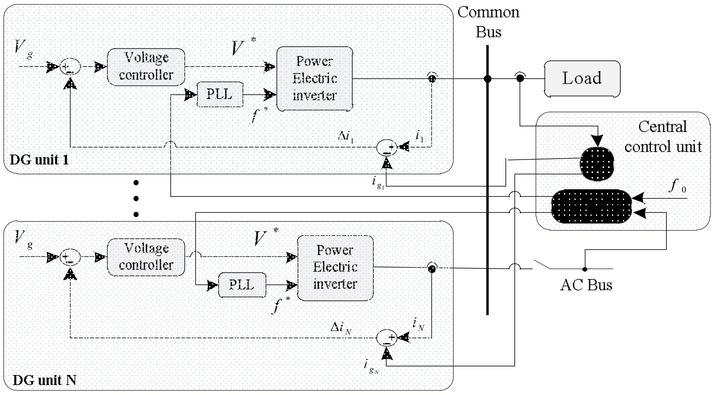


Fig. 3. Schematic of the centralized control.

4.2. Distributed control

This method is applied to the parallel converters [17,18]. One of the typical distributed control techniques for parallel converter is instantaneous average current sharing. In this technique, there is no need for a central controller and an individual control circuit is used for each converter. A current sharing bus is required to share the same average reference current among the converters. In control system of each converter, an additional current control loop is required to make the converter track the reference current that is provided by the current sharing bus. Fig. 4 shows the block diagram of this control technique. In each converter, the d-q components of the current error i_{en} are extracted. Then, the frequency and output voltage amplitude are regulated by the current regulators. The distinctive feature of this control technique is that the required information is adjacent for any DG units. So, it needs a lower band-with communication link than the centralized control scheme. In summary, the distributed control scheme has no need for the central control unit and all of the modules are symmetric. It gives a proper current sharing. However, the interconnections among the converters are still necessary which in turn degrades the expandability and redundancy of the system.

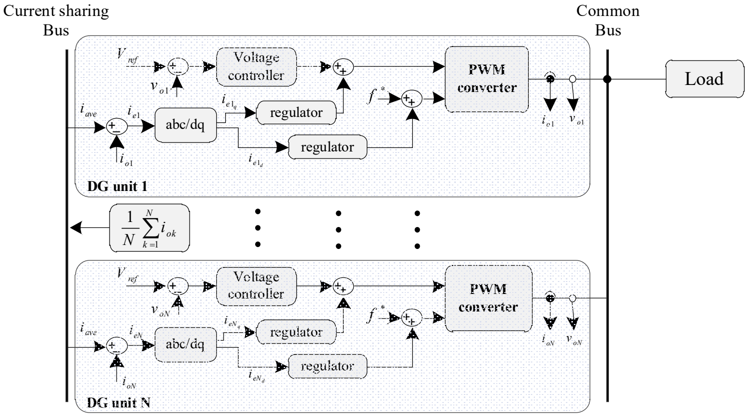


Fig. 4. Schematic of distributed control.

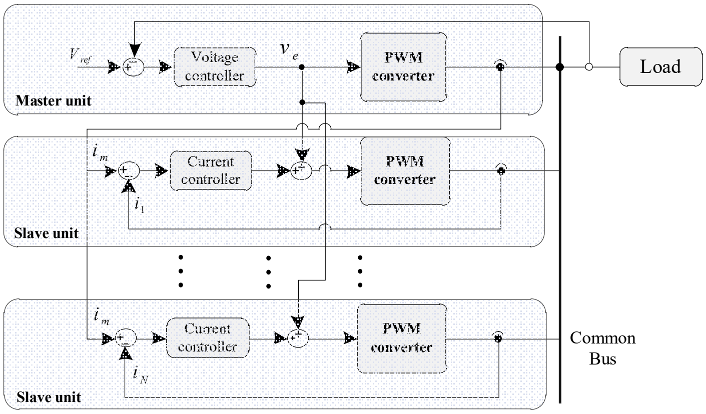


Fig. 5. Schematic of master-slave control.

4.3. Master-Slave control

The schematic of master-slave control method is shown in Fig. 5. In this technique, one unit acts as the master module and the others serve as slaves [19–21]. The master unit regulates the voltage and determines the current reference for the slave units. In order to achieve current sharing, the slave units track the reference provided by the master unit. Since all converters are communicated with the master converter, there is no need for any PLL to make the synchronization. The master-slave control provides excellent power sharing. If the master converter fails, an improved control strategy is anticipated to switch to another normal converter which will then work as the new master unit. Output current overshoot during transients is one of the drawbacks of this method since the master converter current is not controlled. Moreover, similar to the other communication based methods, the required communication among the converters degrades the expandability and redundancy of the system.

4.4. Angle droop control

The angle droop control method is presented in [22,23]. This method is similar to the conventional P/f-Q/U droop control with the difference that instead of frequency, the voltage angle drops with the active power. In [23], it has been shown that the frequency variation by using the angle droop controller is significantly lower than the one with the conventional P/f-Q/U droop controller. The main drawback of this technique is requirement for the GPS signals to determine the reference angle [13].

5. Droop-based primary control methods

These control techniques are based on the droop concept that operates without communications for power sharing. Generally, the operation without communication link is crucial to connect remote inverters. Likewise, without communication links the systems due to the plug-and-play feature of modules which make it easier to replace the faulted units without any interruption in the whole system. Consequently, communication lines are usually avoided specially for long distances and investment cost. The droop-based methods are discussed in the following subsections.

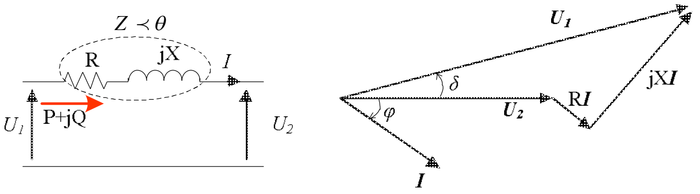


Fig. 6. Power flow between two voltage sources.

5.1. P-F/Q-U droop control

The idea of using droop control for inverters is originated from the control of the synchronous generators in conventional power system [54–56]. Conventional droop control is discussed in [4,9,39,51,54,57–60]. Fig. 6 describes the power flow in a distribution line and to help better understanding of the relations, a phasor diagram is also depicted.
By considering $\boldsymbol{Z} = Z \angle \theta, \boldsymbol{U_1} = U_1 \angle \delta, \boldsymbol{U_2} = U_2 \angle 0^\circ$, the active and reactive power flow is obtained as follows:

$$P = \frac{U_1^2}{Z}\cos\theta - \frac{U_1U_2}{Z}\cos(\theta+\delta) \tag{1}$$

$$Q = \frac{U_1^2}{Z}\sin\theta - \frac{U_1U_2}{Z}\sin(\theta+\delta) \tag{2}$$

By substituting $\boldsymbol{Z} = Ze^{j\theta} = R + jX$ in above equation, (1) and (2) can be rewritten as:

$$P = \frac{U_1}{R^2+X^2}[R(U_1 - U_2\cos\delta) + XU_2\sin\delta] \tag{3}$$

$$Q = \frac{U_1}{R^2+X^2}[-RU_2\sin\delta + X(U_1 - U_2\cos\delta)] \tag{4}$$

$$U_2\sin\delta = \frac{XP - RQ}{U_1} \tag{5}$$

$$U_1 - U_2\cos\delta = \frac{RP + XQ}{U_1} \tag{6}$$

In high voltage lines, $X >> R$ and R can be ignored. Likewise, usually the power angle δ is small. So, cos $\delta = 1$, sin $\delta = \delta$ and we can write:

$$\delta \cong \frac{XP}{U_1U_2} \tag{7}$$

$$U_1 - U_2 \cong \frac{XQ}{U_1} \tag{8}$$

Above equations show that the power angle δ can be controlled by active power flow and the voltage can be controlled through reactive power, as well. Control of the frequency leads to control the power angle. Therefore, by controlling P and Q independently, the frequency and voltage can be controlled. According to this basis, the conventional P/f-Q/U droop is specified with following equations [54,61]:

$$\omega = \omega_{ref} - k_p P \tag{9}$$

$$U = U_{ref} - k_q Q \tag{10}$$

where, ω_{ref} and U_{ref} are the nominal frequency and voltage of the grid. In above equations, k_p , k_q are static droop gains that according to a given operation range of inverter can be calculated as follows [62–64]:

$$k_p = \frac{\omega_{\max} - \omega_{\min}}{P_{\max}} \tag{11}$$

$$k_q = \frac{U_{\max} - U_{\min}}{Q_{\max}} \tag{12}$$

Fig. 7 shows the P-F/Q-U characteristic. Fig. 8 shows the block diagram of an inverter-based DG that is controlled through the conventional P-F/Q-U droop control.

5.2. Modification of P-F/Q-U droop control

The conventional P/F-Q/U droop has some problem such as dependency to the line parameter, inability to share harmonics among DGs in the case of existing non-linear loads, undesirable transient response, inaccurate regulation of active and reactive power due to the coupling between the active and reactive power and circulating current existence among the DGs [11,29,37,41]. To overcome these shortages, researchers have introduced some methods which are represented in following sections.

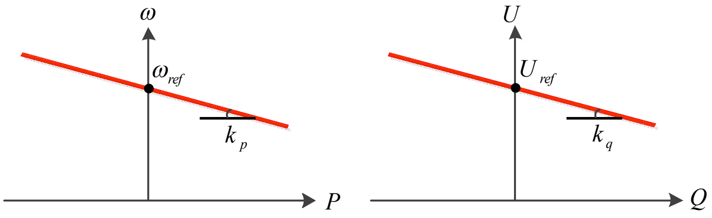


Fig. 7. Conventional P-f /Q-U droop characteristics.

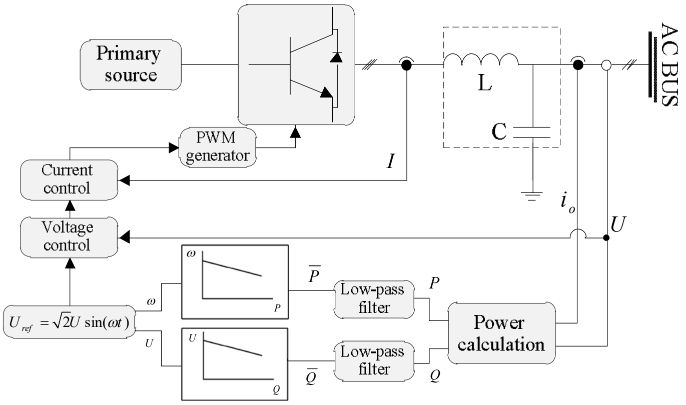


Fig. 8. Conventional droop control system.

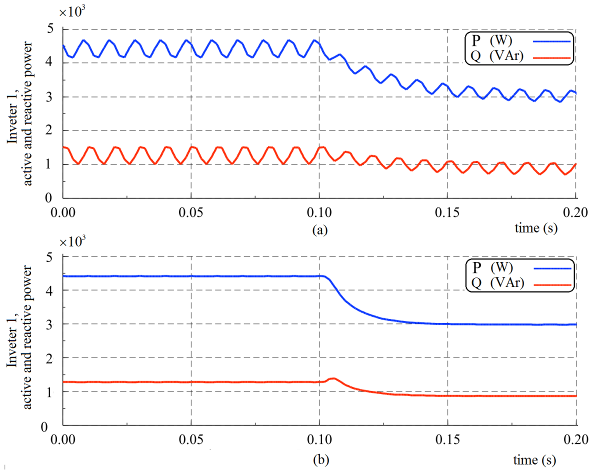


Fig. 9. Output power of inverter. (a) with conventional LPF, (b) with improved filter [65].

5.2.1. Filter improvement

It can be seen in Fig. 8 that instantaneous power component, before being applied to the conventional droop, pass thorough the low-pass filter (LPF). So, the average power will be extracted. The transfer function of the LPF is a first order function that determined as follow [66]:

$$F(S) = \frac{\omega_c}{S + \omega_c} \tag{13}$$

In [65], authors have added a notch filter to the existing LPF to decrease the ripple in the output active and reactive power of the DG. The new transfer function of the filter is:

$$F(S) = \frac{\omega_c}{S + \omega_c} \times \frac{S^2 + 2\zeta_1 \omega_n S + \omega_n{}^2}{S^2 + 2\zeta_2 \omega_n S + \omega_n{}^2} \tag{14}$$

By selecting adequate values for ζ_1 and ζ_2, the Q factor of filter is well designed that it will leads to better ripple rejection. However, the prerequisite of designing such filter is to know the line parameters. Fig. 9 shows the output power of an inverter-based DG in a test system with two DGs. It can be observed that the proposed filter in [65] has decreased the undesirable ripples. However, this method makes just an improvement in the transient response and the other drawbacks still has existed.

5.2.2. Adding derivative terms

In [67], authors have added the derivative terms to the conventional P/f-Q/U droop so as to improve the dynamic response of the DGs to the small contingencies like load changing. The new droop equations are specified as follow:

$$\omega = \omega_{ref} - k_p P - \hat{c}_p \frac{dP}{dt} \tag{15}$$

$$U = U_{ref} - k_q Q - \hat{c}_q \frac{dQ}{dt} \tag{16}$$

where $\hat{c}_p$ and $\hat{c}_q$ are coefficients used for improving the transient response of the DG. The additive terms are zero in steady state and just have effect on systems dynamics. Fig. 10.a shows the response of a DG unit in a microgrid with three DG unit to a load change. In this case, the DG is controlled through the conventional droop control and the transient in the DG power is considerable. In Fig. 10.b it can be seen that by adding the derivative terms to the conventional droop characteristics, the system dynamics is improved.

5.2.3. Virtual impedance consideration

To avoid the coupling between the active and the reactive power, enhance stability of the system, power harmonic sharing and eliminating the circulating current among the DG units, the virtual impedance loop is proposed in [37,38,59,68]. In [68], authors considered a virtual impedance in the DG control system. Fig. 11 shows the control system with virtual impedance loop. In this scheme, the reference voltage is obtained as follows:

$$U_{ref}^{\ *} = U_{ref} - Z_v(s) i_o \tag{17}$$

where Z_v *(s)* is the virtual output impedance of the inverter. With proper design of Z_v *(s)*, the coupling between the P and Q becomes negligible and also the harmonics in case of supplying nonlinear loads can be shared among the DG units [68]. However this method has complexity to implement and doesn't guarantee the proper voltage regulation.

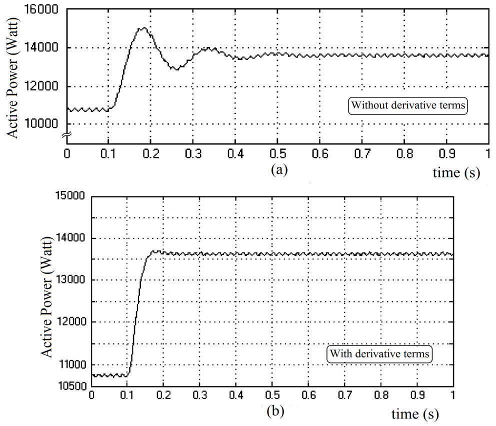


Fig. 10. Active power response of the DG unit due to load change: a) conventional droop control without derivative terms. b) droop control with derivative terms [67].

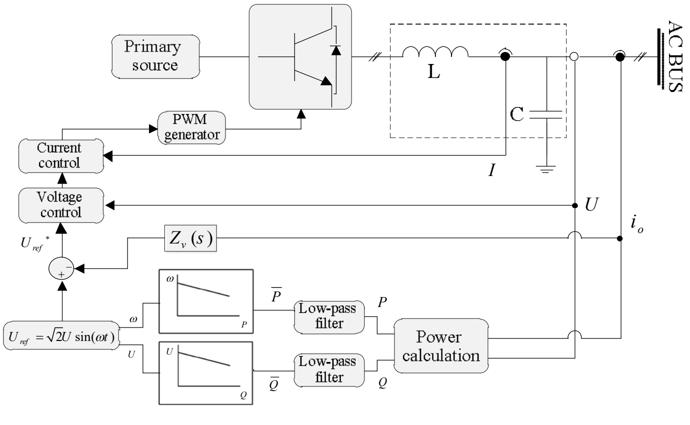


Fig. 11. Block diagram of the system with virtual output impedance.

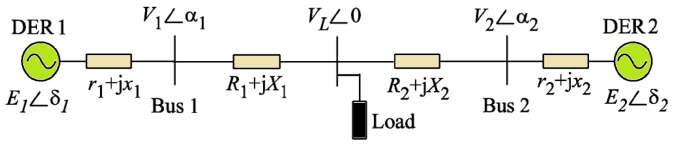


Fig. 12. Stand-alone system whit two DGs [6].

5.2.4. Voltage regulation improvement

In [6], authors proposed a droop scheme that has some additive terms to better voltage regulation. Fig. 12 shows a stand-alone system that can be considered as a part of a microgrid. The proposed droop scheme is as follows:

$$\omega_i = \omega_{ref} - k_{p_i} P_i \tag{18}$$

$$U_i = U_{ref} - k_{q_i} Q_i + k_{r_i} \frac{r_i P_i}{U_{ref}} + k_{x_i} \frac{x_i Q_i}{U_{ref}} - k_{q_i} Q_i^{\,3} - k_{p_i} P_i^{\,2} Q_i \tag{19}$$

In this method, the frequency is controlled by the conventional droop characteristic and four terms are added to the conventional droop characteristic. The terms $k_{r_i} r_i P_i / U_{ref_i}, k_{x_i} x_i Q_i / U_{ref_i}$ compensate the drop of voltage on the line impedance and reduce the coupling between the active and reactive power of the inverter. The two other terms improve the load sharing in the case of heavy loading [6]. In this method, the terms k_{pi} , k_{qi} are determined through the conventional method (Eq. (11), Eq. (12)) and the other coefficients (k_{ri} , k_{xi} , k_{pi} , k_{qi}) are determined by solving an optimization problem in which the circulating reactive power elimination and flat voltage profile are objective functions. The main drawbacks of this method are dependency to the line parameters, inability to handle non-linear loads and inappropriate transient response.

5.2.5. Voltage regulation and transient response improvement

In [61], a droop characteristic is proposed in which both dynamic terms and line impedance are considered. The droop characteristic is obtained as follows:

$$\omega_i = \omega_{ref} - k_{p_i} P_i - k_{wp} \frac{dP_i}{dt} + k_{wq} \frac{dQ_i}{dt} \tag{20}$$

$$U_i = U_{ref} - k_{q_i} Q_i + k_{r_i} \frac{r_i P_i}{U_{ref}} + k_{x_i} \frac{x_i Q_i}{U_{ref}} + k_{ep} \frac{dP_i}{dt} - k_{eq} \frac{dQ_i}{dt} \tag{21}$$

According to above equations, the frequency is controlled based on the conventional droop characteristic and some terms are added to improve the transient response. In the voltage characteristic, in addition to these terms, the terms related two the line impedance are added that play virtual impedance role and by proper adjusting the coefficient, the coupling between the active and reactive power is reduced. In this method, the terms k_{pi} , k_{qi} are also determined through the conventional method and the other coefficients are determined by solving an optimization problem in which the circulating reactive power elimination and flat voltage profile are objective functions. The main drawbacks of this method are dependency to the line parameters and inability to handle non-linear loads.

5.3. P-U/Q-F droop control

In low voltage lines, the inductance in the impedance is negligible in comparison to the resistance. Therefore, the impedance is almost resistive. The typical low voltage line impedance R/X ratio is about 7.7 [31,55,69]. So, and the approximation used in (7), (8) is not correct. In this case, $R >> X$ and approximated equations from (5), (6) are obtained as follows:

$$\delta \cong -\frac{RQ}{U_1 U_2} \tag{22}$$

$$U_1 - U_2 \cong \frac{RP}{U_1} \tag{23}$$

From these equations, it can be understood that the voltage difference is correspond to the active power and the power angle correspond to the reactive power. Therefore, the frequency can be controlled by reactive power flow and the voltage can be controlled through the active power, as well. According to this principle, the conventional P-U/Q-F droop control is specified with following equations [31]:

$$\omega = \omega_{ref} + k_q P \tag{24}$$

$$U = U_{ref} - k_p P \tag{25}$$

Fig. 13 shows the conventional P-U/Q-F droop characteristics. In most cases, the components of the distribution system impedance, especially for medium voltage lines, cannot be ignored. In this condition, the active power is not just an approximate function of power angle (for LV lines) or voltage difference (HV lines). Similarly, reactive power is not dependent only on the voltages difference or power angle. So, there is a cross coupling between the active and reactive powers of the DG and it is not possible to control them separately by the power angle and voltages amplitude respectively [34,70]. To solve this problem, researchers have introduced the virtual frame transformation methods.

5.4. Virtual frame transformation

5.4.1. Virtual P-Q frame

To solve decoupling problem, an orthogonal frame transformation is proposed in [54]. In this method, the active and the reactive power are transformed to a virtual framework in which there is no coupling between them. The P-Q transformation is defined as follows:

$$\begin{pmatrix} \hat{P} \\ \hat{Q} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} P \\ Q \end{pmatrix} = \begin{pmatrix} \frac{X}{Z} & -\frac{R}{Z} \\ \frac{R}{Z} & \frac{X}{Z} \end{pmatrix} \begin{pmatrix} P \\ Q \end{pmatrix} \tag{26}$$

$$T_{PQ} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \tag{27}$$

In above equations, T_{PQ} is the transformation matrix. It can be shown that by applying this transformation to (1), (2), the following relations can be obtained:

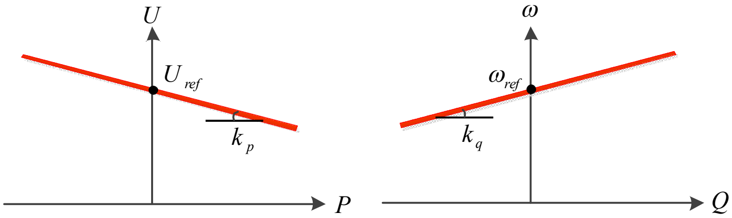


Fig. 13. Conventional P-U /Q-F droop characteristics.

$$\sin\delta = \frac{Z\hat{P}}{U_1 U_2} \tag{28}$$

$$U_1 - U_2\cos\delta = \frac{Z\hat{Q}}{U_1} \tag{29}$$

If the power angle δ is considered small, the above equation can be updated as:

$$\delta = \frac{Z\hat{P}}{U_1 U_2} \tag{30}$$

$$U_1 - U_2 = \frac{Z\hat{Q}}{U_1} \tag{31}$$

These relations show that the power angle δ and the voltage difference can be controlled through the $\hat{P}$ and $\hat{Q}$, respectively. So, the new droop equation becomes:

$$\omega = \omega_{ref} - k_p\hat{P} = \omega_{ref} - k_p\frac{X}{Z}P + k_p\frac{R}{Z}Q \tag{32}$$

$$U = U_{ref} - k_q\hat{Q} = U_{ref} - k_q\frac{R}{Z}P - k_q\frac{X}{Z}Q \tag{33}$$

Fig. 14 shows the block diagram of the P-Q virtual frame transformation that is used to control the inverter. Although the virtual P-Q transformation method can decouple the relation between the active and reactive power, it is a bit hard to implementation. For example, in the DG with unity power factor, by use of the conventional droop (i.e. P-F/Q-U), only the frequency control is sufficient to regulate the active power and voltage magnitude is fixed to achieve Q=0. While, in this virtual frame, both $\hat{P}$ and $\hat{Q}$ must be controlled simultaneously [35]. Another weakness is that in the virtual P-Q frame, the power range calculation of the DGs is difficult.

5.4.2. Virtual ω -U frame

To solve the problems related to the virtual P-Q frame, another orthogonal frame transformation can be defined as:

$$\begin{pmatrix}\hat{\omega}\\ \hat{U}\end{pmatrix} = \begin{pmatrix}\sin\theta & \cos\theta\\ -\cos\theta & \sin\theta\end{pmatrix}\begin{pmatrix}\omega\\ U\end{pmatrix} = \begin{pmatrix}\frac{R}{Z} & \frac{X}{Z}\\ -\frac{X}{Z} & \frac{R}{Z}\end{pmatrix}\begin{pmatrix}\omega\\ U\end{pmatrix} \tag{34}$$

$$T_{\omega U} = \begin{pmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{pmatrix} \tag{35}$$

In this case, first *ω,U* are calculated from the conventional droop control. Then, by use of this transformation, $\hat{\omega},\hat{U}$ are specified and are used as reference values for converter control. With such virtual *ω-U* frame, the output power of DG can be controlled totally decoupled [34–36]. Fig. 15 shows the block diagram of this method.

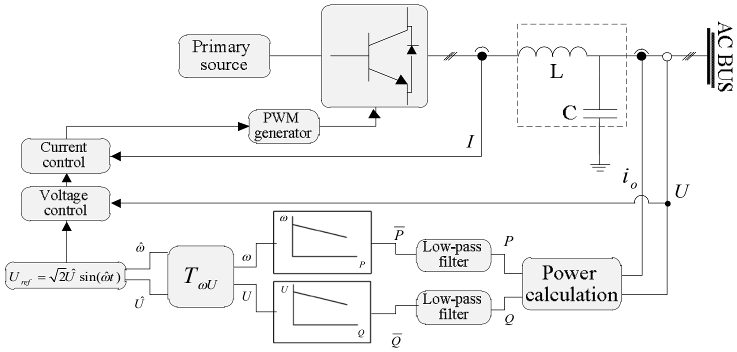


Fig. 14. Block diagram of P-Q virtual transformation.

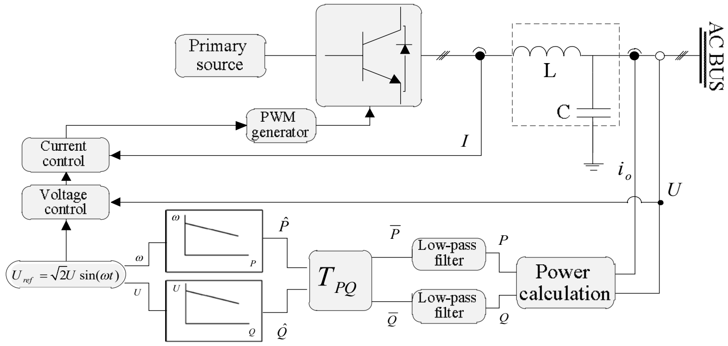


Fig. 15. Block diagram of *ω-U* virtual transformation.

Table 1. A comparison among the primary control methods.

	Method	**advantages**	**disadvantages**
Primary control methods	Communication-based methods	✓ Accurate power sharing ✓ High power quality ✓ Circulating power elimination ✓ Good transient response	× High-investment cost × Reduce the expandability and redundancy of system × Current overshoot in the case of master-slave method
	Conventional P-F/Q-U	✓ Simple implementation	× Poor voltage regulation × Inability to handle non-linear loads × Undesirable transient response × Circulating current among the DG units × Undesirable ripple in the output power
	(P-F/Q-U) + filter improvement	✓ Simple implementation ✓ Reduction of undesirable ripple in the output power	× Poor voltage regulation × Inability to handle non-linear loads × Dependency to the line parameters × Circulating current among the DG units
	(P-F/Q-U) + derivative terms	✓ Simple implementation ✓ Good transient response	× Poor voltage regulation × Inability to handle non-linear loads × Circulating current among the DG units
	(P-F/Q-U) + virtual impedance	✓ Decouples the active and reactive Power control ✓ Ability to handle non-linear loads (good harmonic sharing among the DG units)	× No guarantee to voltage regulation
	(P-F/Q-U) + Voltage regulation terms	✓ Decouples the active and reactive power control ✓ Adequate voltage regulation (especially in heavy loading) ✓ Eliminates the circulating current among the DG units	× Dependency to the line parameters × Inability to handle non-linear loads × Undesirable transient response
	(P-F/Q-U) + Voltage regulation terms + derivative terms	✓ Decouples the active and reactive power control ✓ Adequate voltage regulation ✓ Eliminates the circulating current among the DG units ✓ Good transient response	× Dependency to the line parameters × Inability to handle non-linear loads
	Conventional P-U/Q-F	✓ Simple implementation	× Poor voltage regulation × Inability to handle non-linear loads × Undesirable transient response × Circulating current among the DG units × Undesirable ripple in the output power
	Virtual frames	✓ Simple implementation ✓ Decouples the active and reactive power control	× Poor voltage regulation × Dependency to the line parameters × Inability to handle non-linear loads × Undesirable transient response

6. Comparison of various methods and future trends

As mentioned in the previous sections, the primary control is the first level of the microgrid hierarchical control system. The primary control is responsible for establishing the balance between the generation and consumption, proper load sharing among the DG units and regulation and stabilization of the voltage and frequency in MG. This paper reviewed the primary control methods in detail. It can be seen that each control scheme has its own advantages and disadvantages.

The communication-based methods provide an accurate power sharing, fast transient response, high power quality and reduce circulating power among the inverters. However, implementation of these methods needs a high-band width communication link. Moreover, due to the requirement for knowing the number of the inverter in the MG and the need for load current measurement, it is not easy to expand the system. The required interconnections reduce the reliability of the system and make the system not truly redundant and distributed. Droop based methods are based on the local measurement of the system variables which provide a truly distributed operation for the DG units. They do not depend on cables to ensure the reliable operation. Moreover, the redundancy can be easily achieved. Droop based methods have many desirable features including flexibility, modularity, expandability and redundancy [10,52,71]. However, these methods have some limitation including slow transient response, frequency and voltage amplitude deviations and circulating current among inverters due to the line impedance. The potential advantages and disadvantages of the primary control methods are outlined in Table 1. The challenges of each method such as ability to decouple the voltage and frequency control, voltage and frequency regulation, output ripple rejection, eliminating circulating power among the DG units and ability to handle the non-linear loads are examined.

It can be found that each of these proposed control methods has its own characteristics, advantages, and disadvantages and it is difficult for only one control scheme to overcome all drawbacks for all applications. However, further investigation of these control methods will help to improve the design and implementation of future microgrid architectures. Recently, the researchers have improved these two categories of methods (i.e., communication-based and droop-based methods). In [72], a droop-free distributed control for AC microgrids is proposed in which only a sparse communication graph is sufficient for the limited message passing among inverters. In [73], the combination of these two strategies is presented that gives proper results. So, a low band-width communication is required and the investment cost is reduced. The future trends in primary control strategies for microgrid are toward the hybrid mechanisms to take the advantage of both communication-based and droop based methods depending on the applications.

7. Conclusion

With recent interests in reliable and economic operation of the power systems, microgrids have been conceived as operative solutions. Proper control of a microgrid in both grid-connected and islanded operating modes encounters many challenges. Islanded microgrid control is more challenging, as stiff networks do not exist to provide stable frequency and voltage. So, the microgrid itself is responsible to maintain the frequency and voltage around the nominal values. The main goals of the microgrid control are frequency and voltage control. In addition to the main goals, various grid conditions dictate other circumstances such as proper active and reactive power sharing, network stability, and voltage quality to be also checked. The three-level hierarchical control system, comprising the primary, secondary and tertiary level, is a clear trend of research in microgrids control. This paper reviewed the state-of-the-art in the field of primary control methods for islanded microgrids. Detailed description of the control schemes was given and various techniques were discussed and their challenges were examined. Finally, the future trends for primary control techniques of inverter-based microgrids were briefly discussed. The studies indicate that in the microgrid development procedure, challenges and opportunities coexist.

Acknowledgment

This work was supported by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, and UID/EMS/00151/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

References

[1] Ahmadi S, Shokoohi S, Bevrani H. A fuzzy logic-based droop control for simultaneous voltage and frequency regulation in an AC microgrid. Int J Electr Power Energy Syst 2015;64:148–55. doi:10.1016/j.ijepes.2014.07.024.
[2] Lasseter RH. Microgrids. Power Eng. Soc. Winter Meet. 2002 IEEE, vol. 1, IEEE; 2002, p. 305–308.
[3] Lasseter B. Microgrids [distributed power generation]. Proc IEEE Power Eng Soc Winter Meet Columb OH USA Jan 2001 Vol 1 Pp 146–149 n.d.
[4] Lopes JP, Moreira CL, Madureira AG. Defining control strategies for microgrids islanded operation. IEEE Trans Power Syst 2006;21:916–924.
[5] Kim Y-S, Kim E-S, Moon S-I. Frequency and Voltage Control Strategy of Standalone Microgrids With High Penetration of Intermittent Renewable Generation Systems. IEEE Trans Power Syst 2016;31:718–28. doi:10.1109/TPWRS.2015.2407392.
[6] Rokrok E, Golshan MEH. Adaptive voltage droop scheme for voltage source converters in an islanded multibus microgrid. IET Gener Transm Distrib 2010;4:562–578.
[7] Katiraei F, Iravani R, Hatziargyriou N, Dimeas A. Microgrids management. IEEE Power Energy Mag 2008;6:54–65. doi:10.1109/MPE.2008.918702.
[8] Liang Che, Khodayar M, Shahidehpour M. Only Connect: Microgrids for Distribution System Restoration. IEEE Power Energy Mag 2014;12:70–81. doi:10.1109/MPE.2013.2286317.
[9] Bidram A, Davoudi A. Hierarchical Structure of Microgrids Control System. IEEE Trans Smart Grid 2012;3:1963–76. doi:10.1109/TSG.2012.2197425.
[10] Guerrero JM, Vasquez JC, Matas J, De Vicuña LG, Castilla M. Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization. IEEE Trans Ind Electron 2011;58:158–172.
[11] Han H, Hou X, Yang J, Wu J, Su M, Guerrero JM. Review of Power Sharing Control Strategies for Islanding Operation of AC Microgrids. IEEE Trans Smart Grid 2016;7:200–15. doi:10.1109/TSG.2015.2434849.
[12] Olivares DE, Mehrizi-Sani A, Etemadi AH, Canizares CA, Iravani R, Kazerani M, et al. Trends in Microgrid Control. IEEE Trans Smart Grid 2014;5:1905–19. doi:10.1109/TSG.2013.2295514.
[13] Palizban O, Kauhaniemi K. Hierarchical control structure in microgrids with distributed generation: Island and grid-connected mode. Renew Sustain Energy Rev 2015;44:797–813. doi:10.1016/j.rser.2015.01.008.
[14] Wu TF, Siri K, Banda J. The central-limit control and impact of cable resistance in current distribution for parallel-connected DC-DC converters. 25th Annu. IEEE Power Electron. Spec. Conf. PESC 94 Rec., 1994, p. 694–702 vol.1. doi:10.1109/PESC.1994.349662.
[15] Banda J, Siri K. Improved central-limit control for parallel-operation of DC-DC power converters. 26th Annu. IEEE Power Electron. Spec. Conf. 1995 PESC 95 Rec., vol. 2, 1995, p. 1104–10 vol.2. doi:10.1109/PESC.1995.474953.
[16] Shanxu D, Yu M, Jian X, Yong K, Jian C. Parallel operation control technique of voltage source inverters in UPS. Proc. IEEE 1999 Int. Conf. Power Electron. Drive Syst. 1999 PEDS 99, vol. 2, 1999, p. 883–7 vol.2. doi:10.1109/PEDS.1999.792823.
[17] Prodanovic M, Green TC. High-Quality Power Generation Through Distributed Control of a Power Park Microgrid. IEEE Trans Ind Electron 2006;53:1471–82. doi:10.1109/TIE.2006.882019.
[18] Tan J, Lin H, Zhang J, Ying J. A novel load sharing control technique for paralleled inverters. Power Electron. Spec. Conf. 2003 PESC 03 2003 IEEE 34th Annu., vol. 3, 2003, p. 1432–7 vol.3. doi:10.1109/PESC.2003.1216797.
[19] Tenti P, Caldognetto T, Costabeber A, Mattavelli P. Microgrids operation based on master-slave cooperative

control. IECON 2013 - 39th Annu. Conf. IEEE Ind. Electron. Soc., 2013, p. 7623–8. doi:10.1109/IECON.2013.6700403.

[20] Pei Y, Jiang G, Yang X, Wang Z. Auto-master-slave control technique of parallel inverters in distributed AC power systems and UPS. 2004 IEEE 35th Annu. Power Electron. Spec. Conf. IEEE Cat No04CH37551, vol. 3, 2004, p. 2050–2053 Vol.3. doi:10.1109/PESC.2004.1355433.

[21] Low KS, Cao R. Model Predictive Control of Parallel-Connected Inverters for Uninterruptible Power Supplies. IEEE Trans Ind Electron 2008;55:2884–93. doi:10.1109/TIE.2008.918474.

[22] Majumder R, Chaudhuri B, Ghosh A, Majumder R, Ledwich G, Zare F. Improvement of stability and load sharing in an autonomous microgrid using supplementary droop control loop. IEEE PES Gen. Meet., 2010, p. 1–1. doi:10.1109/PES.2010.5589665.

[23] Majumder R, Ghosh A, Ledwich G, Zare F. Angle droop versus frequency droop in a voltage source converter based autonomous microgrid. 2009 IEEE Power Energy Soc. Gen. Meet., 2009, p. 1–8. doi:10.1109/PES.2009.5275987.

[24] He J, Li YW. An Enhanced Microgrid Load Demand Sharing Strategy. IEEE Trans Power Electron 2012;27:3984–95. doi:10.1109/TPEL.2012.2190099.

[25] Tuladhar A, Jin H, Unger T, Mauch K. Control of parallel inverters in distributed AC power systems with consideration of line impedance effect. IEEE Trans Ind Appl 2000;36:131–8. doi:10.1109/28.821807.

[26] Li YW, Kao CN. An Accurate Power Control Strategy for Power-Electronics-Interfaced Distributed Generation Units Operating in a Low-Voltage Multibus Microgrid. IEEE Trans Power Electron 2009;24:2977–88. doi:10.1109/TPEL.2009.2022828.

[27] Katiraei F, Iravani MR. Power Management Strategies for a Microgrid With Multiple Distributed Generation Units. IEEE Trans Power Syst 2006;21:1821–31. doi:10.1109/TPWRS.2006.879260.

[28] Yu X, Khambadkone AM, Wang H, Terence STS. Control of Parallel-Connected Power Converters for Low-Voltage Microgrid—Part I: A Hybrid Control Architecture. IEEE Trans Power Electron 2010;25:2962–70. doi:10.1109/TPEL.2010.2087393.

[29] Yao W, Chen M, Matas J, Guerrero JM, Qian ZM. Design and Analysis of the Droop Control Method for Parallel Inverters Considering the Impact of the Complex Impedance on the Power Sharing. IEEE Trans Ind Electron 2011;58:576–88. doi:10.1109/TIE.2010.2046001.

[30] Goya T, Omine E, Kinjyo Y, Senjyu T, Yona A, Urasaki N, et al. Frequency control in isolated island by using parallel operated battery systems applying H∞ control theory based on droop characteristics. IET Renew Power Gener 2011;5:160–166.

[31] Ao SI, Douglas C, Grundfest WS, editors. Study and Development of a Modified Droop Control Strategy for Autonomous Microgrids. Hong Kong: IAENG, International Association of Engineers; 2016.

[32] Sao CK, Lehn PW. Autonomous load sharing of voltage source converters. IEEE Trans Power Deliv 2005;20:1009–16. doi:10.1109/TPWRD.2004.838638.

[33] Sao CK, Lehn PW. Control and Power Management of Converter Fed Microgrids. IEEE Trans Power Syst 2008;23:1088–98. doi:10.1109/TPWRS.2008.922232.

[34] Li Y, Li YW. Power Management of Inverter Interfaced Autonomous Microgrid Based on Virtual Frequency-Voltage Frame. IEEE Trans Smart Grid 2011;2:30–40. doi:10.1109/TSG.2010.2095046.

[35] Li Y, Li YW. Decoupled power control for an inverter based low voltage microgrid in autonomous operation. Power Electron. Motion Control Conf. 2009 IPEMC09 IEEE 6th Int., IEEE; 2009, p. 2490–2496.

[36] Li Y, Li YW. Virtual frequency-voltage frame control of inverter based low voltage microgrid. Electr. Power Energy Conf. EPEC 2009 IEEE, IEEE; 2009, p. 1–6.

[37] Vasquez JC, Mastromauro RA, Guerrero JM, Liserre M. Voltage Support Provided by a Droop-Controlled Multifunctional Inverter. IEEE Trans Ind Electron 2009;56:4510–9. doi:10.1109/TIE.2009.2015357.

[38] He J, Li YW, Guerrero JM, Blaabjerg F, Vasquez JC. An Islanding Microgrid Power Sharing Approach Using Enhanced Virtual Impedance Control Scheme. IEEE Trans Power Electron 2013;28:5272–82. doi:10.1109/TPEL.2013.2243757.

[39] Planas E, Gil-de-Muro A, Andreu J, Kortabarria I, Martínez de Alegría I. General aspects, hierarchical controls and droop methods in microgrids: A review. Renew Sustain Energy Rev 2013;17:147–59. doi:10.1016/j.rser.2012.09.032.

[40] Yazdanian M, Mehrizi-Sani A. Distributed Control Techniques in Microgrids. IEEE Trans Smart Grid 2014;5:2901–9. doi:10.1109/TSG.2014.2337838.

[41] Ashabani SM, Mohamed YAI. New family of microgrid control and management strategies in smart distribution

grids—analysis, comparison and testing. IEEE Trans Power Syst 2014;29:2257–2269.

[42] Eid BM, Rahim NA, Selvaraj J, Khateb AHE. Control Methods and Objectives for Electronically Coupled Distributed Energy Resources in Microgrids: A Review. IEEE Syst J 2016;10:446–58. doi:10.1109/JSYST.2013.2296075.

[43] Rajesh KS, Dash SS, Rajagopal R, Sridhar R. A review on control of ac microgrid. Renew Sustain Energy Rev 2017;71:814–9. doi:10.1016/j.rser.2016.12.106.

[44] Andishgar MH, Gholipour E, Hooshmand R. An overview of control approaches of inverter-based microgrids in islanding mode of operation. Renew Sustain Energy Rev 2017;80:1043–60. doi:10.1016/j.rser.2017.05.267.

[45] Mehrizi-Sani A, Iravani R. Potential-function based control of a microgrid in islanded and grid-connected modes. IEEE Trans Power Syst 2010;25:1883–1891.

[46] De Brabandere K, Vanthournout K, Driesen J, Deconinck G, Belmans R. Control of microgrids. Power Eng. Soc. Gen. Meet. 2007 IEEE, IEEE; 2007, p. 1–7.

[47] Karimi H, Nikkhajoei H, Iravani R. Control of an electronically-coupled distributed resource unit subsequent to an islanding event. 2008 IEEE Power Energy Soc. Gen. Meet. - Convers. Deliv. Electr. Energy 21st Century, 2008, p. 1–1. doi:10.1109/PES.2008.4596149.

[48] Nikkhajoei H, Lasseter RH. Distributed Generation Interface to the CERTS Microgrid. IEEE Trans Power Deliv 2009;24:1598–608. doi:10.1109/TPWRD.2009.2021040.

[49] Shafiee Q, Stefanovic C, Dragicevic T, Popovski P, Vasquez JC, Guerrero JM. Robust Networked Control Scheme for Distributed Secondary Control of Islanded Microgrids. IEEE Trans Ind Electron 2014;61:5363–74. doi:10.1109/TIE.2013.2293711.

[50] Shafiee Q, Guerrero JM, Vasquez JC. Distributed secondary control for islanded microgrids—A novel approach. IEEE Trans Power Electron 2014;29:1018–1031.

[51] Simpson-Porco JW, Shafiee Q, Dörfler F, Vasquez JC, Guerrero JM, Bullo F. Secondary frequency and voltage control of islanded microgrids via distributed averaging. IEEE Trans Ind Electron 2015;62:7025–7038.

[52] Guerrero JM, Chandorkar M, Lee T-L, Loh PC. Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control. IEEE Trans Ind Electron 2013;60:1254–1262.

[53] Vandoorn TL, De Kooning JDM, Meersman B, Vandevelde L. Review of primary control strategies for islanded microgrids with power-electronic interfaces. Renew Sustain Energy Rev 2013;19:613–28. doi:10.1016/j.rser.2012.11.062.

[54] De Brabandere K, Bolsens B, Van den Keybus J, Woyte A, Driesen J, Belmans R. A Voltage and Frequency Droop Control Method for Parallel Inverters. IEEE Trans Power Electron 2007;22:1107–15. doi:10.1109/TPEL.2007.900456.

[55] Rocabert J, Luna A, Blaabjerg F, Rodríguez P. Control of Power Converters in AC Microgrids. IEEE Trans Power Electron 2012;27:4734–49. doi:10.1109/TPEL.2012.2199334.

[56] Rodriguez P, Candela I, Citro C, Rocabert J, Luna A. Control of grid-connected power converters based on a virtual admittance control loop. 2013 15th Eur. Conf. Power Electron. Appl. EPE, 2013, p. 1–10. doi:10.1109/EPE.2013.6634621.

[57] Chiang SJ, Chang JM. Parallel control of the UPS inverters with frequency-dependent droop scheme. 2001 IEEE 32nd Annu. Power Electron. Spec. Conf. IEEE Cat No01CH37230, vol. 2, 2001, p. 957–61 vol.2. doi:10.1109/PESC.2001.954243.

[58] Piagi P, Lasseter RH. Autonomous control of microgrids. Power Eng. Soc. Gen. Meet. 2006 IEEE, IEEE; 2006, p. 8–pp.

[59] Guerrero JM, Berbel N, Matas J, Sosa JL, de Vicuna LG. Droop control method with virtual output impedance for parallel operation of uninterruptible power supply systems in a microgrid. Appl. Power Electron. Conf. APEC 2007-Twenty Second Annu. IEEE, IEEE; 2007, p. 1126–1132.

[60] Weedy BM, editor. Electric power systems. 5th ed. Chichester, West Sussex, UK: John Wiley & Sons, Ltd; 2012.

[61] Rokrok E, Rokrok E, Mahmoudi A. A voltage/frequency control scheme for distributed resources in an autonomous multi-bus microgrid. 2016 24th Iran. Conf. Electr. Eng. ICEE, 2016, p. 954–9. doi:10.1109/IranianCEE.2016.7585659.

[62] Pegueroles-Queralt J, Bianchi F, Gomis-Bellmunt O. Optimal droop control for voltage source converters in islanded microgrids. IFAC Proc Vol 2012;45:566–571.

[63] Hassanzahraee M, Bakhshai A. Transient droop control strategy for parallel operation of voltage source converters in an islanded mode microgrid. Telecommun. Energy Conf. INTELEC 2011 IEEE 33rd Int., IEEE; 2011, p. 1–9.

[64] Kan Z, Guo Z, Zhang C, Meng X. Research on droop control of inverter interface in autonomous microgrid. Power

Electron. Appl. Conf. Expo. PEAC 2014 Int., IEEE; 2014, p. 195–199.

[65] Raciti A, Bignucolo F, Caldon R. Assessment of an improved droop control scheme for DG inverter based microgrids. Power Eng. Conf. UPEC 2015 50th Int. Univ., IEEE; 2015, p. 1–6.

[66] Pogaku N, Prodanovic M, Green TC. Modeling, Analysis and Testing of Autonomous Operation of an Inverter-Based Microgrid. IEEE Trans Power Electron 2007;22:613–25. doi:10.1109/TPEL.2006.890003.

[67] Mohamed Y, El-Saadany EF. Adaptive Decentralized Droop Controller to Preserve Power Sharing Stability of Paralleled Inverters in Distributed Generation Microgrids. IEEE Trans Power Electron 2008;23:2806–16. doi:10.1109/TPEL.2008.2005100.

[68] Guerrero JM, GarciadeVicuna L, Matas J, Castilla M, Miret J. Output Impedance Design of Parallel-Connected UPS Inverters With Wireless Load-Sharing Control. IEEE Trans Ind Electron 2005;52:1126–35. doi:10.1109/TIE.2005.851634.

[69] Engler A. Applicability of droops in low voltage grids. Int J Distrib Energy Resour 2005;1:1–6.

[70] Dvorskỳ LR-E. Voltage and Frequency Control for Islanded Microgrids Containing Photovoltaic Power Plants. J Electr Eng 2014;65:9–14.

[71] Mojica-Nava E, Macana CA, Quijano N. Dynamic Population Games for Optimal Dispatch on Hierarchical Microgrid Control. IEEE Trans Syst Man Cybern Syst 2014;44:306–17. doi:10.1109/TSMCC.2013.2266117.

[72] Nasirian V, Shafiee Q, Guerrero JM, Lewis FL, Davoudi A. Droop-Free Distributed Control for AC Microgrids. IEEE Trans Power Electron 2016;31:1600–17. doi:10.1109/TPEL.2015.2414457.

[73] Yu X, Wang HH, Khambadkone AM, Siew TS. A hybrid control architecture for low voltage microgrid. Energy Convers. Congr. Expo. ECCE 2010 IEEE, IEEE; 2010, p. 3161–3168.