Overview of Power Management Strategies of Hybrid AC/DC Microgrid

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***Abstract*—Today, conventional power systems are evolving to modern smart grids, where interconnected microgrids may dominate the distribution system with high penetration of renewable energy and energy storage systems. The hybrid ac/dc systems with dc and ac sources/loads are considered to be the most possible future distribution or even transmission structures. For such hybrid ac/dc microgrids, power management strategies are one of the most critical operation aspects. This paper presents an overview of power management strategies for a hybrid ac/dc microgrid system, which includes different system structures (ac-coupled, dc-coupled, and ac–dc-coupled hybrid microgrids), different operation modes, a thorough study of various power management and control schemes in both steady state and transient conditions, and examples of power management and control strategies. Finally, discussion and recommendations of power management strategies for the further research are presented.**

***Index Terms*—AC-coupled hybrid microgrid, ac–dc-coupled hybrid microgrid, control strategies, dc-coupled hybrid microgrid, energy management, hybrid ac/dc microgrid, power management schemes.**

I. INTRODUCTION

SMARTGRIDS are being developed as the next generation power systems. These smart grids encompass interconnected microgrids, especially at the distribution level where distributed generations (DGs) are increasingly used. The DG technologies can be classified into power generation from renewable energy (RE) resources such as wind, photovoltaic (PV), micro hydro, biomass, geothermal, ocean wave and tides, the clean alternative energy (AE) generation technologies such as fuel cells (FCs) and microturbines, as well as the traditional rotational machine-based technologies such as diesel generators. Due to several benefits of these sources such as cleanness and simple technologies, compounded with increasing demands for electrical energy and the exhaustible nature of fossil fuels, the RE and AE-based DGs play an important role in microgrids.

The microgrids can work in grid-connected or stand-alone operation modes. Particularly, the stand-alone operation, although may only for very limited period, can provide improved reliability to the smart grids. Some other systems, such as electric vehicles (EV) can be considered as always operating in stand-alone mode. Due to the intermittent nature of RE resources, other energy sources (such as diesel) and storage elements (SEs) are critical part to enable the stand-alone operation of microgrids or to smooth the microgrid power during grid-connected operation. SEs can be classified into two categories: capacity-oriented energy storage and access-oriented energy storage [1]–[3]. Capacity-oriented energy storage does not have fast response time and they are used for long-term energy balancing to buffer out low-frequency power oscillation of DGs output power and compensate intermittency of RE sources in microgrids [4]. Batteries, pumped hydroelectric systems, compressed air energy storage, and hydrogen storage are types of capacity-oriented energy storage. Access-oriented storage devices have fast response time and they are responsible for short time disturbances in microgrids, by providing the high-frequency component of power. They can supply or absorb the high-power transients with high-power density [4]. Flywheels, supercapacitors (SCs), and superconducting magnetic energy storage are considered as access-oriented storage devices.

Due to the presence of dc power sources in microgrids such as PV, FC, and energy storages, and modern dc loads, and considering the existing century-long ac power systems, interests on hybrid ac/dc microgrids are growing rapidly. These hybrid ac/dc microgrids contain ac/dc loads and power sources, have advantages of both ac and dc power systems, and are considered to be the most possible future distribution and transmission systems [5]–[7]. One critical aspect of the operation of such a hybrid ac/dc microgrid is the control strategy and power management scheme, which are essential for providing sound operation in both grid-connected and stand-alone operation modes. In microgrids, the terms "energy management" and "power management" are different considering control tasks and time scale. The global objective of long-term energy management algorithms is matching the total power production to the demand in an optimal way [8], [9]. These algorithms deal with monitoring and operation of a complex system of electrical, thermal, and mechanical components with emphasis on desired and longer term outcomes. Factors like fuel costs, capital costs, maintenance costs, mission profiles, lifetimes, etc., are considered in energy management algorithms. In general, the energy management strategies include hourly prediction of RE sources, management of controllable loads, providing appropriate level of power reserve capacity, etc. [9]. On the other hand, the objective of short-term power management strategy is to affect the instantaneous operational conditions toward certain desired parameters such as voltage, current, power, and frequency. The power management strategies include voltage and frequency regulations, and real-time power dispatching among different power sources in microgrids

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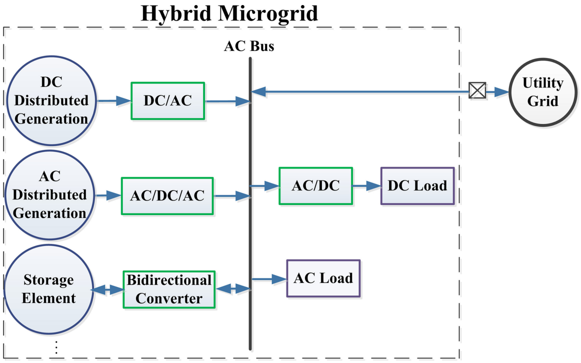


Fig. 1. AC-coupled hybrid microgrid.

[9]. As the short-term power management is more relevant to the interface and control of power converters in the microgrid, and is, therefore the focus of this paper.

While the control strategies and power management schemes for the traditional ac microgrid or dc microgrid are well understood with active research in recent years, the operation and power management of a hybrid ac/dc microgrid system has not been well studied so far. This paper presents an overview of control strategies and power management schemes for hybrid ac/dc microgrid. First, different hybrid ac/dc microgrid structures are discussed, including real-world implement examples. Then, the control strategies and power management schemes of different types of hybrid ac/dc microgrid under different operation conditions are discussed. A few representative implementation examples of control strategies are also presented. Finally, recommendations for the future research on the control and power management of hybrid ac/dc microgrid are provided.

II. HYBRID AC/DC MICROGRID STRUCTURES

In this paper, the term "hybrid ac/dc microgrid" refers to a microgrid that contains both ac/dc power sources and ac/dc loads. Depending on how the sources and loads are connected to the system and how the ac and dc buses are configured, the structure of hybrid ac/dc microgrids can be classified into ac-coupled, dc-coupled, and ac–dc-coupled microgrids. In ac-coupled hybrid microgrids, various DGs and SEs are connected to the common ac bus through their interfacing converters (IFCs). In dc-coupled hybrid microgrids, DGs and SEs are connected to the common dc bus, and an IFC is used to link the dc and ac buses. In ac–dc-coupled hybrid microgrids, DGs and SEs are connected to dc and ac buses, where these buses are linked by interlinking converter (ILC). In this section, these microgrid structures and their real-world implement examples are provided.

A. AC-Coupled Hybrid Microgrid

In an ac-coupled hybrid microgrid, shown in Fig. 1, various DGs and SEs are connected to the common ac bus through their IFCs. The SEs need bidirectional converters to provide the bidirectional power flow capability. In this structure, ac and dc loads are also connected to the common bus (with or without power electronic converters). This structure is commonly used when dominant generation sources in the microgrid produce grid level ac voltages directly (such as from diesel generator) or indirectly through interfacing power converters.

In such an ac-coupled system, the control strategy and power management scheme is mainly focused on power generation/consumption balance and the ac bus voltage/frequency control, especially in stand-alone operation mode.

The ac-coupled microgrid is the dominant structure now due to its simple structure and simple control and power management scheme. Around the world, most implemented hybrid ac/dc microgrids are ac coupled. Some of them are:

1) Hachinohe microgrid in Japan [10]–[12]. In this microgrid, a gas engine system (3×170 kW), several PV systems (2×50 kW one plant and 3×10 kW dispersed), a small wind farm (2×2 kW one plant and 2×8 kW dispersed), and $100-$kW battery storage are connected to the ac distribution line. This microgrid provides electrical power for four schools and a water supply authority office. The control and energy management scheme balance supply and demand powers by weekly planning, economic dispatch control once every 3 min, and second-by-second power flow control at interconnection points.
2) Bronsbergen Holiday Park Netherland [11], [13]. This low-voltage ac-coupled microgrid project, consisting of 208 homes, was supported by European Union. In this microgrid, PV units with the peak generation capacity of 315 kW are connected to common ac bus through the interfacing inverters. Two battery banks, as a central energy storage system, are connected at the point of common coupling. For energy management, the central control receives all the system data, and controls active and reactive power of sources.
3) Kythnos Greece [11], [14]. In this microgrid, 10-kW PV, a 53-kWh battery bank, and a 5-kW diesel generator are connected to the common ac bus, and electrify 12 houses. In this system, other 2-kW PV array and 32-kWh battery bank are used to provide power for monitoring and communication systems. Residential service is powered by three parallel battery inverters using frequency droop control method in which grid frequency is used as communication signal.
4) Aichi microgrid in central Japan airport city [11], [15]. In this system, two molten carbonate FCs (270 and 300 kW), one 25-kW solid oxide fuel-cell, four phosphoric acid FCs with the capacities of 200 kW, 330-kW PV, and a sodium–sulfur battery storage system are connected to ac bus through their IFCs. In this ac-coupled microgrid, matching the supply and demand power and voltage control is done by the battery converter. In addition, optimization technique (genetic algorithm and a tabu search called a metaheuristic technique) is used for a day-ahead generation planning.

In some ac-coupled microgrids, instead of using IFCs for each DG or SE, several power conversion stages can be replaced by multiple-port converters that combine different power sources in a single power converter. As a result, the whole system can be viewed as a single power processing stage that has multiple

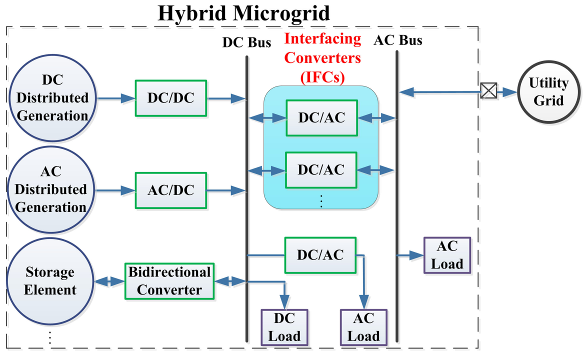


Fig. 2. DC-coupled hybrid microgrid.

interfacing ports. In these systems, input power sources are usually connected to a high-frequency ac link, and isolation transformer plus ac/dc/ac IFCs are utilized to connect the generation into the load/grid [16]–[20].

B. DC-Coupled Hybrid Microgrid

Fig. 2 shows a dc-coupled hybrid microgrid, where DGs and SEs are connected to the common dc bus, and IFCs are used to link the dc and ac buses. This structure can be used when dc power sources are major power generation units in the microgrid. Note that in this structure, all the DGs and SEs are connected to the dc bus. If there are DGs and SEs on an ac bus, it would be an ac–dc-coupled hybrid microgrid as will be discussed later. In this dc-coupled microgrid, variable frequency ac load such as adjustable speed motors can be connected to dc bus with a dc/ac converter (to avoid the extra ac/dc conversion for ac bus connection). In this system, IFCs provide bidirectional power flow between ac and dc buses. Depending on the power exchange requirement between dc and ac buses, parallel IFCs are typically used with increased rating and reliability.

The dc-coupled microgrid features simple structure and does not need any synchronization when integrating different DGs. However, the control and power management of parallel IFCs, and their output voltage synchronization (with each other or with the grid in grid-connected mode) can present some challenges. Moreover, both dc and ac voltage control and subsystem power management are necessary in a dc-coupled system. In some dc-coupled hybrid microgrids, SEs are connected to dc bus directly without converters, which introduce different control schemes. These methods will be discussed in Section III.

In dc-coupled hybrid microgrids, various projects have been implemented around the world. Some of them are presented in following:

1) CESI RICERCA DER microgrid in Italy [21]. This low-voltage dc-coupled microgrid is connected to 23-kV medium voltage grid through a 800-kVA transformer. This microgrid consists of several generators, controllable loads, and storage systems, and can provide maximum power of 350 kW to the main grid. The system contains of PV, different kinds of batteries, a diesel engine coupled with an asynchronous generator, a simulated asynchronous wind generator, solar thermal plant, CHP system fuelled by biomass, CHP plant with a gas microturbine, flywheel, and loads in dc bus, which is connected to an ac bus through interlinking inverter. In this microgrid, central control scheme, which uses optimization techniques, controls the set-points of each source.
2) Kahua Ranch Hawaii Hydrogen Power Park in US [22]. In this dc-coupled hybrid microgrid, PV (10 kW), wind turbine (WT) (7.5 kW), battery (85 kWh), and FC (5 kW) are connected to dc bus through their converters. The electricity generated by the WT and solar array are used to power electrolyzer to make hydrogen, which is stored without further compression. In case that electricity is needed, the hydrogen is supplied to a FC to produce electrical power. In addition, the stored hydrogen could also be used to fuel an internal combustion engine, which would power an electric generator.

Similar to ac-coupled hybrid microgrid, in dc-coupled hybrid microgrids multiple-port power converters can be used to connect different input power sources to a common dc link in a unified structure [23]–[25].

C. AC–DC-Coupled Hybrid Microgrid

The structure of an ac–dc-coupled hybrid microgrid is shown in Fig. 3. As seen from this figure, both dc and ac buses have DGs and SEs, and these buses are linked by ILCs. Different from the dc-coupled system, the ac–dc-coupled hybrid microgrid has DGs and SEs on an ac bus too, which requires more coordination for the voltage and power control between the dc and ac subsystems. On the other hand, similar to dc-coupled microgrid, parallel ILCs are desired to link ac and dc buses with increased capacity and reliability. In general, this structure is considered if major power sources include both dc and ac powers. This structure improves overall efficiency and reduces the system cost with reduced number of power converters by connecting sources and loads to the ac and dc buses with minimized power conversion requirements. Considering these benefits, ac–dc-coupled hybrid microgrids will be the most promising microgrid structures in the near future. Europe is leading research efforts in this direction through the European supergrid [26]–[28], in which power of various dc and ac power sources such as offshore WTs and desert-based solar are transmitted using ac and dc grids.

Although the idea of ac–dc-coupled hybrid microgrid is promising, it necessitates thorough study and investigations, particularly for the energy and power management aspects. Control of such a system needs to consider both dc and ac bus voltages (and frequency) control, as well as the power balance within the dc and ac subsystems.

III. CONTROL STRATEGIES AND POWER MANAGEMENT SCHEMES OF HYBRID AC/DC MICROGRIDS

For the operation of hybrid ac/dc microgrids, control strategies and power management schemes are the most important aspects. The power management strategies determine output active and reactive powers of DGs and SEs, and control the voltages and frequency at the same time. Details of strategies

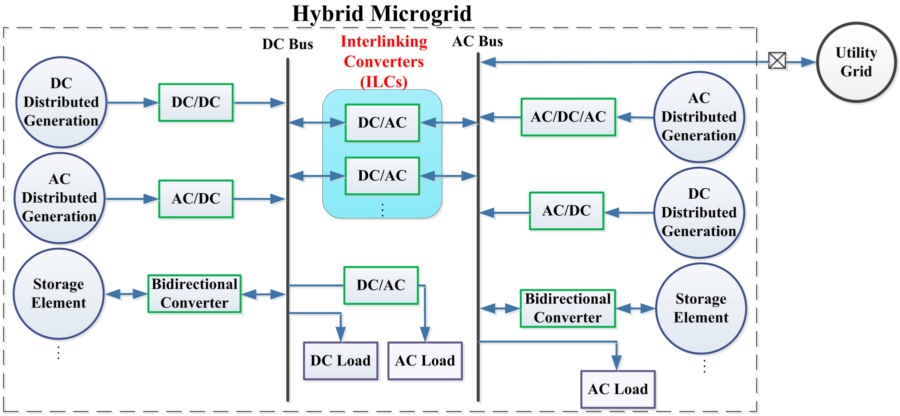


Fig. 3. AC–dc-coupled hybrid microgrid.

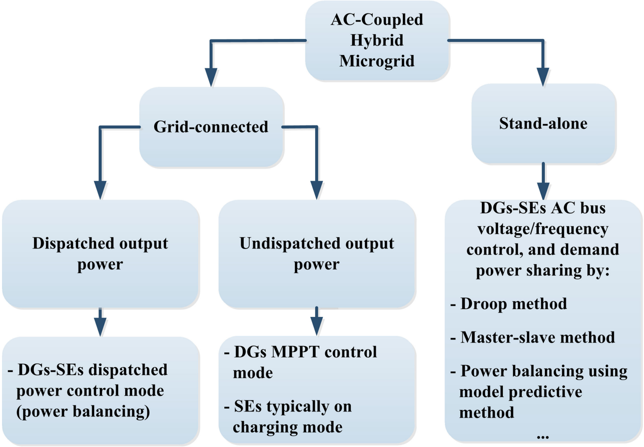


Fig. 4. Overview of power management strategies of the ac-coupled hybrid microgrid.

for different types of hybrid ac/dc microgrids are explained in this section.

A. AC-Coupled Hybrid Microgrid

The control strategies and power management schemes of ac-coupled hybrid microgrid are mainly focused on power balancing within the microgrid, and the ac bus voltage and frequency control especially in stand-alone operation mode. In this structure, DGs and SEs can be treated like parallel ac voltage sources or current sources. The overview of power management schemes for ac-coupled microgrids is shown in Fig. 4. These strategies can be separated into grid-connected and stand-alone operation modes.

In a grid-connected mode, the power management strategies can be classified into dispatched power mode (where the power exchange between the microgrid and the main grid is dispatched from a higher level control/optimization scheme) and undispatched output power mode (where the microgrid output power is not dispatched). In a dispatched output power mode, the microgrid behaves like a controllable source or load to the main grid and can provide valuable grid-support or load management functions as a whole. To realize this, SEs are inevitable. In this mode, DGs and SEs operate on power control mode. The power control can be realized by current control or voltage control. In a current control mode, which is popularly used in grid-connected operations, DG's output current is controlled in order to track the reference power, and the output voltage and frequency are determined by the grid. In a voltage control mode, which can be used in both grid-connected and stand-alone operation modes, DG's output voltage is controlled to regulate its output power, and DG behaves like a synchronous generator [29]. To produce the dispatched microgrid output power, power balancing schemes within the microgrid are used to share dispatched power among input power sources [30]–[33]. For example, renewable-energy-based DGs can work on their maximum power point (MPP), and other power sources can provide power deficiency between generation and demand considering input power sources operation range, response time, etc. [32], [33]. Power balancing control scheme will be explained in detail in Section VI.

In grid-connected undispatched output power operation mode, all generated powers are fed to the grid; DGs work on MPP, and SEs are typically charged [34], [35]. Moreover, SEs can be controlled to smooth DGs output power oscillation especially for DGs with intermittent nature such as wind and PV systems.

Moreover, in grid-connected operation mode (both in dispatched and undispatched power mode), the microgrid can be used for the grid support (for example, grid voltage and frequency regulations) by controlling active and reactive powers delivered to the grid [36], [37]. This grid support will be included in the dispatched/reference microgrid power in the dispatched power control mode. In an undispatched power mode, the grid-support function will be realized individually through the DG or SE IFCs.

In a stand-alone operation mode, power management and control schemes are focused on microgrid ac bus voltage and frequency control, as well as demand power sharing among DGs and SEs. Various schemes have been proposed to realize this. Droop method is probably the most common method in this group that emulates the behavior of synchronous generator, where the voltage and frequency vary with the output real and reactive power of DG. This method is used for determining the output active and reactive power of each source in order to regulate the frequency and voltage of ac bus on their desired values [6], [29], [30], [38]–[46]. Other than droop control, DGs can work on their MPP, and SEs control ac bus voltage and frequency [47], [48]. In other words, SEs balance the demand and generated powers in order to regulate frequency and voltage of ac bus. In addition to the aforementioned methods, there are other power management schemes that can be used in stand-alone ac-coupled hybrid microgrids such as power balancing using a model predictive method [32], and heuristic methods [8].

In ac-coupled hybrid microgrids, since DGs and SEs are treated like parallel ac voltage sources or current sources, control strategies and power management schemes of parallel ac sources such as master–slave [49]–[51], circular-chain control [52], and average-current control methods [53], [54] can be applied with some minor changes. For example, utilizing master–slave control scheme, one DG unit, which has mainly high-output power, works on voltage-controlled operation mode and controls ac bus voltage and frequency (master module) while the other DGs and SEs (slave units) work on current-controlled operation mode and track the current command provided by the master unit.

Many of the aforementioned power management strategies require communication mechanisms to share information among DGs and SEs [55]. For example, power balancing and master–slave methods are communication-based schemes. However, these methods are costly and their reliabilities depend on the effective communications. Communication-less control methods, on the other hand, attract more interests as they are more reliable and enable true plug-and-play of DGs and SEs. For communication-less control, demand power is shared between DGs and SEs without communication among them. These methods eliminate the physical location limitation of DGs and loads, and improve the microgrid performance. For example, droop control method is the most popular communication-less control scheme. However, without the information of other DGs and loads, very accurate or optimal control of the DGs and SEs is difficult in the communication-less methods. As a result, a combination of both techniques can be a better option for future system. For example, communication-based method combined with droop control as backbone can provide both high performance and reliability. More discussions about communication systems in hybrid microgrid will be provided in Section V.

B. DC-Coupled Hybrid Microgrid

In dc-coupled hybrid microgrids, the dc link voltage control, power balancing between generation and demand, and ac link voltage and frequency control (especially in stand-alone mode) are the objectives of power management schemes. The overview of the power management and control schemes of dc-coupled hybrid microgrid system is shown in Fig. 5. Similarly, the power management methods can be divided into grid-connected operation and stand-alone operation, where the grid-connected operation has dispatched power mode and undispatched power mode.

In the dc-coupled microgrid, the IFC that connects dc and ac buses can work on bidirectional power control mode, dc link voltage control mode, or ac link voltage control mode [56]–[58]. In a power control mode, as explained before, the converter output current or voltage is controlled to regulate IFC output power on its reference value. In a dc link voltage control mode, IFC controls dc link voltage and, therefore, balancing the power generation and consumption on dc bus. This operation mode is used when the control of output power of grid-connected IFC is not required. AC link voltage control mode of IFC is mainly for a stand-alone microgrid operation, where the IFC controls the ac subsystem voltage and frequency.

For a grid-connected dc-coupled microgrid, if it is in a dispatched power mode, the dc link voltage can be controlled by two methods. In the first method, IFC works on a dc link voltage control mode, and regulates dc link voltage at the desired value; in addition, DGs and SEs provide dispatched power of hybrid microgrid through power balancing control [59]–[61]. In the second method, SEs on dc bus control the dc link voltage collectively using a droop control method [6], [7], [62]–[64], and the DGs can be a part of the droop control or work in MPP [59], [65]–[68]. In this operation mode, IFC operates in a power control mode and provides dispatched power to the grid. In an undispatched output power operation mode [69], [70], IFC operates in a dc link voltage control mode. With the fixed dc bus voltage, DGs work on MPP, and SEs are typically charged or controlled to smooth DGs output power oscillation.

Finally, the grid-support functions can be realized in the grid-connected operation. Unlike in ac-coupled microgrid, where the function can be realized by all the dc/ac IFCs of DGs and SEs, the grid support is realized by the IFC between dc and ac bus here in the dc-coupled microgrid.

In a stand-alone operation of a dc-coupled hybrid microgrid, dc bus voltage and ac bus voltage and frequency should be controlled simultaneously. For ac bus voltage and frequency control, IFC works on ac link voltage control mode [38], [71] and controls an ac bus voltage and frequency. On the other hand, the dc bus voltage can be controlled directly or indirectly. In a direct dc link voltage control, DGs and/or SEs regulate a dc link voltage on its reference value (with droop control, for example) [72]–[78].

In an indirect dc link voltage control mode, power balancing between demand and generation regulates dc link voltage [79]. In this operation mode, with the presence of parallel IFCs, it is possible that some of the converters work on an ac link voltage control mode and the others control the dc link voltage and balance the generation and demand powers.

In some structures of dc-coupled hybrid microgrids, SEs are directly connected to dc bus. Typically, these SEs are capacity-oriented storage devices such as battery. Since SEs fix the dc bus voltage, the power management of dc bus is focused on the control of currents. The current and power of dc bus can be controlled by access-oriented storage [80]–[83], capacity-oriented storage [84], or other DGs, which are connected to dc bus with IFCs.

C. AC–DC-Coupled Hybrid Microgrid

In ac–dc-coupled hybrid microgrids, multiple DGs and SEs are connected to ac and dc buses. Therefore, more coordination between the dc and ac subsystems are necessary. In these

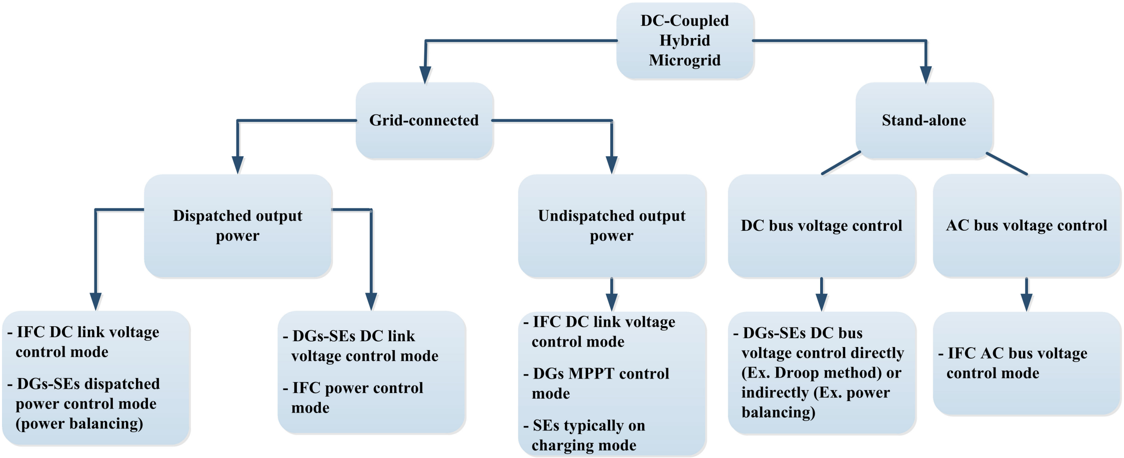


Fig. 5. Overview of power management strategies of the dc-coupled hybrid microgrid.

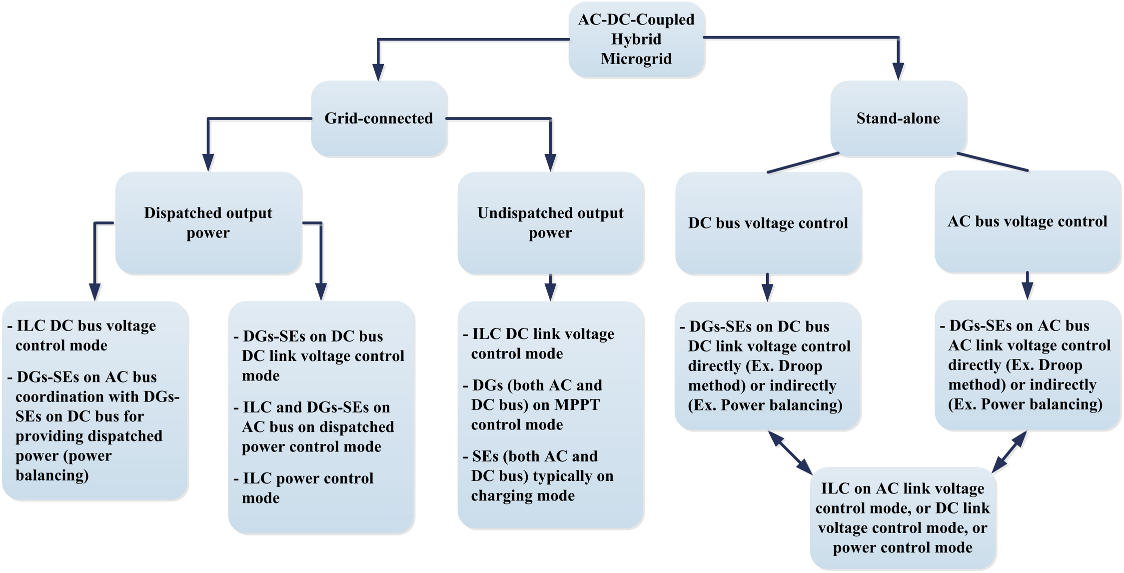


Fig. 6. Overview of power management strategies of the ac–dc-coupled hybrid microgrid.

systems, the control strategies and power management schemes need to consider the power balance and voltage control in both dc subsystem and ac subsystem. An overview of power management schemes of ac–dc-coupled hybrid microgrid is shown in Fig. 6.

Similar to the IFC of dc-coupled microgrid, the ILC in an ac–dc-coupled microgrid can be in a bidirectional power control mode, dc voltage control mode or ac voltage control mode. However, the coordination between ILC and ac bus DGs and SEs is necessary herein the power and ac bus control modes.

In a grid-connected operation mode with dispatched microgrid output power, two methods can be used for dc link voltage control and dispatched power generation. In the first method, ILC works on dc link voltage regulation mode to set the dc bus voltage on its desired value. In this mode, coordination between DGs–SEs on dc bus and DGs–SEs on ac bus is necessary to produce the dispatched output powers. In the second operation mode, DGs–SEs on dc bus regulate dc link voltage on its reference value while ILC and DGs–SEs on ac bus collectively provide the dispatched power [6], [7], [85]. In this operation mode, ILC works on power control mode.

In a grid-connected undispatched output power operation mode, DGs in both dc and ac buses work on MPP [86], [87]. In addition, SEs are charged if necessary or discharged for smoothing output power injected to the grid. In this mode, ILC regulates dc link voltage on its desired value and injects all power generated by DGs–SEs in dc bus to the load/grid.

In ac–dc-coupled hybrid microgrid in grid-connected operation modes, similar to other structures of hybrid microgrids, DGs on ac bus together with ILC can be controlled to realize the grid-support functions.

In a stand-alone operation mode, coordination among ILC, DGs–SEs on a ac bus, and DGs–SEs on dc bus is essential to regulate dc bus voltage, ac bus voltage and frequency, and balance microgrid total generation and demand powers at the same time. In this operation mode, the power management strategies of ac-coupled hybrid microgrids in a stand-alone operation mode such as droop [29], [38]–[45], master–slave [49]–[51], [87], etc., can be used for ac subsystem voltage and frequency regulation and demand power sharing. For the dc subsystem control, similar to a dc-coupled hybrid microgrid in a stand-alone operation, a dc bus voltage can be controlled by DGs–SEs on dc bus directly [6], [7] (for example, utilizing droop control method in dc bus) or indirectly (for example, utilizing power balancing control strategy) [9], [86], [88].

It is important to note that in a stand-alone operation mode, ILC plays an important role in power management and control [6], [7]. Depend on types of control strategies used in ac and dc buses, this converter can be used on dc-bus control mode, ac-bus control mode, or output power control mode as discussed. However, providing coordination among these control strategies (ac-bus, dc-bus, and ILC control strategies) is the most important objective in this operation mode. For example, in the condition that dc bus voltage is controlled by DGs–SEs connected to dc bus, and ac bus voltage is controlled by DGs–SEs connected to ac bus, the ILC is responsible to manage the power flow between ac and dc sides in order to equalize the demand and generated power. Also, in case of parallel ILCs, the ILCs can work on different operation modes: some of them can work on dc link voltage control mode, while the others work on ac link voltage control mode or power control mode. More explanation on the ILC control is provided in Section VI.

IV. POWER MANAGEMENT STRATEGIES DURING TRANSIENT AND DIFFERENT LOADING CONDITIONS

The aforesaid reviewed hybrid microgrid power management strategies are mainly focused on the steady-state power balancing and voltage/current control. The power management strategies during microgrid operation mode transitions and during different loading conditions are reviewed in this section.

A. Power Management During Transition Between Grid-Connected and Stand-Alone Operation Modes

The transition between grid-connected and stand-alone operating modes should be seamless and smooth to minimize voltage and frequency disturbances and deviations, and ensure balanced power flows to prevent DGs overloading and circulating powers. Here, the control strategies for transition from grid-connected to stand-alone operation and transition from stand-alone to grid-connected operation are discussed separately. An overview of these transitions is shown in Fig. 7.

1) Transition From Grid-Connected to Stand-Alone Operation Mode: There are mainly two groups of control strategies for microgrid transition from grid-connected operation to stand-alone operation: 1) switch of control strategies from current/power control mode in grid-connected operation to the voltage control mode in stand-alone operation; and 2) uniformed control in both grid-connected mode and stand-alone mode.

In the first group, different control strategies are used in grid-connected and stand-alone operation modes, and the control strategy is switched between these two controllers [89]–[93]. Specially, DGs are working on current control mode (MPPT control or dispatched power control) in grid-connected operation mode to inject power to main grids, while voltage control (droop method or conventional voltage control) is used in a stand-alone operation mode to ensure supplying continuous power to sensitive loads and sharing the load demand among voltage controlled DGs. This switching of control can be applied to dc/dc converter interfaced DG or energy storage units, dc/ac converter interfaced DG or energy storage units, as well as interfacing or interlinking converters. For a seamless transition, there are a number of recently proposed methods. For example, the line current of DG can be reduced to zero before switching to a stand-alone voltage control mode [89], [90]. It is also possible for faster transition without reducing the DG line current to zero. To realize this, the current controller (in a grid-connected mode) and voltage controller (in a stand-alone mode) control states can be carefully coordinated to avoid transient current or voltage spikes during the transition [91]–[93].

To realize this control scheme switch, an islanding detection algorithm (passive, active, and communication-based detection schemes [94], [95]) is usually used to determine the disconnecting time instance, which is used to switch the microgrid controller from grid-connected to stand-alone mode. As a result, achieving seamless and smooth transitions can be quite difficult when the islanding detection is delayed. After isolation, the voltage controller is immediately applied, and synchronization unit works as an oscillator at a fixed frequency. In case of multiple DGs, droop control or other stand-alone operation control strategies as reviewed earlier can be applied.

In the second group, the power management and control strategies are the same in both grid-connected and stand-alone operation modes, and it is not necessary to modify the control strategy during the transitions [29], [96]–[104]. Therefore, it is challenging to design and implement a robust control strategy to work on grid-connected, stand-alone, and transient modes. For this group of control methods, islanding detection algorithm is not necessary in theory, but is usually needed due to utility requirements as well as for better control performance. This group may include smaller DG units that work in MPPT or current control mode in both grid-connected and stand-alone operations. For larger DGs and energy storage units which are dominant microgrid power sources, voltage control mode is implemented in operation modes to avoid control scheme transients. However, some modifications should be applied to the voltage control strategies in order to use them in grid-connected, stand-alone, and transient operation modes [29], [96]–[104]. For example, conventional droop method have been modified in [96]–[98] using the concept of virtual impedance, and combining PI controller with droop control, to be used in both grid-connected and stand-alone operation modes in the presence of DGs. As another example, conventional hierarchical control have been modified in [99] in order to improve weak disturbance rejection performance of conventional voltage and power sharing controllers to be used in both operation modes of microgrid.

In the transition from grid-connected to stand-alone operation mode, the control strategy, which can contain the

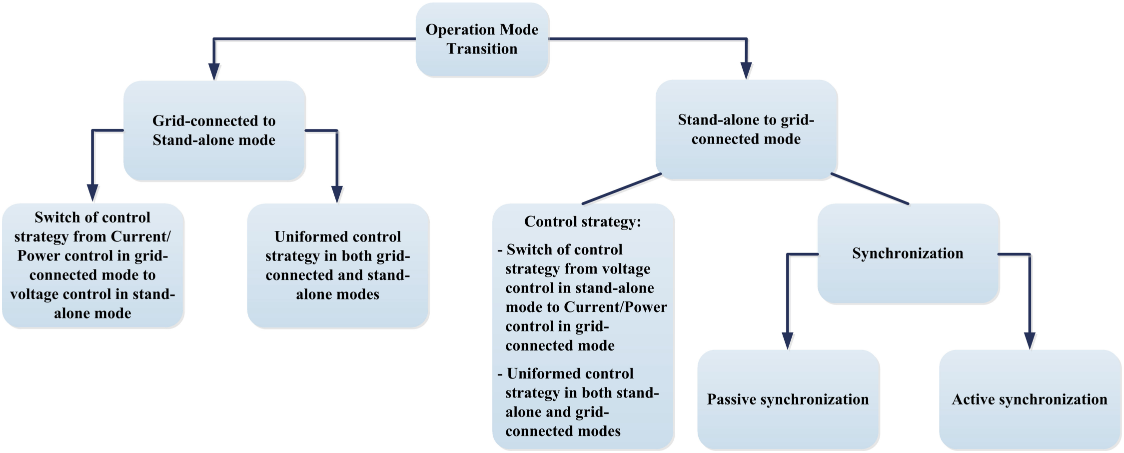


Fig. 7. Overview of power management during transition between grid-connected and stand-alone operation modes.

synchronization unit, should provide a stable voltage with a fixed frequency in the microgrid. Moreover, it should share the power demand among DGs to continue supplying power to the loads within the microgrid. Transient power sharing among DGs or energy storage units are important for both groups of control strategies, and during stand-alone operation, the power electronic interfaced DGs initially picks up the majority of any load step, in some cases poor transient load sharing exist in the presence of DGs and conventional synchronous generators. In order to improve the transient power sharing, the coordination among DGs and conventional synchronous generators is necessary, and the DGs must allow the voltage and frequency to swing in the expense of increased voltage and frequency dip. For example, in [105] control strategy has been modified for the droop control in order to improve the transient load sharing by changing the droop slope during transient and restoring it to normal in steady state. The synchronverter concept proposed in [106] and [107] and synchronous converter concept proposed in [108] are other methods that allow the power electronic interfaced DGs to follow the conventional synchronous generators principles and may help the transient load sharing.

2) Transition From Stand-Alone to Grid-Connected Operation Mode: In the transition from stand-alone to grid-connected operation mode, other than the control scheme (switch from voltage control to current/power control or through the uniformed control scheme as discussed earlier), an important task is that the microgrid voltage should be synchronized with the grid voltage before reconnection.

For synchronization of the microgrid to the main grid, there are mainly two types: 1) passive synchronization, and 2) active synchronization. For passive synchronization, the microgrid voltage and main grid voltage are monitored and the two grids are connected when they have the same phase angle. This method is based on the assumption that microgrid and the main grid have very close voltage magnitude and slightly different frequency (which is typically the case). The passive synchronization is the easiest and probably the most practical method so far. However, this method will lead to some transients upon reconnection of the two grids (due to not exactly matched voltage magnitude), and it does not guarantee a fast and controllable synchronization process.

On the other hand, active synchronization can achieve fast synchronization and seamless connection of the microgrid and the main grid, and has attracted considerable research efforts. However, since the microgrid consists of different RE-based and AE-based DGs, severely changing electrical loads, and storage devices, the synchronization of a microgrid is quite different in comparison to a single traditional machine. For active synchronization, coordination of multiple DGs and energy storages is required. In some cases, synchronization unit is embedded in the control strategies; while in others, separate synchronization unit provides the synchronization signals in order to provide microgrid reconnection to the grid.

As discussed earlier in Section III, in a stand-alone operation mode, two control strategies are possibly used; all DGs working on voltage control mode (for example, droop control or conventional voltage control mode applied to all DGs), or some DGs working on current control mode while the others working on voltage control mode (for example, master–slave control strategy or RE-based DGs working on MPPT, while the controllable DGs working on voltage control mode). Depending on utilized control strategy, the active synchronization strategies can be classified into two groups; 1) one/more DGs initiate the synchronization process and the other DGs follow them, and 2) all DGs take part in the synchronization process simultaneously.

The first group of synchronization strategy is mainly used in the microgrids that some DGs are working on current control mode, while the others are working on voltage control mode [102], [109], [110]. For example, in [109] active synchronization is applied for the controllable DGs to control the frequency and voltage of the microgrid while RE-based DGs are working on their MPP mode, and in [110], synchronization schemes utilized in master–slave control strategy are discussed, where master DGs lead to the synchronization process.

The second group of synchronization strategy is mainly used in the microgrids that all DGs are working on the voltage control mode [29], [93], [96], [111]. For example, in [96] and [111], synchronization strategies are discussed in droop control methods, where synchronizations are realized by droop characteristics adjustment, virtual impedance concept utilization of all DGs. After synchronization, the microgrid will be reconnected to the grid at the voltage zero crossing.

In both types of synchronization strategies, communication system is essential in order to communicate the system information among power sources. The communication systems utilized in the hybrid microgrids will be discussed in Section V.

B. Power Management Strategies Under Different Loading Conditions

In hybrid microgrids, loads and/or the grid conditions can have significant impacts on the performance of microgrid. As a result, robust current or voltage control is needed in these conditions. In the presence of nonlinear/unbalance loads, which result in unbalance voltage at PCC, various control strategies have been used. Detailed discussion will be provided in Section VI-C.

On the other hand, constant power loads (CPLs) that are mainly interfaced by active rectifiers to an ac grid or dc/dc converter to a dc grid cause instability problems in the microgrids because of their negative impedance characteristics. These problems have been studied in different researches using small-signal method and large signal methods [112], [113], and various solutions have been proposed to ensure the system stability. These include oscillation compensation technique used to increase stability margin [114], active-damping techniques to overcome the negative impedance instability problem [115], nonlinear control of ac/dc converters [116], just to name a few. In addition, in some cases, CPLs are controlled to provide ancillary services to microgrids, such as harmonic minimization caused by power electronic nonlinear load, shunt active filter, etc. [117].

In addition to CPLs, which affect the microgrid stability, frequency- and voltage-dependant loads can influence the microgrid stability. It has been shown that in a stand-alone operation, the frequency and voltage deviations are dependent on each other [118]. Therefore, microgrid unstable operation may be resulted as a consequence of load's voltage and frequency dependence [118]. For example, induction motors are frequency- and voltage-dependant loads in the microgrids, where conventional P/Q control strategies cannot guarantee the microgrid stability with these loads [119]. In the presence of frequency- and voltage-dependant loads, accurate loads models are essential for control system design in order to enhance the stability and transient performance [120]–[122].

V. COMMUNICATION SYSTEMS IN HYBRID MICROGRIDS

In hybrid microgrids or in general in microgrids, the control and power management strategies can be classified into communication-based and communication-less strategies. In the communication-based strategies, the system information such as current, voltage, and power is communicated to determine operation point of each DG, while DGs operate independently in communication-less strategies. Communication system may affect the reliability of a microgrid. However, it can further improve the power quality, accuracy, and the protection issues, compared to a communication-less method. For example, in some cases, low-bandwidths communication systems are used in droop control strategies [123], [124] to improve the droop control performance. Therefore, a suitable, cost-effective and reliable communication network is important in microgrids.

The communication technologies in microgrids can be classified into wireless technologies (such as a WiFi, ZigBee, and/or cellular communication network [125]–[127]) and wireline technologies (such as Power line communication (PLC) or low bandwidth communication (LBC) [30], [128], [129]). Each technology has its advantages, shortcomings, and range of applications. Although the wired network offers higher transmission speed (especially when optical cables are used), the wireless networks (for example, the WiFi) provides easy installation of a remote terminal, low installation cost, plug and play capability [130]. Recently, in order to serve as the main networking technology, different wireless communication techniques such as cognitive radio have been proposed [125]–[127].

In a microgrid, different communication protocols like RS-232 serial communication, RS422/485 Modbus communication, etc., can be used in devices [130]. Considering recent studies, Modbus standard TCP/IP protocol is more suitable than other protocols for control and power management strategies [130]. Since different protocols have different features in transmission speed, data format, function codes, etc., all information need to be put in the same Ethernet communication using a simple communication protocol converter. Ethernet technology offers a flat architecture, which provides higher speed and longer connection distance, and it is easily extendable and supports multiple protocols. Therefore, it accommodates a broad range of devices in microgrids. More information about the communication systems can be found in [131].

VI. IMPLEMENTATION EXAMPLES OF POWER MANAGEMENT AND CONTROL STRATEGIES

In this section, a few examples on how to realize and implement the power management schemes are presented.

A. Power Balance Control in Hybrid Microgrids

The objective of this power management strategy is to balance the generated and demand powers in order to regulate the ac and dc buses voltages on their reference values and at the same time adjust the ac subsystem frequency (when in a stand-alone operation).

This strategy can be used in all structures of hybrid ac/dc microgrids. For example, in a grid-connected ac-coupled hybrid microgrid in a dispatched output power operation mode, power balancing control is utilized for sharing dispatched power among DGs and SEs [30]–[33]. Moreover, in a dc-coupled and an ac–dc-coupled hybrid microgrid, this strategy can be used in both grid-connected and stand-alone operation modes [6], [59].

The power balancing of a dc-coupled grid-connected WT/ FC/ SC hybrid microgrid in [59], where all sources are connected to the common dc bus, is presented here as an example. Fig. 8 shows the block diagram of this power management scheme. In

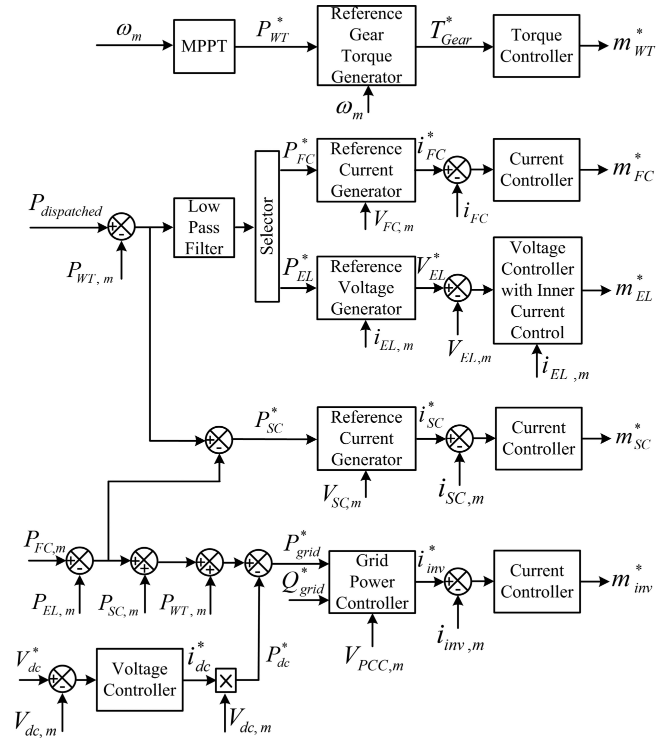


Fig. 8. Power balance scheme in dc-coupled grid-connected wind/ fuel cell/supercapacitor hybrid microgrid.

this figure, subscript m represents the measured values, while superscript * shows the reference values. Moreover, ω and T_{Gear} represent rotational speed of WT and gear torque, and m_{WT}, m_{FC}, m_{EL}, m_{SC}, m_{inv} are the modulation functions of power converters of WT, FC, electrolyser (EL), SC, and grid-connected IFC.

In this microgrid, central power dispatch unit determines the output power of microgrid ($P_{\mathrm{dispatched}}$), the wind power system works on MPP, and the storage devices provide power deficiency between WT output and dispatched power. In this system, the combination of FC and EL act as a capacity-oriented storage device which is responsible for long-term energy balancing and providing the low-frequency component of power deficiency between dispatched power and wind power by producing or absorbing necessary power with FC and EL, respectively. In addition, SC (access-oriented storage device) is used for short-time disturbances and buffering out the high-frequency oscillations.

In this control strategy, in the condition that the dispatched power is lower than wind maximum power, their low-frequency power deficiency is consumed by EL (P_{EL}) to generate hydrogen which is stored in the tanks. It is important to consider that the FC and the EL should not work at the same time for efficiency reasons. Therefore, selector is used in order to switch the control scheme between FC and EL based on its input power sign. Positive input power sign (low-frequency components of $P_{\mathrm{dispatched}} > P_{\mathrm{WT}}$) leads to FC power control mode, while EL power control mode is activated in negative input power sign (low-frequency component of $P_{\mathrm{dispatched}} < P_{\mathrm{WT}}$). Here, the voltage and current controllers can be simple PI controllers. In this system, IFC works on dc link voltage control mode, and injects all dc-side generated power ($P_{\mathrm{FC}} + P_{\mathrm{SC}} + P_{\mathrm{WT}} - P_{\mathrm{EL}}$) to ac bus/grid ($P^*_{\mathrm{grid}}$). Moreover, reactive power reference of IFC (Q^*_{grid}) is determined considering the grid voltage conditions and control objectives.

Obviously, this power balancing control scheme needs to have access to the output power of different sources, which makes it a communications-based control strategy. The experimental verifications of this power balancing strategy of dc-coupled hybrid microgrid can be found in [59].

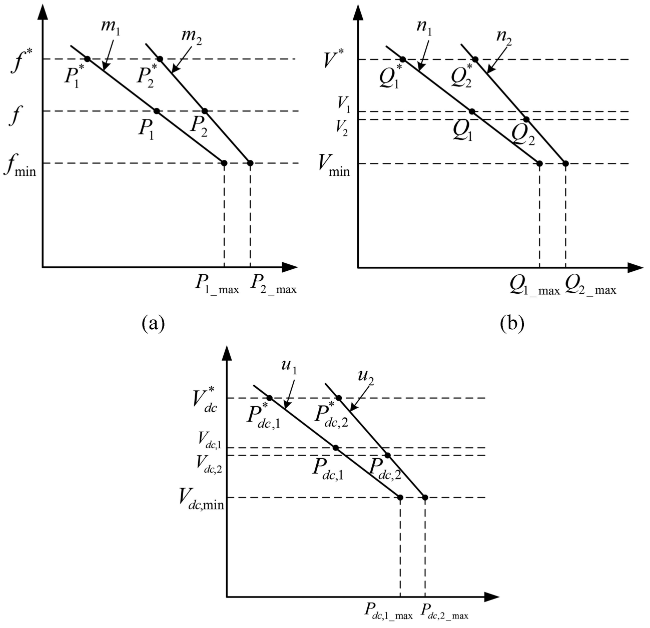
B. Stand-Alone Operation of AC–DC-Coupled Hybrid Microgrid

In ac–dc-coupled hybrid microgrids, good coordination between the dc and ac subsystems are necessary in order to control dc bus voltage, balance the power within dc bus and ac bus, and regulate ac bus voltage and frequency. Here, an example of droop control for both dc and ac buses voltage regulation is presented [6]. It is important to note that power sharing in both dc and ac buses is highly depend on the ILC control strategy (see Fig. 6).

1) Droop Control Method: Droop control method can be applied for both dc bus and ac bus. In an ac droop control method, ac bus voltage and frequency are controlled, and the demand power is shared among input power sources (respective to their power capacities). In this method, each DG–SE on an ac bus accompany with its power converter and ILC are modeled as inverters connected to ac bus through coupling impedances. To emulate the behavior of synchronous generators, the $P - f$ droop and *Q–V* droop characteristics are programmed to the converters control [29], [45], [46]. In order to make the sources share the demand power in proportion to their power ratings, the droop coefficients should be adjusted in inverse proportion to their rated power. The $P - f$ droop and *Q–V* droop diagrams of two DG units are shown in Fig. 9(a) and (b). In this figure, P_1^*, P_2^*, Q_1^*, and Q_2^* are the reference active and reactive powers in the grid-connected mode (no-load operation), and $P_{1\_\max}$, $P_{2\_\max}$, $Q_{1\_\max}$, and $Q_{2\_\max}$ are the maximum possible output real and reactive powers of two DGs. According to this figure, DGs produce their reference output active and reactive powers at the grid frequency and voltage (f^* and V^*) by adjusting the droop slopes (m_1 and m_2) and (n_1 and n_2).

In addition to the aforementioned droop method (direct droop control method), in nondispatchable DGs such as wind power and PV systems, an inverse droop method is used [132], [133]. In this control strategy, the inputs of the droop controller block are the PCC voltage parameters (amplitude and frequency), and its outputs are the reference active and reactive powers. In other words, in inverse droop control, $P - f$ and $Q - V$ droop characteristics are used to change the active and reactive powers generation according to control frequency and voltage variations. In this strategy, DGs work on output power control mode to provide grid-support functions. More discussion in this is provided later.

Compared to ac bus droop control, the dc bus droop control is simpler as only the active power and voltage magnitude droop



(a) (b)

(c)

Fig. 9. Droop slopes for two DGs; (a) *P-f* droop in ac subsystem, (b) *Q–V* droop in ac subsystem, and (c) *P–V* droop in dc subsystem.

(*P–V* droop) is relevant [62], [64]. Similarly, for proportional active power sharing to DGs power ratings, the droop coefficients should be adjusted in inverse proportion to DG's or SE's rated power [6]. Fig. 9(c) represents the *P–V* droop diagram of two DG units connected to dc bus. In this figure, V_{dc}^* is the maximum voltage of dc bus under no-load condition, $V_{\mathrm{dc,min}}$ is the allowable minimum voltage of dc bus, and $P_{\mathrm{dc},1\_\max}$ and $P_{\mathrm{dc},2\_\max}$ are the maximum real power of DGs. With this droop control, different line impedances lead to unequal dc source terminal voltages [$V_{\mathrm{dc},1}$ and $V_{\mathrm{dc},2}$ in Fig. 9(c)], which cause an error in active power sharing [6], [7]. This is similar to the effects of line impedance to the reactive power sharing in an ac system [see Fig. 9(b)] [40], [134].

2) ILC Control Strategy: The ILC is responsible to link ac and dc subsystem to form ac–dc-coupled hybrid microgrid. Among various power management schemes (see Fig. 6), autonomous control scheme is considered in this example [6], [7]. In this scheme, Per-Unit (P.U.) values of the dc subsystem voltage and ac subsystem frequency are measured, and their difference is used to adjust the power demand of the ILC for dc or ac subsystem support. Multiple ILCs could be used in parallel with enhanced capacity and reliability. In Fig. 10, the block diagram of an ac–dc-coupled hybrid microgrid in a stand-alone operation mode is shown, and the control scheme of one ILC (in $\alpha\beta$ frame) is shown in Fig. 11.

For proper power sharing among ILCs in order to control normalized dc subsystem voltage and ac subsystem frequency, different power controllers (K_P) are used for each ILC, which provide the alternative droop control technique among ILCs. These controllers are designed based on maximum difference of dc voltage and ac frequency P.U. values (e) in the microgrid and each ILC's power rating.

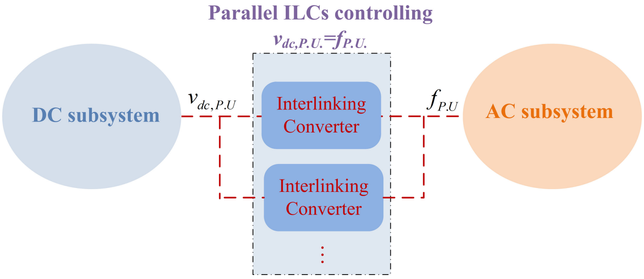


Fig. 10. AC–dc-coupled hybrid microgrid in stand-alone operation mode with normalized droop method in both ac and dc subsystems and autonomous ILCs control.

After determining the reference active and reactive powers, ILCs work on power control mode in order to regulate output active and reactive powers on their reference values, and regulates ac and dc buses voltages (see Fig. 11). Note that the reactive power control of ILCs can be realized with $Q-V$ droop control, unity power factor control, etc. In this example, unity power factor control is considered as the focus is on real power exchange.

The experiments are conducted on a three-phase ILC prototype, and the system is controlled by dSPACE 1103. In this test, the frequency range of $59\,\mathrm{Hz} < f < 61\,\mathrm{Hz}$ is considered for an ac subsystem, and voltage range of $140\,\mathrm{V} < V_{\mathrm{dc}} < 160\,\mathrm{V}$ is considered for a dc subsystem. Moreover, the ILC is rated at 375 W, which can transfer a maximum of 80% rated capacity from underloaded to overloaded subsystem. In the control system, the normalization is done considering following expressions [6]:

$$f_{\mathrm{P.U.}} = \frac{f - 0.5 \times (f_{\max} + f_{\min})}{0.5 \times (f_{\max} - f_{\min})}$$

$$V_{\mathrm{dc,\,P.U.}} = \frac{V_{\mathrm{dc}} - 0.5 \times (V_{\mathrm{dc,max}} + V_{\mathrm{dc,min}})}{0.5 \times (V_{\mathrm{dc,max}} - V_{\mathrm{dc,min}})}.$$

In this test, two types of experiments are conducted; dc subsystem voltage variation and ac subsystem frequency variation. In the first test, a dc subsystem voltage is varied from 150 to 160 V and then from 160 to 155 V, while the ac subsystem frequency is fixed at 60 Hz, and the ILC behavior is analyzed. The results are shown in Fig. 12, where it can be seen that variation of V_{dc} from 150 V (where the power transfer is zero in the ac subsystem frequency of 60 Hz) to 160 V will result in active power transferring from dc subsystem to ac subsystem, and the reduction of V_{dc} from 160 to 155 V will reduce the injected power to ac subsystem as expected.

In the second test, the ac subsystem frequency is varied from 60 to 59 Hz and from 59 to 59.5 Hz, while the dc subsystem voltage is set at 150 V. As shown in Fig. 13, the active power is transferred from dc subsystem to ac subsystem to support the frequency reduction when an ac subsystem frequency is varied from 60 to 59 Hz. Moreover, increasing the ac subsystem frequency from 59 to 59.5 Hz will reduce the transferred power from dc to ac subsystem. The results are shown in Fig. 13.

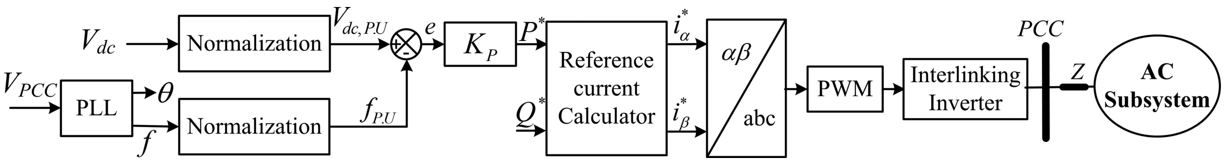


Fig. 11. Control block diagram of one ILC in stand-alone operation mode with normalized droop method in both ac and dc buses.

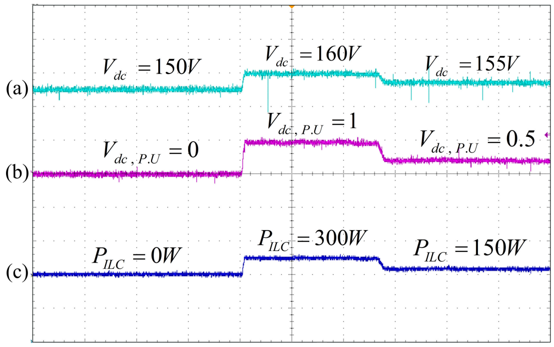


Fig. 12. Variation of dc subsystem voltage; (a) dc subsystem voltage 20 V/div, (b) dc subsystem voltage P.U. values 1/div, and (c) ILC output active power transferred to the ac subsystem 500 W/div; (time: 10 s/div).

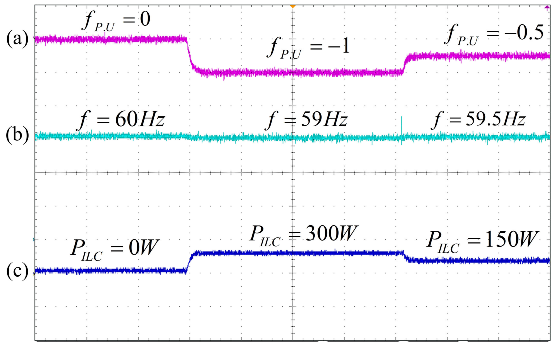


Fig. 13. Variation of ac subsystem frequency; (a) ac subsystem frequency P.U. values 1/div, (b) ac subsystem frequency 20 Hz/div, and (c) ILC output active power transferred to the ac subsystem 500 W/div; (time: 1 s/div).

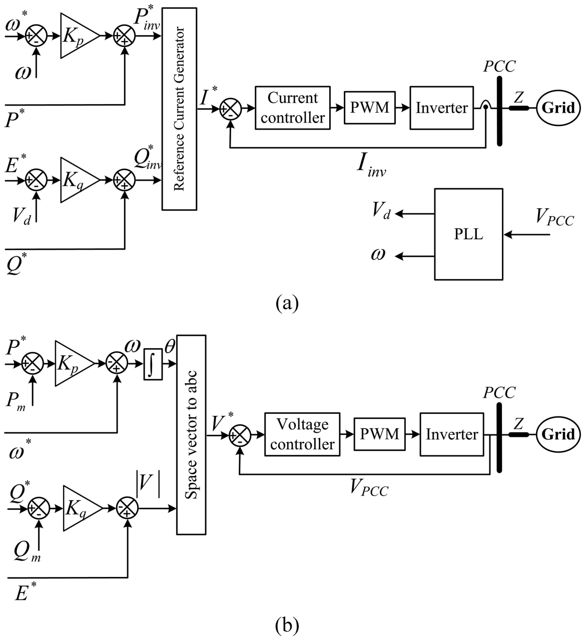


Fig. 14. Power converter control in grid voltage amplitude and frequency support: (a) as a current source and (b) as a voltage source.

C. Grid-Support Control Examples

As discussed earlier, the ac bus connected DGs–SEs as well as the ILCs and IFCs can be used for supporting the grid. The main objective of the grid support is regulating the ac voltage by controlling active and reactive powers delivered to the ac bus. In addition to the aforementioned objectives, unbalance compensation, harmonic control, power factor correction, etc., can be considered as grid-support objectives. Here, two examples of the grid-support control strategies are presented: the grid voltage (amplitude and frequency) support and the grid unbalanced voltage compensation.

1) Grid Voltage Amplitude and Frequency Support: In this control strategy, the grid-supporting power converter can be controlled as a current source or voltage source [135]. In the current source operation, the grid-supporting power converter regulates the variations of voltage amplitude and frequency of microgrid and ac grid. The block diagram of this control strategy is shown in Fig. 14(a).

In this control strategy, the frequency variation is controlled by the active power, while the reactive power controls the amplitude of voltage. The frequency and voltage controllers are proportional controllers (K_p and K_q) for realizing the inverse $P - f$ and $Q - V$ droop control. Depend on the utilized reference frame (dq or $\alpha\beta$), the reference currents are generated using reference active and reactive powers and PCC voltage amplitude. In this strategy, PI controllers with decoupling terms between $d-$ and $q-$ axes can be used as a current controller in dq reference frame, while proportional current controllers are used in $\alpha\beta$ reference frame.

In a voltage source operation [see Fig. 14(b)] where the power converter works as a controllable voltage source, a linking impedance will be necessary between the converter and grid, which can be a physical impedance or a virtual impedance [134], [135]. In this control scheme, the active and reactive power controllers are proportional controllers (k_P and k_q) for realizing $P - f$ and $Q - V$ droop control. In this strategy, the output three-phase voltages at PCC are regulated on their reference values with closed-loop control system.

2) Grid Unbalance Voltage Support: Unbalance voltage compensation can be used in grid-connected operation mode

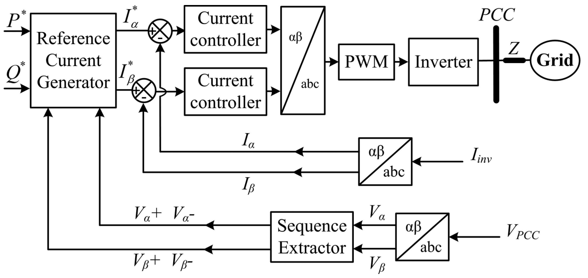


Fig. 15. Control block diagram for unbalance voltage compensation in grid-support control.

with unbalance loads or grid faults. In this control, negative sequence current is generated to reduce negative sequence of voltage at PCC. The control block diagram for unbalance voltage compensation is shown in Fig. 15. The control is implemented in the stationary $\alpha\beta$ frame to avoid multiple frame transformations for different sequence components control [136]. In this control scheme, the active power reference $P^*$is provided by power management strategies or dc-link voltage regulator, and reactive power reference is provided by voltage support strategies, phase current limitation scheme, etc. [137].

In the control system, different sequence extractor can be used to extract voltage sequence components [138]–[140]. These positive and negative sequence voltages generate the reference currents of inverter as following [136]:

$$\begin{aligned} I_\alpha^* &= P^* \left(\frac{k_1}{|v^+|^2} V_\alpha^+ + \frac{(1-k_1)}{|v^-|^2} V_\alpha^- \right) \\ &\quad + Q^* \left(\frac{k_2}{|v^+|^2} V_\beta^+ + \frac{(1-k_2)}{|v^-|^2} V_\beta^- \right) \\ I_\beta^* &= P^* \left(\frac{k_1}{|v^+|^2} V_\beta^+ + \frac{(1-k_1)}{|v^-|^2} V_\beta^- \right) \\ &\quad - Q^* \left(\frac{k_2}{|v^+|^2} V_\alpha^+ + \frac{(1-k_2)}{|v^-|^2} V_\alpha^- \right) \end{aligned}$$

where k_1 and k_2 provide flexible control of positive and negative sequences. By controlling these coefficients, in addition to unbalance voltage compensation, active power oscillation cancellation, reactive power oscillation cancellation, DG phase current limitation, etc., can be obtained [136].

As a case study, the aforementioned grid unbalance voltage support strategy (active power oscillation cancellation) is conducted. The experiments are conducted on a three-phase grid interfacing DG system prototype. In this test, the control system is switched between two operation modes. In the first operation mode, just positive sequence of active and reactive powers are injected to the grid ($k_1 = 1$ and $k_2 = 1$), and in second mode, cancellation of active power oscillation method is applied ($k_1 = |v^+|^2/(|v^+|^2 - |v^-|^2)$ and $k_2 = |v^+|^2/(|v^+|^2 + |v^-|^2)$) [136]. The negative sequence component of PCC voltage is shown in Fig. 16, where it can be seen that the control strategy decreases the negative sequence component of PCC voltage.

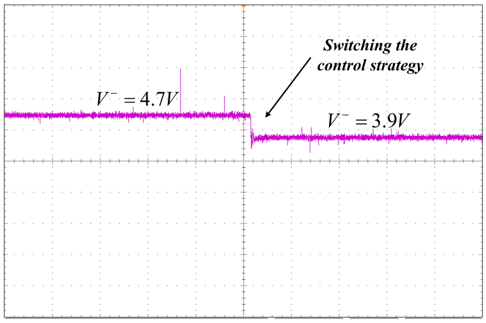


Fig. 16. Negative sequence of PCC voltage in positive sequence powers injection mode and cancellation of active power oscillation mode (time: 1 s/div, voltage: 1 V/div).

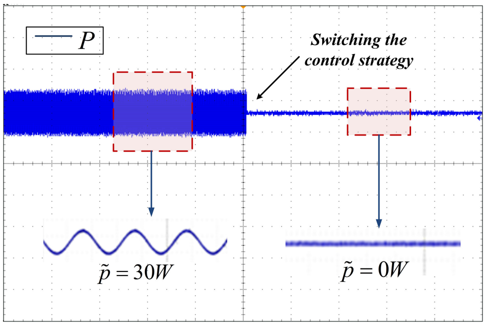


Fig. 17. Inverter output active power injected to the PCC in positive sequence powers injection mode and cancellation of active power oscillation mode (time: 2 s/div, power: 50 W/div).

The active power oscillations as plotted in Fig. 17 show that oscillations are zero with the aforementioned method.

VII. DISCUSSIONS AND FUTURE TRENDS

Considering the increasing penetration of dc voltage-based RE sources, energy storage and dc loads, as well as the existing widespread ac systems; hybrid ac/dc microgrids are inevitable parts of future power systems. So far in this paper, a thorough review and discussion of different hybrid microgrid structures, power management schemes under different operation and loading conditions, and implementation examples have been conducted. In this section, some discussions and recommendations about future trends of hybrid ac/dc microgrids are provided:

A. *Structures of Hybrid AC/DC Microgrids*

Among different structures of hybrid ac/dc microgrids, ac-coupled hybrid microgrids have been the dominant structure up to now because of its simple structure and control schemes. However, with the increase of modern dc loads and the necessity of connecting more RE sources and energy storage systems into the grid, ac–dc-coupled hybrid microgrids are the future trend of power system. AC–dc-coupled hybrid microgrids can reduce the number of power conversion process, which improves overall efficiency and reduces cost. However, in these systems, control schemes and power management strategies are the major concern and challenges. Since DGs and SEs are connected to both ac and dc buses, more coordination between the dc and ac subsystems are necessary. Future ac–dc-coupled microgrids will have several dc and ac buses in different voltage levels (and maybe frequencies if there is high-frequency links). As a result, dc bus voltage control, power balancing within dc bus, ac bus and grid/load, and ac bus voltage and frequency control (if necessary) are the main power management challenges and objectives. Moreover, the operation of ILCs connecting different dc and ac buses in different voltage levels can be an interesting research topic in the future.

B. Power Quality Issues

In future hybrid ac/dc microgrids, with more interfacing power electronics from the DGs, SEs and the loads, together with the increasing nonlinear loads, power quality will be an important topic. Currently, harmonics, unbalances, and voltage sag/swell have already caused concerns in today's power distribution system, and it may get worse in the near future. However, with the increasing utilization of DG/SE IFCs, they can be properly controlled to help address the power quality issues. This is a promising idea as most DGs, SEs, and interlinking or interfacing converters in the hybrid microgrids are not operating at full rating all the time (especially true when considering the intermittent nature of RE sources). The available converter rating can be used in a smart way to help improve the power quality. Therefore, development of ancillary services such as flicker mitigation, unbalance voltage compensation, harmonic compensation, power factor correction, etc., can be a good research direction for future microgrid systems.

C. Parallel Operation of ILCs and IFCs

Interfacing converters (IFCs) and interlinking converters (ILCs) are critical links between ac and dc bus in a hybrid microgrid system. Their control is the key for the power balance between dc and ac subsystems. Due to the requirement of higher ratings compared to other DG's or SE's interfaces, these IFCs and ILCs will typically have parallel converters operating together. Therefore, the parallel operation of these converters is an interesting topic for further research.

For the parallel converters, control strategies such as master–slave and instantaneous current sharing methods such as average current control and circular-chain control can be used. In addition to the aforementioned methods that need communication, communication-less control strategy (such as droop control as discussed in the example in Section VI) can also be considered for controlling parallel converters, which may be important when the parallel IFCs and ILCs are not physically close as there might be multiple links between the dc and ac buses at various locations with higher reliability.

In addition, as discussed earlier, the IFCs and ILCs can be in power control mode, dc voltage control mode, or ac voltage control mode. However, it is not necessary for all parallel IFCs or ILCs to work in the same control mode together. For example, for an ac–dc-coupled microgrid, it is possible that some ILCs control the dc link voltage, some ILCs control the ac link voltage and some ILCs balance the power. This combination of control strategies requires further study and investigation.

Moreover, the performance of parallel IFCs or ILCs during the microgrid transition between grid-connected and stand-alone operation modes need to be considered in the future research.

D. Communication Systems in Microgrids

Future microgrids will most likely consist of combination of various communication technologies that operate efficiently together. These technologies will be both wireless and wireline technologies, where using the appropriate technology for the right application is still an open problem. For instance, although PLC can be used for advanced metering infrastructures, some challenges such as reliability and performance should be considered. In the other hand, a wireless technique can provide a better alternative for long-range transmission because of its possibility of adopting cooperative communications or cognitive radio. However, the security concerns should be considered in the future communication systems. All in all, the communication systems play an important role in the future microgrids and need more investigations.

E. Transient Power Management Under Different Load/Grid Conditions

The power management and control strategies of hybrid microgrid should have a good performance under grid-connected, stand-alone, and during transition operation modes. Moreover, the transition between grid-connected and stand-alone operating modes should be seamless and smooth. On the other hand, loads and/or the grid conditions can have significant impacts on the performance of microgrid. Although these challenges have been considered separately in different researches, considering the real hybrid microgrids, transient power management under different load/grid conditions need to be further studied in future researches.

F. Economic Concerns

In general, economics is an important aspect of microgrids design and operation. Although microgrids may not be economical compared to traditional ac grids, in some regions with high electricity rate and demand charges, microgrids can be cost-effective. Moreover, as technology and industry mature, their cost will decrease that leads to more economical microgrids. Further, the grid support and ancillary functions of microgrid could potentially improve the cost-effectiveness of a microgrid system. After all, the economic issues need to be properly addressed before large-scale penetration of microgrids can be the reality.

G. New Semiconductor Technologies

Recently, emerging new semiconductor devices using silicon carbide and gallium nitride has improved the power electronic switches technology. Utilizing these materials in the power converters, higher switching frequency can be used that can improve the overall performance of hybrid microgrid. These device technologies are in their early stages of development that require more study in the future, but in applications that require better performance with no concern about cost, they are already being used.

VIII. CONCLUSION

In this paper, the topology and control schemes of hybrid ac/dc microgrids are reviewed. Various structures of hybrid ac/dc microgrids (ac-coupled, dc-coupled, and ac–dc-coupled) are discussed, and real-world examples of different types of hybrid microgrid are presented. In the operation of hybrid ac/dc microgrids, the control schemes and power management strategies are one of the most important considerations. Therefore, a thorough review and discussion of different control schemes and power management strategies of different types of microgrids under different operation and loading conditions are conducted in this paper. Implementation examples of some representative control schemes are presented to better illustrate the power management strategies. At last, discussion and recommendations about the future research directions on ac/dc hybrid microgrids and power management strategies are provided.

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