Hybrid ac/dc microgrids—Part II: Review and classification of control strategies

Eneko Unamuno*[1] and Jon Andoni Barrena[2]

Electronics and Computing Department, Mondragon Unibertsitatea, Loramendi 4, 20500 Mondragon, Spain
**Corresponding author*
E-mail addresses: [1]eunamuno@mondragon.edu and [2]jabarrena@mondragon.edu

Abstract

Microgrids are envisioned as one of the most suitable alternatives for the integration of distributed generation units in the utility grid, as they efficiently combine generation, energy storage and loads in the same distribution network. In this context, hybrid ac/dc microgrids are arising as an interesting approach as they combine the advantages of ac and dc networks and do not require excessive modifications in the distribution network. However, they require more complex control strategies as they need to control the ac and dc networks and the interface power converter simultaneously. This paper identifies and analyses the control strategies that can be implemented in hybrid microgrids for an adequate power management in grid-tied and islanded modes of operation. The review is focused on hierarchical controls as they are the most extended approach in the literature. A classification has been elaborated, which covers the three main levels of hierarchical control strategies (primary, secondary and tertiary). Each of the levels has been independently studied in order to provide a comprehensive analysis of the alternatives found in the literature. The future trends related to this topic show that a higher research effort is required regarding the control of the interface device and the ancillary services that the management strategy must provide—e.g. blackstart, transition between islanded and grid-connected modes of operation, interconnection of microgrids, etc.

Keywords: Centralized control, decentralized control, distributed control, droop control, hierarchical control, hybrid, microgrids, smart grids

1. Introduction

The integration of renewable energy sources (RES) as distributed generation (DG) is an attractive solution to deal with the dependency on fossil fuels, the constant increment of the energy consumption and the poor energy quality supplied by a conservative and aged power network.

Microgrids are a feasible solution towards the integration of RES, energy storage systems (ESS) and loads in the same grid, and several reviews can be found where different aspects of these networks are analyzed: control strategies [1]–[16], test beds around the world [13], [17]–[19], optimization techniques and available software tools [20]–[25], protection devices [7], [14], [16], [26], [27], etc.

Although the configuration of microgrids can be either ac, dc or hybrid ac/dc, during the last years hybrid solutions (Figure 1) are becoming an interesting alternative as they combine the main advantages of ac and dc networks [28]–[32]. The greatest part of the research focuses on ac- or dc-based microgrids independently, so a more detailed analysis of the factors related to hybrid microgrids is required.

In this context, the most used hybrid topologies have been reviewed and studied in the first part of this paper [Reference to Part I]. This second part of the paper is focused on control strategies because microgrids, and specially hybrid ones, require more complex control strategies than conventional power distribution networks [16], [32].

Hybrid microgrids are composed by an ac network, a dc network and a power converter interface between both of them that controls the power flow between the networks and the utility grid (Figure 1). These configurations have several advantages as ac- and dc-based devices can be easily connected to the grid with less interface converters. However, their control strategy must provide several features: adequate power sharing of RES and ESS units, stability of voltage and frequency at grid tied and islanded modes of operation, optimal power exchange between the microgrid and the power network, etc.

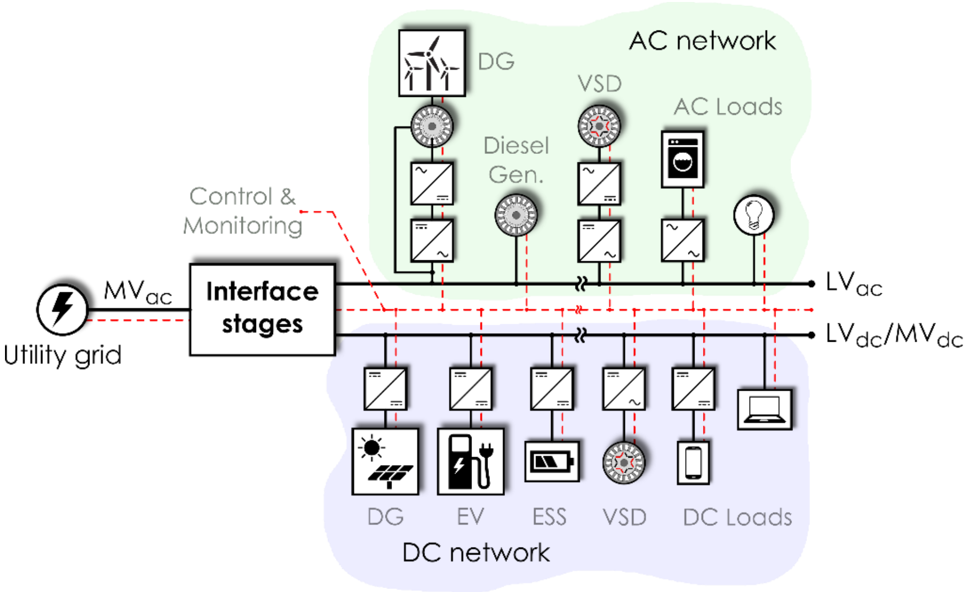

Figure 1 – Example of a hybrid microgrid configuration.

Although several control strategies can be found in the literature, there is a reduced number of them that directly focuses on hybrid ac/dc microgrids. In addition, the information around the strategies for hybrid microgrids is very disperse and has not been previously reviewed. Therefore, the main purpose of this paper is to identify and analyze the most important control strategies that can be implemented in hybrid microgrids. Many of them have been originally studied for ac and dc microgrids independently, but might be also feasible for hybrid microgrids with higher or lower modifications. The classification and analysis of the most important features of control strategies will support researchers and developers to adopt the most suitable management strategy depending on the requirements of their microgrid.

The structure of the paper is as follows: in Section 2 a brief overview of the hybrid microgrid concept is performed, where the main features and associated problems are stated. A classification of the most relevant strategies can be also found in this section. Subsequently, Section 3 collects a wide literature review related to the architectures used in hybrid microgrids and a comparative evaluation of the revised topologies. Finally, in Section 4 and 5 the most important future trends and conclusions of the research are presented, respectively.

2. Control strategies overview

One of the most characteristic features that distinguishes microgrids from conventional distribution grids is the control strategy that manages the devices attached to the network. This strategy is necessary for an optimal management mainly due to the distributed nature of microgrids [33]. On the one hand, the intermittent behavior of DG units must be controlled in an optimal way with ESS units so that a stable and constant power flow is provided. Apart from that, the microgrid must be controlled properly when operating on an autonomous mode to ensure a seamless transition between modes of operation and provide stable voltage and frequency.

Therefore, control strategies for microgrids are a challenging field that is being widely researched in order to find the most suitable one depending on the requirements.

Generally, the characteristics that a control strategy must fulfil in the microgrid environment are the following [16], [34]–[36]:

- **Stability:** regulation of the voltage and frequency of the microgrid operating at different modes. Moreover, it ensures a stable and reliable power network both in the ac- and dc-side of the microgrid.
- **Protection:** monitoring of energy flow and critical devices, and fault management of the grid.
- **Power balance:** optimal load sharing and DG supply coordination.
- **Transition:** seamless transition between microgrid modes of operation—i.e. islanding to grid-tied mode or vice versa.
- **Power transmission:** exchange of power between the microgrid and the utility grid.
- **Synchronization:** synchronization of the microgrid with the power network for an optimal transmission of power.
- **Optimization:** depending on the conditions of the microgrid and the utility grid (e.g. market situation, power demand/supply or energy forecast), management of the systems to reduce costs, improve energy efficiency, etc.

These features cause the need to adopt a more complex control architecture compared to the controls found in conventional distribution networks. In the typical power grid the management of generation or storage units is not controlled by the grid operator unless their magnitude is representative for the network.

It is not simple to identify and classify the control strategies that are most common as they mainly depend on the characteristics of the microgrid. However, the control strategies that are adopted by most authors in order to provide the aforementioned features are based on a hierarchical structure [1], [2], [9], [16], [33]–[35], [37]–[43]. In this approach three main control levels are distinguished: global/tertiary, microgrid/secondary and local/primary control. Each level is responsible for the control of the microgrid at a different scale and their main functions are summarized in Figure 2.

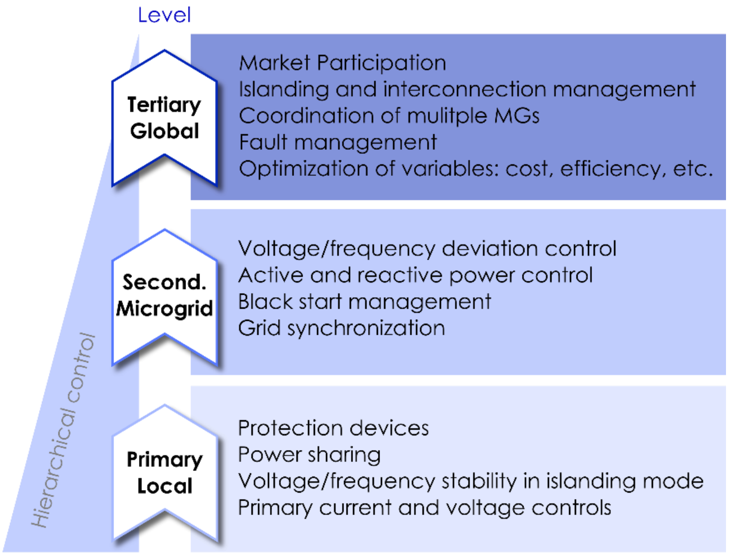

Figure 2 – Main functions of control levels of a hierarchical control architecture.

The classification of the most relevant hierarchical control level strategies can be observed in Figure 3. This classification has been performed based on the studies found in the literature, and their characteristics are explained more in detail in the following sections.

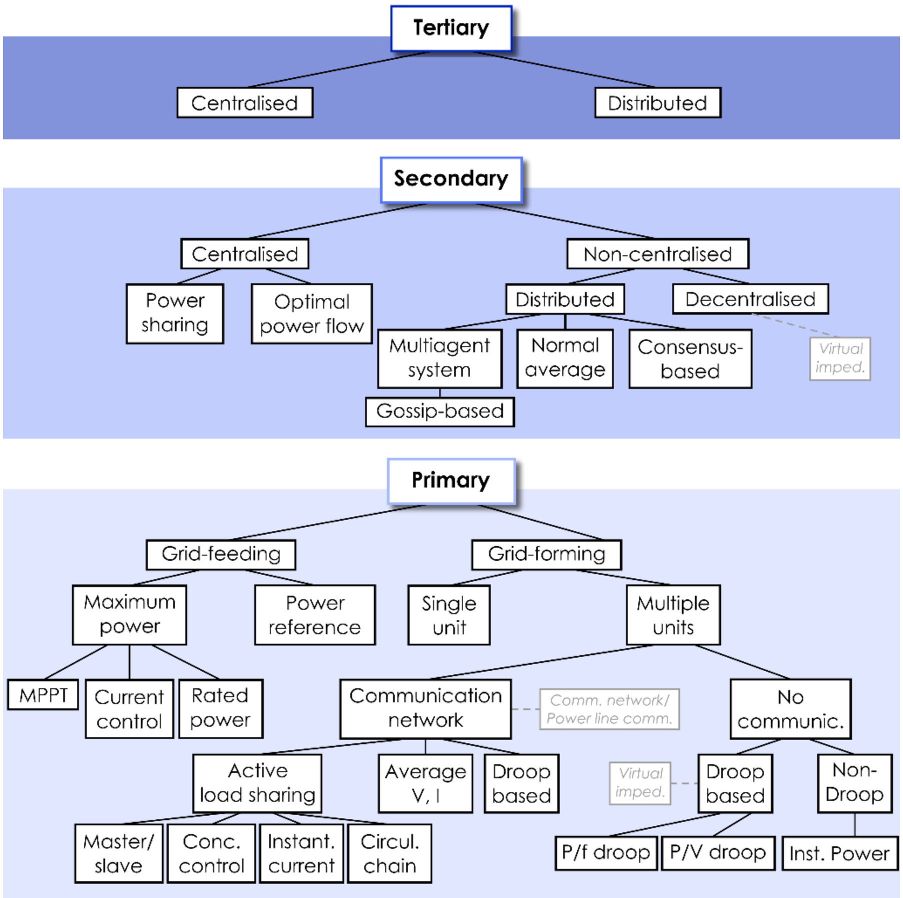

Figure 3 – Classification table of the microgrid control strategies identified in the literature.

3. Hierarchical control levels

3.1. Primary control

The purpose of the local controller is to perform the current and voltage control of the interface devices connected to DG and ESS units. Optimal power management of resources and power sharing has to be ensured while providing voltage and frequency stability. In addition, lower-level protection is performed at this stage—e.g. inhibition of converters, contactors, etc.

In the literature usually two or three types of primary control levels are distinguished, depending on their function. Some authors state that three strategies can be implemented, namely grid-forming, grid-feeding/following and grid-supporting ones [2], [44]. However, this classification could be simplified by reducing the number of primary control strategies to grid-forming and grid-feeding ones as described in [1], [40]. The grid-supporting strategies are introduced in the grid-forming group because they contribute to the regulation of the grid voltage.

Although some studies can be found where primary control strategies are reviewed [34], [45], they usually focus on ac or dc-based microgrids. In this case, grid-following and grid-forming control startegies are analyzed for their implementation in hybrid ac/dc microgrids. Therefore, not only the control of DG and ESS devices is reviewed but also the control for the interface converter between the ac and dc networks.

3.1.1. Grid-following control

When operating in grid-tied mode, the voltage and frequency of the microgrid are established by the utility grid, so the local controllers of RES systems usually operate in current-control mode to extract as much power as possible from energy resources—e.g. maximum power point tracking (MPPT) mode in wind turbine or photovoltaic systems, rated power operation in diesel/biomass generators, etc. [40]. Apart from that, this type of control can work in a non-optimal point—out of the maximum power range—when the references are set by upper control levels. Usually the purpose of this approach is to optimize the power sharing strategy of the network [44]. These strategies are equally implemented in ac- and dc-based units; the main difference is the synchronization process of the ac-based ones to the ac side of the microgrid.

In this context, Blaabjerg *et al.* perform a review of some of the most relevant grid-following control strategies for DG systems and identify the most suitable network synchronization methods in the case of ac-based DG units—i.e. zero crossing, grid voltage filtering and phase locked loop (PLL) techniques [46]. Based on that, Palizban *et al.* have recently performed a review and classification of primary control strategies where the most common grid-following techniques are identified [1]: synchronous reference frame (*dq*), stationary reference frame (*αβ*) and natural frame (*abc*). For more information regarding these control strategies refer to [1], as internal current and voltage control strategies are out of the scope of this review.

On a similar approach, Rocabert *et al.* and Rodríguez *et al.* identify some of the most suitable control techniques for the connection of devices to ac grids [44], [47]. These strategies could be implemented on the ac side of the hybrid microgrid or in both ac and dc networks after some adaptations.

3.1.2. Grid-forming control

When an intentional or non-intentional islanding occurs, voltage and frequency stability of the ac and dc networks of the microgrid has to be ensured by DG and ESS systems. Therefore, an optimal active and reactive power control has to be performed so as to provide adequate power sharing between devices. This feature has been previously studied for lower-scale uninterruptible power supply systems [48], [49].

Depending on the requirements, some or all the DG units will operate to control the network voltage [40]—i.e. in grid-forming mode—while the rest continue in grid-following mode. Two configurations have been identified for this control strategy [40]:

- **Single grid-forming unit:** one of the interface converters connected to DG units is in grid-forming mode and its reference is established to supply a certain voltage and frequency. The rest of the devices connected to this network are controlled to absorb as much power as possible from energy resources—i.e. in grid-following mode [40].
- **Multiple grid-forming units:** in this strategy, more than one interface converter is controlled in grid-forming mode. Consequently, a synchronization process is required to ensure voltage and frequency stability for both the ac and dc microgrid networks while performing a balanced power sharing.

  According to several authors, approaches under this category can be distinguished depending on whether interface converters are interconnected by a communication network or not [9], [10], [15], [34]. Vandoorn *et al.*, for example, make an extensive review of grid-forming control strategies for multiple grid-forming DG interface converters where this classification is observed [10].
  - Communication network between devices: these strategies are usually based on active load sharing. They include master/slave, central or concentrated control, instantaneous current sharing or circular chain approaches, among others [1], [10]. The main disadvantage of these techniques is that the communication network can become extremely complex in highly extended microgrids, and it can cause failures in the control strategy if any part of the communication network has a fault. Moreover, plug and play capability is not ensured, what makes the integration of upcoming devices a challenging task.

    As an example of this control strategy, Liu *et al.* propose in [50] a primary control strategy for a hybrid ac/dc microgrid consisting of an energy storage system, a photovoltaic panel, a doubly-fed induction generator-based wind turbine and an ac and dc load. The authors employ a cascaded voltage and current regulator for the DG and ESS devices and for the interface converter, and some information is exchanged between these control strategies in order to ensure a good stability and demanded power sharing.

    Another approach can be observed in [51], where Bidram *et al.* develop a two-layer control strategy based on the droop control technique—which is a proportional control—for voltage- and current-controlled voltage-source inverters. The control strategy of each device requires its own information and the information of the neighboring systems, but it does not make use of a central controller for the management of the microgrid.

    Other solutions can be found where communication between DG and ESS devices is necessary but no communication network is present. These approaches are based on the communication between the power lines of the microgrid, which is also known as power line communication (PLC) or power line signaling (PLS). An example of this strategy can be observed in [52], where signals of different frequencies are sent through the power line so as to synchronize the converters connected to the grid. Although this strategy does not require any additional communication network, the control signals that circulate through the microgrid pollute the voltage and frequency of the networks. Moreover, the integration of new generation or storage units in the microgrid is more complex as the range of frequencies where the signals can be injected is reduced when the number of devices already connected is high.

    Even if primary control strategies based on a communication network provide adequate power sharing and stability for the microgrid, they are not very used in the literature. A more usual approach is to employ an autonomous primary control with a centralized or distributed secondary control, which is explained more in detail in the following sections.
  - No communication network:

    <u>*Droop-based control*</u>

Droop control is one of the most studied strategies where no communication between devices is necessary [13], [36], [37], [43], [53]–[73]. During the last decade, a lot of research effort has been focused on this topic due to the advantages it provides over other control alternatives: plug and play capability, power sharing, less faults due to the lack of a communication network, simple implementation, etc. The purpose of droop control is to vary the voltage amplitude and frequency references depending on the active and reactive power demand to perform the power sharing between devices. This strategy is widely used for the power sharing of synchronous generators in the conventional utility grid. In microgrids, ESS units often include this strategy to perform optimal current sharing when operating both in islanded or grid-tied mode. Moreover, its integration in DG systems is often limited to islanded operating mode to perform an optimal power sharing and to take advantage of MPPT regulation in grid-tied mode as mentioned in Section 3.1.1 [37].

Under this category, Guerrero *et al.* propose in [37] some primary droop-based control strategies for ac and dc microgrid architectures which are suitable for their implementation in hybrid microgrids. According to the authors, even if conventional droop control strategies have several advantages over other alternatives, they also present some drawbacks: no capability for non-linear load sharing, load-dependent frequency deviation or trade-off between the voltage regulation and the current sharing between the converters, among others. In order to cope with these problems, a hierarchical control consisting of three levels is proposed, where voltage and frequency deviations are compensated by the secondary level (explained more in detail in Section 3.2).

Similarly, Bidram and Davoudi perform an extensive comparative evaluation of several droop control strategy variants for ac microgrids [34], and collect their most relevant advantages and disadvantages (refer to Table I in [34] for more information).

A slightly different approach which is based on droop control can be also observed in [74]. In this case, the authors have adapted the droop curves depending on the mode of operation of the microgrid, so that a certain device operates in each case. The modes of operating are defined based on the voltage levels of the microgrid. The authors in this case state that a fully decentralized control can be obtained as the devices modify their operating mode autonomously.

Each droop method has its own advantages and disadvantages. Therefore, there is not an optimal solution that can cover all type of applications, and their feasibility has to be studied in detail depending on each situation.

The above mentioned studies focus on ac or dc microgrid droop controls independently, but they can be implemented in hybrid microgrids with slight modifications. As an example, Loh *et al.* combines both strategies for their operation in a hybrid microgrid by the use of an interlinking converter [64]. In this approach, the power flow between both sides of the microgrid is studied through a normalization process of the ac frequency and dc voltage.

Similarly, Eghtedarpour and Farjah make use of droop control strategies for the management of the interface converter that is located between the ac and dc network [75]. The authors propose a solution based on a two-stage droop control by measuring the ac microgrid frequency and the dc microgrid voltage. With this control a bidirectional power control can be performed under different modes of operation.

<u>Virtual impedance</u>

As an extra feature of droop-based techniques, many authors introduce the concept of the virtual impedance in the control strategy [47], [76]. These virtual impedances are mainly used to provide active stabilization and disturbance rejection or to provide ancillary services to the microgrid.

Shi *et al.*, for example, introduce an adaptive virtual impedance in the control strategy in order to perform the voltage and frequency regulation of the ac microgrid [77]. The authors in [78] and in [79] have also employed a virtual impedance to control the power sharing of distributed converters. Moreover, Li and Kao use a virtual impedance in order to decouple the control of the active and reactive power of converters, and they defend that the reactive power control and sharing accuracy is significantly improved.

An ancillary service provided by the virtual impedance can be to avoid circulating power flows between converters connected in parallel, as studied by Kim *et al.* in [57] or by Zhang *et al.* in [68]. The latter study, for example, contemplates the interconnection of six three-stage SST converters in parallel, and employs an adaptive virtual impedance to mitigate currents circulating between them.

Another interesting approach is the solution proposed by Gu *et al.* in [80], where different virtual impedances are employed for the ESSs that regulate the voltage of the dc microgrid. Depending on whether the ESS unit is based on batteries or supercapacitors, the virtual impedance is adapted so the response of their converters corresponds to their power capabilities. As an example, the dynamics of the virtual impedance of the supercapacitors will be faster than the one from the batteries.

Other ancillary services such as state of charge balancing of ESS [55] or soft-start techniques for wind turbines [37] can be also seen in the literature.

<u>Non-droop-based control</u>

Apart from droop-based techniques, other strategies can be found where no communication network is required. Ovalle *et al.*, for example, propose an alternative that is based on the instantaneous power theory [81]. The authors imply that power sharing between devices can be achieved without any communication, barely with local measurements.

Another approach is proposed by Sun *et al.* in [82], where the modes of operation of the photovoltaic panels attached to the microgrid are varied autonomously depending on the level of the voltage.

Regarding the control of the interface device, Davari and Mohamed propose a fixed-parameter low-order strategy in [83]. The authors state that this control strategy provides a great tracking performance and a robust disturbance rejection and stability over operating point or parameter variations.

As it can be deduced, the vast majority of control strategies that do not require a communication network are based on droop control techniques. However, as aforementioned, droop techniques require additional modifications in order to ensure an efficient management of the microgrid.

In some cases hybrid control solutions are also used, although they are not as common as the above mentioned approaches [10]. An example of a hybrid control strategy can be observed in [78], where a communication-based and autonomous control strategy are mixed. In this case, the autonomous control is used for DG converter blocks that are physically apart, and it is based on the droop control technique. On the other hand, the converters inside each block, which are near each other, are controlled with a dynamic power distribution technique. The authors state that this strategy improves the system efficiency while ensuring balanced power sharing.

3.2. Secondary control

The main purpose of this control level is to compensate the voltage and frequency deviations in the networks that compose the microgrid (in the dc side of microgrids only the voltage). After a change in the load or generation of the microgrid, the secondary control regulates the difference between the established voltage/frequency references and the measured ones towards zero [37], [84], [85].

When operating in islanded mode, the secondary control strategy is the higher hierarchical control level, so it must ensure other features such as black-start management and resynchronization on the transition from islanding to grid-tied mode of operation.

Secondary control strategies are primarily categorized as centralized or non-centralized [33], [36], [86], [87]. Depending on the architecture and the state of the microgrid, the control levels adopt different grades of responsibility.

3.2.1. Centralized management

In centralized approaches, the management of the microgrid is performed from a central controller located at the global control level, usually named as microgrid central controller or MGCC (Figure 4) [13], [33], [86]. In order to do so, variables such as active and reactive power are collected from DG, ESS and critical loads; moreover, market conditions, security issues and requests coming from upper control units (e.g. the SCADA of the utility grid) are taken into account [33]. This means that a communication network links all the hierarchical control levels.

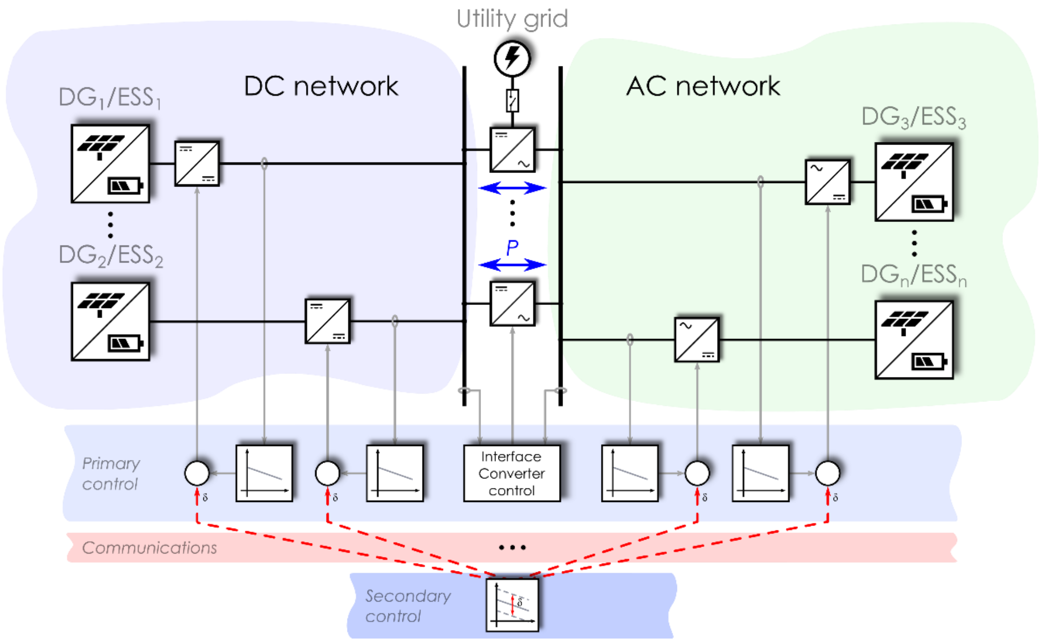

Figure 4 – Concept of the centralized secondary control

Therefore, centralized control strategies become extremely difficult when a high amount of devices are connected at dispersed locations and their owners do not share the same interests. However, they are suitable for the management of small-scale microgrid where there is a single or reduced number of DG and ESS owners, as they provide high plug-and-play capabilities [13], [36].

The secondary centralized control compensates the variations of voltage and frequency in primary control levels based on the references set by the upper tertiary control level when operating in the grid-tied mode. Alternatively, these references are internally generated when an islanding process occurs. The already mentioned study performed by Guerrero *et al.* in [37] shows an example of this strategy. The authors propose a centralized secondary control which could be implemented for both networks of the hybrid microgrid.

A similar approach is proposed by Shafiee *et al.* for dc microgrids in [39]. They study the integration of a control strategy that relies on a communication network for a proper operation and power sharing of generation and storage devices. The authors state that it is not possible to take advantage of this technique when there is an interconnection of microgrids, since power sharing has to be ensured. Therefore, the adoption of a decentralized strategy is proposed for this operating mode.

Milczarek *et al.* also propose a centralized secondary controller that collects the information from the DG units and generates the active and reactive power references for each device [88]. This method provides a balanced active and reactive power sharing between the controlled devices, improving the characteristics of conventional droop-based techniques.

Another approach of this control strategy can be observed in [61], where an optimal power flow algorithm is developed in order to find and generate the optimal reference values for voltages and active powers in a dc microgrid.

The integration of a secondary control strategy for the interface converter of a hybrid microgrid can be also seen in [89]. In this approach, Radwan and Mohamed employ a centralized strategy for the control of the interface converter whereas the management of the generation devices located at the microgrid is performed autonomously. According to the authors, the control of the interface converter operates successfully regardless of the mode DG units are managed.

A general overview of a droop-based hierarchical centralized control is performed by Vasquez *et al.* in [41], and other studies can be found where this control strategy has been used [79], [90]–[93].

3.2.2. Non-centralized management

In non-centralized control strategies, power management responsibilities recall in the generation and storage devices. This means that instead of being implemented in the MGCC, they are integrated in the local controller, avoiding the communication network with upper level control strategies (tertiary and so on) [94]. The main advantage of these management strategies is that in case a fault occurs, the rest of the microgrid can operate normally after disconnecting the faulty unit.

The non-centralized control approach is envisioned as an attractive solution towards the integration of microgrids at the power distribution level, as it offers a more simple communication network while providing plug-and-play connection of devices [13], [33], [36].

Two main variants can be found; one where a communication network is integrated, also named distributed control [42], and another where there is no communication between units (DG, ESS, etc.), also known as decentralized control.

- Distributed secondary control: this is one of the most studied secondary techniques due to the good performance it provides and the relatively simple communication network it requires (Figure 5).
  Yazdanian *et al.* perform a review of some of the suitable solutions—e.g. consensus or agent-based techniques—stating that they provide higher performance over decentralized or centralized approaches thanks to the interaction between units [42].

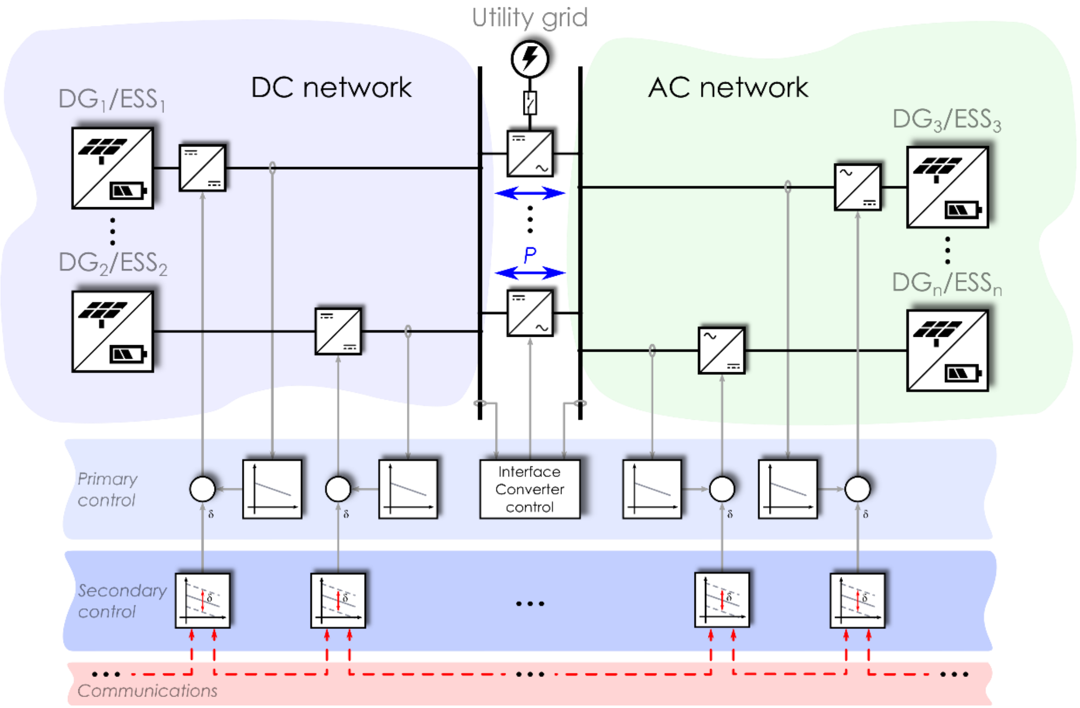

Figure 5 – Concept of the distributed secondary control strategy.

Multi-agent systems (MAS) are one of the solutions for the distributed management of microgrids. In this approach, each local controller acts as an agent, making decisions over the parameters of the DG or ESS unit that is controlling. As it is a distributed strategy, the communication is performed only between neighboring devices.

An example of this alternative is explained and developed by Bidram *et al.* in [95] for ac microgrids. The authors propose a droop-based primary control strategy where the reference values are generated based on the parameters of adjacent devices. The validation in this case is performed by simulation, concluding that adequate voltage control is ensured while performing a good power sharing between devices.

In addition, Liang *et al.* show a MAS-based control algorithm that performs the communication between neighboring devices via wireless connection [96]. The authors state that even if the convergence of the microgrid is slower due to near interferences, this strategy improves previous MAS-based techniques by reducing multiagent coordination errors.

Apart from the mentioned studies, this control strategy has been also adopted by other authors, for example in [97]–[101].

Apart from MAS-based techniques, other distributed strategies have been also identified in the literature. As an example, Shafiee, in cooperation with several other authors has proposed a wide variety of distributed secondary control strategies to provide frequency and voltage deviation controllability while ensuring reactive power sharing [94], [102]–[104]. These strategies are divided into three main groups: normal averaging, gossip-based (a type of MAS technique) and consensus based techniques. As an example a normal averaging control strategy can be seen in [94], which has been experimentally validated and compared to a centralized control structure afterwards. The conclusions are that a good performance is obtained with this strategy and the communication network is simplified considerably comparing to centralized configurations [94].

A similar approach is proposed by Simpson-Porco *et al.* in [105], where a distributed averaging technique is employed for the secondary control of frequency and voltage. According to the authors, the control strategy of each device only requires the information of its neighboring devices to perform the frequency control and power sharing. The authors in [72] have also employed an average voltage sharing in order to compensate the voltage deviations caused by the primary droop-based control, and the study performed in [59] integrates an average current sharing and voltage sharing technique to enhance the accuracy on the current sharing and regulated the bus voltage, respectively.

Regarding consensus-based secondary techniques, some examples can be seen in the literatures such as the solution proposed by Guo *et al.* in [106]. In this paper, the authors state that this control strategy can restore voltage and frequency to their rated values while the power sharing is ensured between the connected devices.

- Decentralized secondary control: several authors imply that decentralized control strategies are more suitable for microgrid systems as they need no communication and therefore plug and play connection of upcoming units can be ensured (Figure 6). In [107], Chandorkar *et al.* develop a control strategy that does not require any type of communication network between devices and relies in locally-measured parameters. Results show that the power sharing between devices is correctly performed under load variations.

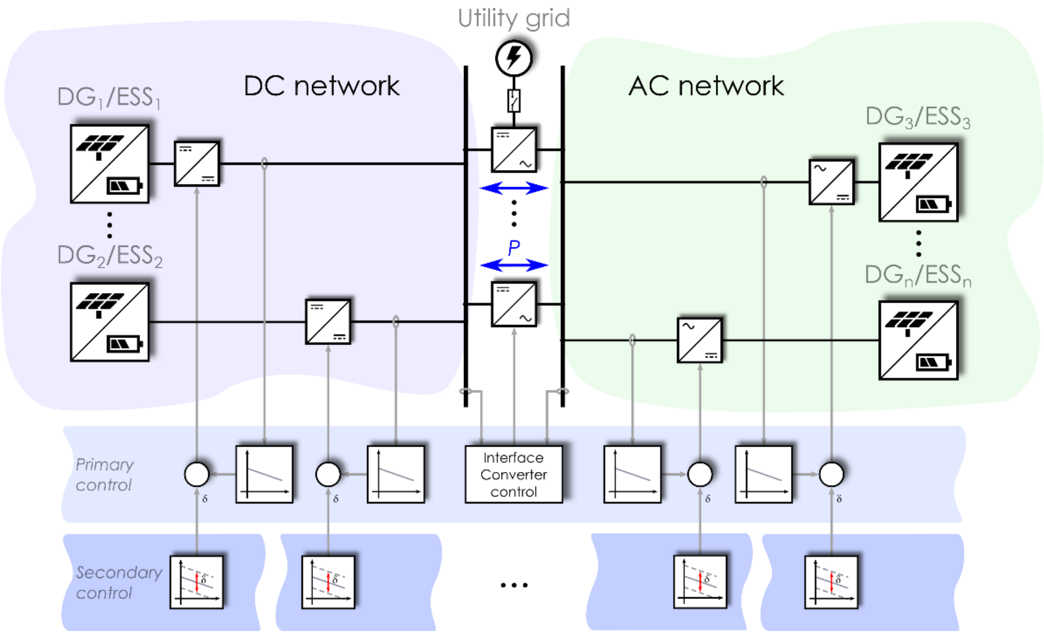

Figure 6 – Concept of the decentralized secondary control

Díaz *et al.* have also proposed a secondary control strategy that merely uses local variables to perform the control of ESS units [63]. The authors mention that with this control technique, which is based on fuzzy inference, it is possible to adequately balance the state of charge of the ESS while providing low voltage deviation. Similarly, a decentralized secondary control strategy is used in [108] in order to restore the frequency deviation of the droop primary control.

The concept of virtual impedance has been also used by some authors in order to provide frequency and voltage compensation without any type of communication between devices [77].

On the other hand, Ahn *et al.* have performed a comparison between distributed and decentralized secondary control strategies [109]. They state that even if it is possible to perform the management of the microgrid without any type of communication between devices, the distributed approach provides a better performance and reliability.

A slightly different approach is employed by Wang *et al.* in [110], where the decentralized control strategy is used to control the DG and ESS systems located at the ac and dc network of a hybrid microgrid.

3.2.3. Centralized vs non-centralized management

Apart from specific studies of centralized or non-centralized control strategies, several articles can be found where the features of each approach are highlighted. Planas *et al.*, for example, compare and identify the main advantages of centralized and non-centralized MAS architectures in terms of complexity of control, communications, fault management and flexibility and modularity [13]. According to the authors, the centralized approach is envisioned as an interesting alternative for small-scale microgrids where few modifications will be performed in the future, whereas decentralized control strategies offer a more flexible system although their higher initial cost. However, as Olivares *et al.* state in [35], usually a compromise between centralized and decentralized approach is adopted because a minimum communication is required for an optimal management of the microgrid. As an example of this, Majumder *et al.* analyze and compare two communication-based and autonomous control strategies, concluding that the low-bandwidth communication significantly improves the power sharing and it is economically feasible [111].

The main features of each control architecture have been summarized by Hatziargyriou *et al.* in [33] and are shown in Table 1.

Table 1 – Main characteristics of centralized and decentralized control architectures [33].

Characteristic	***Centralized control***	***Decentralized control***
DG ownership	Single owner	Multiple owners
Goals	A clear, single task, e.g. minimization of energy costs	Uncertainty over what each owner wants at any particular moment
Availability of operating personnel (monitoring, low level management, special switching operations, etc.)	Available	Not available
Market participation	Implementation of complicated algorithms	Owners unlikely to use complex algorithms
Installation of new equipment	Requirements of specialized personnel	Should be plug-and-play
Optimality	Optimal solutions	Mostly suboptimal solutions
Communication requirements	High	Low
Market participation	All units collaborate	Some units may be competitive
Microgrid operation is attached to a larger and more critical operation	Possible	Not possible

As can be observed in the table, the centralized approach makes sense in microgrids where there is a single owner or the owners share the same interests. Therefore, the main applications that adopt this strategy will be small microgrids where a limited number of controllable devices are integrated and few future integrations are expected.

However, microgrids managed by non-centralized control will comprise the largest part of microgrid applications, as they offer a high level of flexibility by supporting the inclusion of plug-and play devices.

3.3. Tertiary control

When operating in grid-tied mode, the tertiary or global control level manages the active and reactive power flow between the microgrid and the utility grid by regulating the voltage and frequency of the microgrid. Similar to the secondary control level, this can be performed in two ways: as a centralized strategy where the tertiary control level is located at the MGCC (which can be the SCADA system), or as a distributed technique where the entire control is located at the local controllers.

3.3.1. Centralized management

In centralized techniques, power values are measured at the point of common coupling and they are compared to the desired values. P/Q reference values are obtained based on the power requirements of the microgrid and the market situation—i.e. energy cost, generation, storage and/or load forecasting, etc. This way, different variables can be optimized such as efficiency, economical benefit, control simplicity, power quality, etc.

An example of this control level can be seen in [37], where Guerrero *et al.* propose a centralized hierarchical control consisting of three levels. In this solution, the active and reactive power are measured in the PCC and compared to the desired values in order to generate the frequency and voltage references for the secondary level. The algorithms have been tested by simulation and show a good performance of the overall control strategy for the islanded/grid-tied modes and the transition between both modes of operation. Moreover, the authors mention that the management of multiple microgrids can be done with the proposed control.

A centralized tertiary control can be also seen in [112] for the energy management of a hybrid ac/dc microgrid. As well as ensuring an adequate voltage control, this strategy takes into account several factors such as the forecast of electricity price, generation and demand power profiles in order to optimize the overall system—grid interaction and ESS/DG interaction. According to the authors, this strategy reduces the operation cost of the microgrid.

A similar approach is employed by Shi *et al.* in [113], where an optimal power flow problem is formulated in order to generate the schedule of the microgrid. The results in this case show that the proposed energy management strategy operates successfully in grid-tied and islanded modes.

Apart from these studies, a variety of centralized tertiary management strategies can be identified in the literature [93], [114]–[120].

3.3.2. Distributed management

Usually, the tertiary control level is not located at the microgrid itself, but in the MGCC of the main grid (e.g. at the SCADA). However, there exist some approaches where the tertiary control level is placed in the microgrid in a distributed manner, as can be observed in [121]. In this paper the authors propose a gossip-based tertiary control algorithm that is directly located at the local controllers. In addition, all the devices are interconnected via internet, increasing the reliability and efficiency of the system.

A similar architecture has been used by Meng *et al.*, where the three hierarchical levels are integrated in the local controller [122]. In this approach a consensus-based tertiary control strategy has been implemented, and two communication networks have been developed for the adequate operation of the microgrid: one for the communication between consensus-based controls and another one for the primary and secondary levels.

Even if these strategies significantly improve the flexibility of microgrids, the most common trend in the literature is to employ centralized tertiary control strategies. The main reason is that the coordination of the devices attached to the microgrid is performed based on factors that are difficult to be integrated on each device. These factors include forecasting of generation and demand profiles, energy flow in the microgrid, energy market, etc.

4. Future trends

One of the most important conditions that a microgrid must fulfil is the plug-and-play capability of devices such as DG, ESS or loads. Most authors have focused on droop-based control strategies to cope with this, but these present some drawbacks that need to be further researched such as reactive power sharing or frequency and voltage deviations [34], [37].

In hybrid microgrids the control strategy for the interface converter must be improved to provide adequate power flow between the ac and dc network. Several authors have developed the control of these devices independently, but there are not so many where their operation is studied in a microgrid environment (e.g. [123], [124]). In addition, there are very few studies where the control of this converter is synchronized with the control strategies integrated at the devices of the microgrid. Therefore, the management of interface converters that takes into account the topology (as discussed in the first part of this paper) and control strategy of the microgrid needs to be further developed, which is foreseen an interesting research topic.

Regarding higher control levels of the microgrid, there are many aspects that need improvements to be competitive over conventional grid architectures.

As microgrids are capable of controlling the power flow with the utility grid, a high level control technique that performs the management of multiple microgrids can be included. Although this is an interesting solution for the increment of the overall efficiency, there is a small amount of studies that cover this topic in the literature [39], [125].

Other aspects that need to be further researched are the transition between grid-tied and islanded modes of operation or blackstart procedures [11], [27], [126]. Even if these have not been covered in this paper, they are one of the most critical aspects that microgrids need to handle.

Apart from the aforementioned features, the optimization of control strategies is also an interesting approach that has not been covered thoroughly before. In this context, control strategies can be optimized taking into account market conditions, forecasting of energy production or consumption, computational charges or efficiency issues [REFERENCIA REVIEW]. Depending on the requirements and the situation of the microgrid (location, regulatory conditions), the optimization process can be carried out to operate in a certain mode.

It can be observed that even though several studies have been already performed, there are many fields that need to be further researched. The aforementioned topics are likely to be studied in the near future.

5. Conclusions

Microgrids are one of the most promising alternatives towards the integration of DG units in the conventional power network. However, this type of systems require more complex control strategies than the ones employed in the utility grid, especially in hybrid microgrids. In these configurations ac and dc networks and the main power controller need to be managed for an optimal performance of the microgrid, but most of the literature researches have focused on these subsystems independently.

In order to identify the strategies that can be employed in hybrid microgrids, this paper has reviewed the most used ones in the literature for ac and dc microgrids. The main functions that the management strategy should provide have been collected, and a classification of the most studied hierarchical controls has been elaborated.

Three control levels have been distinguished and the variants that are used in this case have been analyzed and explained.

Regarding the primary control level, it has been concluded that droop-based techniques are the most suitable approach towards a scalable microgrid, as they provide high plug-and-play capability while ensuring adequate power sharing of devices both in grid-tied and islanded modes of operation.

Secondary level techniques have been distinguished depending on whether they are located at a central point (centralized) or at the local controller of each device (decentralized). After evaluating the studies found in the literature it has been determined that centralized strategies are more adequate for single-user low-scale microgrid configurations, whereas decentralized ones are suitable for larger scale systems with multiple users that are constantly being adapted to upcoming units.

Something similar has been concluded with tertiary level strategies. Although decentralized approaches are not as common as centralized ones when referring to tertiary level controls, they can improve the integration of new units to the microgrid. However, the systems that are based on centralized strategies provide a more accurate performance and better reliability thanks to the synchronization of units.

Acknowledgements

This work has been partially funded by a predoctoral grant of the Basque Government (PRE_2014_1_408).

References

[1] O. Palizban and K. Kauhaniemi, "Hierarchical control structure in microgrids with distributed generation : Island and grid-connected mode," *Renew. Sustain. Energy Rev.*, vol. 44, pp. 797–813, 2015.

[2] A. M. Bouzid, J. M. Guerrero, A. Cheriti, M. Bouhamida, P. Sicard, and M. Benghanem, "A survey on control of electric power distributed generation systems for microgrid applications," *Renew. Sustain. Energy Rev.*, vol. 44, pp. 751–766, 2015.

[3] P. G. Arul, V. K. Ramachandaramurthy, and R. K. Rajkumar, "Control strategies for a hybrid renewable energy system: A review," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 597–608, Feb. 2015.

[4] R. D. Prasad, R. C. Bansal, and A. Raturi, "Multi-faceted energy planning: A review," *Renew. Sustain. Energy Rev.*, vol. 38, pp. 686–699, Oct. 2014.

[5] P. Paliwal, N. P. Patidar, and R. K. Nema, "Planning of grid integrated distributed generators: A review of technology, objectives and techniques," *Renew. Sustain. Energy Rev.*, vol. 40, pp. 557–570, Dec. 2014.

[6] C. Li, C. Cao, Y. Cao, Y. Kuang, L. Zeng, and B. Fang, "A review of islanding detection methods for microgrid," *Renew. Sustain. Energy Rev.*, vol. 35, pp. 211–220, Jul. 2014.

[7] S. a. Gopalan, V. Sreeram, and H. H. C. Iu, "A review of coordination strategies and protection schemes for microgrids," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 222–228, Apr. 2014.

[8] P. Siano, "Demand response and smart grids—A survey," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 461–478, Feb. 2014.

[9] O. Palizban, K. Kauhaniemi, and J. M. Guerrero, "Microgrids in active network management - Part I: Hierarchical control, energy storage, virtual power plants, and market participation," *Renew. Sustain. Energy Rev.*, vol. 36, pp. 428–439, Aug. 2014.

[10] T. L. Vandoorn, J. D. M. De Kooning, B. Meersman, and L. Vandevelde, "Review of primary control strategies for islanded microgrids with power-electronic interfaces," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 613–628, Mar. 2013.

[11] K. N. E. Ku Ahmad, J. Selvaraj, and N. A. Rahim, "A review of the islanding detection methods in grid-connected PV inverters," *Renewable and Sustainable Energy Reviews*, vol. 21. Elsevier, pp. 756–766, 2013.

[12] A. Khamis, H. Shareef, E. Bizkevelci, and T. Khatib, "A review of islanding detection techniques for renewable distributed generation systems," *Renewable and Sustainable Energy Reviews*, vol. 28. Elsevier, pp. 483–493, 2013.

[13] E. Planas, A. Gil-De-Muro, J. Andreu, I. Kortabarria, and I. Martínez De Alegría, "General aspects, hierarchical controls and droop methods in microgrids: A review," *Renewable and Sustainable Energy Reviews*, vol. 17. pp. 147–159, Jan-2013.

[14] P. Basak, S. P. Chowdhury, and S. Halder nee Dey, "A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid," *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 5545–5556, Oct. 2012.

[15] S. K. Khadem, M. Basu, and M. F. Conlon, "Parallel operation of inverters and active power filters in distributed generation system---A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 9, pp. 5155–5168, Dec. 2011.

[16] J. J. Justo, F. Mwasilu, J. Lee, and J. W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renewable and Sustainable Energy Reviews*, vol. 24. Elsevier, pp. 387–405, Aug-2013.

[17] N. W. A. Lidula and A. D. Rajapakse, "Microgrids research: A review of experimental microgrids and test systems," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1. Elsevier Ltd, pp. 186–202, Jan-2011.

[18] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Recent developments in microgrids and example cases around the world, A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 8, pp. 4030–4041, Oct. 2011.

[19] E. Hossain, E. Kabalci, R. Bayindir, and R. Perez, "Microgrid testbeds around the world: State of art," *Energy Convers. Manag.*, vol. 86, pp. 132–153, Oct. 2014.
[20] S. Sinha and S. S. Chandel, "Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems," *Renew. Sustain. Energy Rev.*, vol. 50, pp. 755–769, 2015.
[21] a. H. Fathima and K. Palanisamy, "Optimization in microgrids with hybrid energy systems – A review," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 431–446, 2015.
[22] C. Gamarra and J. M. Guerrero, "Computational optimization techniques applied to microgrids planning: A review," *Renew. Sustain. Energy Rev.*, vol. 48, pp. 413–424, 2015.
[23] M. Iqbal, M. Azam, M. Naeem, A. S. Khwaja, and A. Anpalagan, "Optimization classification, algorithms and tools for renewable energy: A review," *Renew. Sustain. Energy Rev.*, vol. 39, pp. 640–654, Nov. 2014.
[24] K. Zhou, S. Yang, Z. Chen, and S. Ding, "Optimal load distribution model of microgrid in the smart grid environment," *Renew. Sustain. Energy Rev.*, vol. 35, pp. 304–310, Jul. 2014.
[25] R. Viral and D. K. Khatod, "Optimal planning of distributed generation systems in distribution system: A review," *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 5146–5165, Sep. 2012.
[26] S. Mirsaeidi, D. Mat Said, M. Wazir Mustafa, M. Hafiz Habibuddin, and K. Ghaffari, "Progress and problems in micro-grid protection schemes," *Renew. Sustain. Energy Rev.*, vol. 37, pp. 834–839, Sep. 2014.
[27] O. Palizban, K. Kauhaniemi, and J. M. Guerrero, "Microgrids in active network management --- Part II: System operation, power quality and protection," *Renew. Sustain. Energy Rev.*, vol. 36, pp. 440–451, Aug. 2014.
[28] R. A. Kaushik and N. M. Pindoriya, "A hybrid AC-DC microgrid: Opportunities & key issues in implementation," in *International Conference on Green Computing Communication and Electrical Engineering (ICGCCEE)*, 2014, pp. 1–6.
[29] I. Patrao, E. Figueres, G. Garcerá, and R. González-Medina, "Microgrid architectures for low voltage distributed generation," *Renew. Sustain. Energy Rev.*, vol. 43, pp. 415–424, Mar. 2015.
[30] E. Planas, J. Andreu, J. I. Gárate, I. Martínez de Alegría, and E. Ibarra, "AC and DC technology in microgrids: A review," *Renew. Sustain. Energy Rev.*, vol. 43, pp. 726–749, Mar. 2015.
[31] Z. Jiang and X. Yu, "Hybrid DC- and AC-Linked Microgrids: Towards Integration of Distributed Energy Resources," in *IEEE Energy 2030 Conference*, 2008, pp. 1–8.
[32] P. Wang, L. Goel, X. Liu, and F. H. Choo, "Harmonizing AC and DC: A Hybrid AC/DC future grid solution," *IEEE Power Energy Mag.*, vol. 11, no. 3, pp. 76–83, May 2013.
[33] A. Dimeas, A. Tsikalakis, G. Kariniotakis, and G. Korres, "Microgrids Control Issues," in *Microgrids: Architectures and Control*, N. D. Hatziargyriou, Ed. Chichester: Wiley-IEEE Press, 2013, p. 341.
[34] A. Bidram and A. Davoudi, "Hierarchical Structure of Microgrids Control System," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1963–1976, Dec. 2012.
[35] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Canizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. A. Jimenez-Estevez, and N. D. Hatziargyriou, "Trends in Microgrid Control," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905–1919, Jul. 2014.
[36] R. Zamora and A. K. Srivastava, "Controls for microgrids with storage: Review, challenges, and research needs," *Renew. Sustain. Energy Rev.*, vol. 14, no. 7, pp. 2009–2018, Sep. 2010.
[37] 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.
[38] J. M. Guerrero, M. Chandorkar, T. Lee, and P. C. Loh, "Advanced Control Architectures for Intelligent Microgrids---Part I: Decentralized and Hierarchical Control," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1254–1262, Apr. 2013.
[39] Q. Shafiee, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Hierarchical control for multiple DC-microgrids clusters," in *IEEE 11th International Multi-Conference on Systems, Signals & Devices (SSD14)*, 2014, pp. 1–6.
[40] T. L. Vandoorn, J. C. Vasquez, J. De Kooning, J. M. Guerrero, and L. Vandevelde, "Microgrids: Hierarchical control and an overview of the control and reserve management strategies," *IEEE Ind. Electron. Mag.*, vol. 7, no. 4, pp. 42–55, Dec. 2013.
[41] J. Vasquez, J. Guerrero, J. Miret, M. Castilla, and L. Garcia De Vicuna, "Hierarchical control of intelligent microgrids," *IEEE Ind. Electron. Mag.*, vol. 4, no. 4, pp. 23–29, Dec. 2010.
[42] M. Yazdanian and A. Mehrizi-Sani, "Distributed Control Techniques in Microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 6, pp. 2901–2909, Nov. 2014.
[43] X. Lu, J. M. Guerrero, K. Sun, J. C. Vasquez, R. Teodorescu, and L. Huang, "Hierarchical control of parallel AC-DC converter interfaces for hybrid microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 683–692, Mar. 2014.
[44] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of Power Converters in AC Microgrids," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4734–4749, Nov. 2012.
[45] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, "Review of Power Sharing Control Strategies for Islanding Operation of AC Microgrids," *IEEE Trans. Smart Grid*, pp. 1–1, 2015.

[46] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of Control and Grid Synchronization for Distributed Power Generation Systems,” *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[47] P. Rodriguez, I. Candela, C. Citro, J. Rocabert, and A. Luna, “Control of grid-connected power converters based on a virtual admittance control loop,” in *15th European Conference on Power Electronics and Applications (EPE)*, 2013, pp. 1–10.

[48] J. M. Guerrero, L. Hang, and J. Uceda, “Control of distributed uninterruptible power supply systems,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 8, pp. 2845–2859, Aug. 2008.

[49] M. Wang, F. Li, Y. Liu, L. Huang, and M. Sakane, “Distributed parallel operation of modified deadbeat controlled UPS inverters,” in *PESC Record - IEEE Annual Power Electronics Specialists Conference*, 2007, pp. 1727–1732.

[50] 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.

[51] A. Bidram, A. Davoudi, and F. L. Lewis, “A Multiobjective Distributed Control Framework for Islanded AC Microgrids,” *IEEE Trans. Ind. Informatics*, vol. 10, no. 3, pp. 1785–1798, 2014.

[52] T. Dragicevic, J. M. Guerrero, and J. C. Vasquez, “A Distributed Control Strategy for Coordination of an Autonomous LVDC Microgrid Based on Power-Line Signaling,” *IEEE Trans. Ind. Electron.*, vol. 61, no. 7, pp. 3313–3326, Jul. 2014.

[53] J. M. Guerrero, P. C. Loh, T. Lee, and M. Chandorkar, “Advanced Control Architectures for Intelligent Microgrids---Part II: Power Quality, Energy Storage, and AC/DC Microgrids,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1263–1270, Apr. 2013.

[54] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous Control of Interlinking Converter With Energy Storage in Hybrid AC-DC Microgrid,” *IEEE Trans. Ind. Appl.*, vol. 49, no. 3, pp. 1374–1382, May 2013.

[55] T. Dragicevic, J. M. Guerrero, J. C. Vasquez, and D. Skrlec, “Supervisory Control of an Adaptive-Droop Regulated DC Microgrid With Battery Management Capability,” *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 695–706, Feb. 2014.

[56] S. Eren, M. Pahlevani, A. Bakhshai, and P. Jain, “An Adaptive Droop DC-Bus Voltage Controller for a Grid-Connected Voltage Source Inverter With LCL Filter,” *IEEE Trans. Power Electron.*, vol. 30, no. 2, pp. 547–560, Feb. 2015.

[57] J. Kim, J. M. Guerrero, P. Rodriguez, R. Teodorescu, and K. Nam, “Mode Adaptive Droop Control With Virtual Output Impedances for an Inverter-Based Flexible AC Microgrid,” *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 689–701, Mar. 2011.

[58] C. Lee, C. Chu, and P. Cheng, “A New Droop Control Method for the Autonomous Operation of Distributed Energy Resource Interface Converters,” *IEEE Trans. Power Electron.*, vol. 28, no. 4, pp. 1980–1993, Apr. 2013.

[59] X. Lu, J. M. Guerrero, K. Sun, and J. C. Vasquez, “An Improved Droop Control Method for DC Microgrids Based on Low Bandwidth Communication With DC Bus Voltage Restoration and Enhanced Current Sharing Accuracy,” *IEEE Trans. Power Electron.*, vol. 29, no. 4, pp. 1800–1812, Apr. 2014.

[60] A. Maknouninejad, Z. Qu, F. L. Lewis, and A. Davoudi, “Optimal, Nonlinear, and Distributed Designs of Droop Controls for DC Microgrids,” *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2508–2516, Sep. 2014.

[61] K. Rouzbehi, A. Miranian, A. Luna, and P. Rodriguez, “DC Voltage Control and Power Sharing in Multiterminal DC Grids Based on Optimal DC Power Flow and Voltage-Droop Strategy,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 2, no. 4, pp. 1171–1180, Dec. 2014.

[62] D. Wu, F. Tang, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, “A Control Architecture to Coordinate Renewable Energy Sources and Energy Storage Systems in Islanded Microgrids,” *IEEE Trans. Smart Grid*, pp. 1–1, 2014.

[63] N. L. Diaz, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, “Intelligent Distributed Generation and Storage Units for DC Microgrids---A New Concept on Cooperative Control Without Communications Beyond Droop Control,” *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2476–2485, Sep. 2014.

[64] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of hybrid microgrid with ac and dc subgrids,” *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2214–2223, May 2013.

[65] 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 Syst.*, vol. 25, no. 2, pp. 796–808, May 2010.

[66] H. Han, Y. Liu, Y. Sun, M. Su, J. M. Guerrero, and S. Member, “An Improved Droop Control Strategy for Reactive Power Sharing in Islanded Microgrid,” *IEEE Trans. Power Deliv.*, vol. 30, no. 6, pp. 3133–3141, 2015.

[67] K. De Brabandere, B. Bolsens, J. Van den Keybus, A. Woyte, J. Driesen, and R. Belmans, “A Three-Phase Voltage and Frequency Droop Control Scheme for Parallel Inverters,” *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp. 1107–1115, 2007.

[68] M. Zhang, Z. Du, X. Lin, and J. Chen, “Control Strategy Design and Parameter Selection for Suppressing Circulating Current Among SSTs in Parallel,” *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1602–1609, Jul. 2015.

[69] D. Chen and L. Xu, “Autonomous DC Voltage Control of a DC Microgrid With Multiple Slack Terminals,” *IEEE Trans. Power Syst.*, vol. 27, no. 4, pp. 1897–1905, Nov. 2012.
[70] S. Grillo, V. Musolino, L. Piegari, E. Tironi, and C. Tornelli, “DC Islands in AC Smart Grids,” *IEEE Trans. Power Electron.*, vol. 29, no. 1, pp. 89–98, Jan. 2014.
[71] X. She, A. Q. Huang, and R. Burgos, “Review of Solid-State Transformer Technologies and Their Application in Power Distribution Systems,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 1, no. 3, pp. 186–198, Sep. 2013.
[72] P. Huang, P. Liu, W. Xiao, and M. S. El Moursi, “A Novel Droop-Based Average Voltage Sharing Control Strategy for DC Microgrids,” *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1096–1106, May 2015.
[73] Y. A.-R. I. Mohamed and A. a. Radwan, “Hierarchical Control System for Robust Microgrid Operation and Seamless Mode Transfer in Active Distribution Systems,” *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 352–362, Jun. 2011.
[74] Y. Gu, X. Xiang, W. Li, and X. He, “Mode-Adaptive Decentralized Control for Renewable DC Microgrid With Enhanced Reliability and Flexibility,” *IEEE Trans. Power Electron.*, vol. 29, no. 9, pp. 5072–5080, 2014.
[75] N. Eghtedarpour and E. Farjah, “Power Control and Management in a Hybrid AC/DC Microgrid,” *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1494–1505, May 2014.
[76] X. Wang, Y. Li, F. Blaabjerg, and P. C. Loh, “Virtual-Impedance-Based Control for Voltage-Source and Current-Source Converters,” *IEEE Trans. Power Electron.*, vol. 8993, no. c, pp. 1–1, 2014.
[77] H. Shi, Z. Fang, H. Yi, F. Wang, D. Zhang, and Z. Geng, “A Novel Real-time Voltage and Frequency Compensation Strategy for Photovoltaic-based Microgrid,” *IEEE Trans. Ind. Electron.*, vol. 0046, no. c, pp. 1–1, 2014.
[78] 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, Dec. 2010.
[79] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, “Secondary control for voltage quality enhancement in microgrids,” *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1893–1902, 2012.
[80] Y. Gu, W. Li, and X. He, “Frequency-Coordinating Virtual Impedance for Autonomous Power Management of DC Microgrid,” *IEEE Trans. Power Electron.*, vol. 30, no. 4, pp. 2328–2337, 2015.
[81] A. Ovalle, S. Member, G. Ramos, S. Bacha, A. Hably, and A. Rumeau, “Decentralized Control of Voltage Source Converters in Microgrids Based on the Application of Instantaneous Power Theory,” *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 1152–1162, 2015.
[82] W. Sun, C.-C. Liu, and S. Liu, “Black start capability assessment in power system restoration,” *2011 IEEE Power Energy Soc. Gen. Meet.*, pp. 1–7, 2011.
[83] M. Davari and Y. A.-R. I. Mohamed, “Robust Multi-Objective Control of VSC-Based DC-Voltage Power Port in Hybrid AC/DC Multi-Terminal Micro-Grids,” *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1597–1612, Sep. 2013.
[84] J. A. P. Lopes, C. L. Moreira, and A. G. Madureira, “Defining Control Strategies for MicroGrids Islanded Operation,” *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 916–924, May 2006.
[85] A. Madureira, C. Moreira, and J. Lopes, “Secondary load-frequency control for microgrids in islanded operation,” *Proc. ICREPQ*, pp. 1–5, 2005.
[86] C. Yuen, A. Oudalov, and A. Timbus, “The Provision of Frequency Control Reserves From Multiple Microgrids,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 173–183, Jan. 2011.
[87] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, “Microgrids management,” *IEEE Power Energy Mag.*, vol. 6, no. 3, pp. 54–65, May 2008.
[88] A. Milczarek, M. Malinowski, and J. M. Guerrero, “Reactive Power Management in Islanded Microgrid—Proportional Power Sharing in Hierarchical Droop Control,” *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1631–1638, Jul. 2015.
[89] A. A. A. Radwan and Y. A. I. Mohamed, “Networked Control and Power Management of AC/DC Hybrid Microgrids,” *IEEE Syst. J.*, pp. 1–12, 2014.
[90] A. Micallef, M. Apap, C. S. Staines, and J. M. G. Zapata, “Secondary control for reactive power sharing and voltage amplitude restoration in droop-controlled islanded microgrids,” in *3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems, PEDG Proceedings*, 2012, pp. 492–498.
[91] A. Micallef, M. Apap, C. Spiteri-Staines, J. M. Guerrero, and J. C. Vasquez, “Reactive power sharing and voltage harmonic distortion compensation of droop controlled single phase islanded microgrids,” *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1149–1158, 2014.
[92] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, “Autonomous voltage unbalance compensation in an islanded droop-controlled microgrid,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 2, pp. 1390–1402, 2013.
[93] L. Meng, J. M. Guerrero, J. C. Vasquez, Fen Tang, and M. Savaghebi, “Tertiary Control of Voltage Unbalance Compensation for Optimal Power Quality in Islanded Microgrids,” in *2014 IEEE 11th International Multi-Conference on Systems, Signals & Devices (SSD14)*, 2014, vol. 29, no. 4, pp. 1–6.
[94] Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, “Distributed secondary control for islanded microgrids-a novel approach,” *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 1018–1031, 2014.

[95] A. Bidram, A. Davoudi, F. L. Lewis, and J. M. Guerrero, "Distributed cooperative secondary control of microgrids using feedback linearization," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3462–3470, 2013.
[96] H. Liang, B. J. Choi, W. Zhuang, X. Shen, a. S. a Awad, and A. Abdr, "Multiagent coordination in microgrids via wireless networks," *IEEE Wirel. Commun.*, vol. 19, no. June, pp. 14–22, 2012.
[97] A. L. Dimeas and N. D. Hatziargyriou, "Operation of a Multiagent System for Microgrid Control," *IEEE Trans. Power Syst.*, vol. 20, no. 3, pp. 1447–1455, Aug. 2005.
[98] A. Bidram, A. Davoudi, F. L. Lewis, and Z. Qu, "Secondary control of microgrids based on distributed cooperative control of multi-agent systems," *IET Gener. Transm. Distrib.*, vol. 7, no. October 2012, pp. 822–831, 2013.
[99] W. Liu, W. Gu, W. Sheng, X. Meng, Z. Wu, and W. Chen, "Decentralized multi-agent system-based cooperative frequency control for autonomous microgrids with communication constraints," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 446–456, 2014.
[100] C. Li, T. Dragicevic, M. G. Plaza, F. Andrade, J. C. Vasquez, and M. Josep, "Multiagent Based Distributed Control for State-of- Charge Balance of Distributed Energy Storage in DC microgrids," in *Proceedings of the 40th Annual Conference of IEEE Industrial Electronics Society, IECON*, 2014, pp. 2180–2184.
[101] T. Logenthiran, D. Srinivasan, A. M. Khambadkone, and H. N. Aung, "Multiagent system for real-time operation of a microgrid in real-time digital simulator," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 925–933, 2012.
[102] Q. Shafiee, T. Dragicevic, F. Andrade, J. C. Vasquez, and J. M. Guerrero, "Distributed Consensus-Based Control of Multiple DC-Microgrids Clusters," in *40th Annual Conference of IEEE Industrial Electronics Society*, 2014, pp. 2056–2062.
[103] Q. Shafiee, C. Stefanovic, T. Dragicevic, P. Popovski, J. C. Vasquez, and J. M. Guerrero, "Robust networked control scheme for distributed secondary control of islanded microgrids," *IEEE Trans. Ind. Electron.*, vol. 61, pp. 5363–5374, 2014.
[104] Q. Shafiee, V. Nasirian, J. M. Guerrero, F. L. Lewis, and A. Davoudi, "Team-oriented Adaptive Droop Control for Autonomous AC Microgrids," in *IECON Proceedings (Industrial Electronics Conference)*, 2014, p. 7.
[105] J. Simpson-Porco, Q. Shafiee, F. Dorfler, J. C. Vasquez, J. Guerrero, and F. Bullo, "Secondary Frequency and Voltage Control of Islanded Microgrids via Distributed Averaging," *IEEE Trans. Ind. Electron.*, vol. 0046, no. c, pp. 1–1, 2015.
[106] F. Guo, C. Wen, J. Mao, and Y.-D. Song, "Distributed Secondary Voltage and Frequency Restoration Control of Droop-Controlled Inverter-Based Microgrids," *IEEE Trans. Ind. Electron.*, vol. 0046, no. c, pp. 1–1, 2014.
[107] M. C. Chandorkar, D. M. 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, 1993.
[108] F. Katiraei and M. R. Iravani, "Power Management Strategies for a Microgrid With Multiple Distributed Generation Units," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1821–1831, Nov. 2006.
[109] C. Ahn and H. Peng, "Decentralized Voltage Control to Minimize Distribution Power Loss of Microgrids," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1297–1304, Sep. 2013.
[110] P. Wang, C. Jin, D. Zhu, Y. Tang, P. C. Loh, and F. H. Choo, "Distributed Control for Autonomous Operation of a Three-Port AC/DC/DS Hybrid Microgrid," *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 1279–1290, 2015.
[111] R. Majumder, G. Ledwich, A. Ghosh, S. Chakrabarti, and F. Zare, "Droop Control of Converter-Interfaced Microsources in Rural Distributed Generation," *IEEE Trans. Power Deliv.*, vol. 25, no. 4, pp. 2768–2778, Oct. 2010.
[112] P. T. Baboli, M. Shahparasti, M. P. Moghaddam, and M. R. H. M. Mohamadian, "Energy management and operation modelling of hybrid AC–DC microgrid," *IET Gener. Transm. Distrib.*, vol. 8, no. 10, pp. 1700–1711, Oct. 2014.
[113] W. Shi, X. Xie, C. Chu, and R. Gadh, "Distributed Optimal Energy Management in Microgrids," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1137–1146, 2015.
[114] A. Bracale, P. Caramia, G. Carpinelli, E. Mancini, and F. Mottola, "Optimal control strategy of a DC micro grid," *Int. J. Electr. Power Energy Syst.*, vol. 67, pp. 25–38, May 2015.
[115] A. Kahrobaeian and Y. A.-R. Ibrahim Mohamed, "Networked-Based Hybrid Distributed Power Sharing and Control for Islanded Microgrid Systems," *IEEE Trans. Power Electron.*, vol. 30, no. 2, pp. 603–617, Feb. 2015.
[116] A. Pantoja and N. Quijano, "A population dynamics approach for the dispatch of distributed generators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4559–4567, 2011.
[117] S. A. Pourmousavi, M. H. Nehrir, and R. K. Sharma, "Multi-Timescale Power Management for Islanded Microgrids Including Storage and Demand Response," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1185–1195, 2015.
[118] M. Sechilariu, B. C. Wang, and F. Locment, "Supervision control for optimal energy cost management in DC microgrid: Design and simulation," *Int. J. Electr. Power Energy Syst.*, vol. 58, pp. 140–149, Jun. 2014.
[119] M. Sechilariu, B. C. Wang, F. Locment, and A. Jouglet, "DC microgrid power flow optimization by multi-layer supervision control. Design and experimental validation," *Energy Convers. Manag.*, vol. 82, pp. 1–10, Jun. 2014.

[120] J. Wang, N. Chang, X. Feng, and A. Monti, “Design of Generalized Control Algorithm for Parallel Inverters for Smooth Microgrid Transition Operation,” *IEEE Trans. Ind. Electron.*, vol. 0046, no. c, pp. 1–1, 2015.
[121] K. De Brabandere, K. Vanthournout, J. Driesen, G. Deconinck, and R. Belmans, “Control of microgrids,” in *IEEE Power Engineering Society General Meeting, PES*, 2007, pp. 1–7.
[122] L. Meng and T. Dragicevic, “Agent-based distributed unbalance compensation for optimal power quality in islanded microgrids,” *IEEE 23rd Int. Symp. Ind. Electron.*, pp. 2535–2540, 2014.
[123] S. Falcones, “A DC-DC Multiport Converter Based Solid State Transformer Integrating Distributed Generation and Storage,” Arizona State University, 2011.
[124] S. Falcones, R. Ayyanar, and X. Mao, “A DC--DC Multiport-Converter-Based Solid-State Transformer Integrating Distributed Generation and Storage,” *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2192–2203, May 2013.
[125] R. Majumder and G. Bag, “Parallel operation of converter interfaced multiple microgrids,” *Int. J. Electr. Power Energy Syst.*, vol. 55, pp. 486–496, Feb. 2014.
[126] W. Y. Teoh and C. W. Tan, “An Overview of Islanding Detection Methods in Photovoltaic Systems,” *Int. Sch. Sci. Res. Innov.*, vol. 5, no. 10, pp. 577–585, 2011.