Review on Control of DC Microgrids and Multiple Microgrid Clusters

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Review on Control of DC Microgrids

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***Abstract*-- This paper performs an extensive review on control schemes and architectures applied to DC microgrids. It covers multi-layer hierarchical control schemes, coordinated control strategies, plug-and-play operations, stability and active damping aspects as well as nonlinear control algorithms. Islanding detection, protection and microgrid clusters control are also briefly summarized. All the mentioned issues are discussed with the goal of providing control design guidelines for DC microgrids. The future research challenges, from the authors' point of view, are also provided in the final concluding part.**

***Index Terms*-- Microgrid, direct current, hierarchical control, coordinated control, plug-and-play, nonlinear control, stability.**

I. INTRODUCTION

SINCE 19th Century, the invention of transformers and poly-phase AC machines initiated the worldwide establishment of a complete AC generation, transmission and distribution grid. DC distribution systems, although recognized as a natural and simple solution for utilizing electric power at the beginning, were not widely applied because of difficulties in voltage level conversion and long distance transmission. Since the end of last century, the development of semiconductor based power conversion devices offers the possibility of flexible voltage/current transformation and thus brings DC power back to the main stage finding its applications, for instance, in home appliances, data centers, and vehicle power systems [1]–[3].

Most recently, the revolutionary changes in the electric power grid, including the penetration of renewable energy sources (RES), the distributed allocation of generation and the increasing participation of consumers, aim to establish a more efficient and sustainable energy system, while facing challenges on the organization, control and management aspects. Active and independent distribution systems, named also microgrids (MGs) [1], are thus the key to achieve those goals, realizing the autonomous operation of each regional power system.

Certainly, the combination of DC distribution with the MG concept becomes attractive, since (i) being RES, electric vehicles (EV) and energy storage systems (ESS) naturally in DC, efficiency is enhanced because of less number of power conversion stages; (ii) the control and management of a DC system is much simpler than in AC, which makes DC MGs practically more feasible; (iii) most consumer electronic appliances are in DC, such as computers, microwave-ovens, modern lighting systems, and so on [2]–[6].

As a consequence, an increasing number of academic research works and industrial demonstration projects on DC MGs have been carried out, covering applications in RES parks [2], DC homes [7], [8], ESSs [9], [10] and EV charging stations [11], [12]. A whole picture of future employment of DC MGs can be obtained based on these works, while a number of key issues are also identified, including: (i) planning and design of a DC MG realizing an optimal combination of generation, storage and consumption; (ii) control and management of a DC MG achieving economic and autonomous operation; (iii) coordination of clusters of DC MGs with proper regulation of power and energy exchange in regional areas; (iv) grid policy-making, which enables the overall system operation.

The objective of this paper is to provide an extensive review on the control and management of DC MGs, as well as the stability perspective which is closely coupled with control algorithm. Similar to conventional power grids, power converters interfaced DC MGs also require a multi-layer control scheme, from the local control of distributed generators (DGs) to system level optimization and management. The common definition of hierarchical control is recalled in Section II. Section III, IV and V discuss the control algorithms applied in primary, secondary and tertiary levels respectively. Section VI gives a summary on the coordinated control schemes. Plug-and-play control and operation is discussed in Section VII. Stability aspects and active damping design are reviewed in Section VIII. Islanding, protection and control of MG clusters are described in Section IX and X. Section XI closes the paper.

II. MULTI-LEVEL CONTROL SCHEME OF DC MICROGRIDS

With the development and increasing utilization of power electronic devices, the voltage/current regulation, power flow control and other advanced control functions can be realized in MGs by properly operating the interfacing power converters. As widely accepted, MGs control and management is actually

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multi-objective task which covers different technical areas, time scales and physical levels. The domains of interest include the above mentioned issues, for which a multi-level control scheme [13], [14] has been proposed and widely accepted as a standardized solution for efficient MGs management. It comprises three principal control levels, as shown in Fig. 1:

- Primary control performs the control of local power, voltage and current. It normally follows the set-points given by upper level controllers and performs control actions over interface power converters.
- Secondary control appears on top of primary control. It deals with issues in the system level, such as power quality regulation, MG synchronization with external grid for smooth reconnection, DG coordination, etc.
- Tertiary control is issued with optimization, management and overall system regulations.

Based on the same hierarchy shown in Fig. 1, the way of implementing the control levels can be centralized, decentralized, distributed or in a hierarchical fashion, as shown in Fig. 2. It should be noted that the structures shown in Fig. 2 are based on the control engineering definitions summarized, for instance, in [15]–[17]. A central control unit exists in centralized structure which collects and transmits information to local DGs. Decentralized and distributed structures (Fig. 2 (b) and (c)) do not require a central controller. Decentralized control, as defined in [15], [16], performs regulation based on local measurements, while in comparison, distributed control is based on both local measurement and neighboring communication [17]. The hierarchical control structure distributes the control functions into local controllers and upper level controllers so that the complete system operates in a more efficient way. The choice of the control structure can be different according to the MG type (residential, commercial or military), and the legal and physical features (location, ownership, size, topology, etc.).

Centralized control [18]–[35], as shown in Fig. 2 (a), requires data collection from all the essential MG components. Based on the gathered information, control and management procedures can be executed in the controller to achieve proper and efficient operation. The advantages of centralized control include strong observability and controllability of the whole system, as well as straightforward implementation. However, it entails a single point of failure issue, and the central controller breakdown will cause the loss of all the functions. Other disadvantages are reduced flexibility and expandability, as well as the necessity of considerable computational resources. Therefore, centralized control is usually more suitable for localized and small size MGs where the information to be gathered is limited and centralized optimization can be realized with low communication and computation cost [18], [29], [33], [36].

Decentralized control in MGs, as shown in Fig. 2 (b), refers to the control methods which do not require information from other parts of the system. The controller regulates respective unit with only local information. Decentralized schemes have the advantage of not requiring real-time communication, even though the lack of coordination between local regulators limits the possibility of achieving global coordinated behaviors. Droop control is a typical example of decentralized control methods. It achieves power sharing between DGs without communication, but the accuracy is limited by system configuration as well as control and electrical parameters.

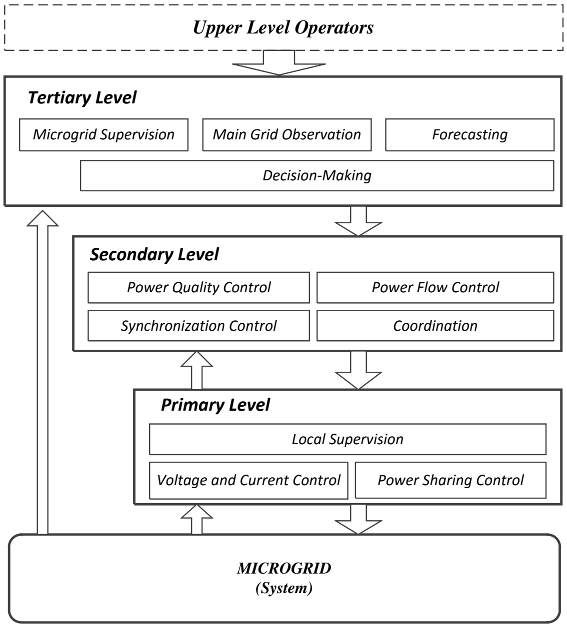
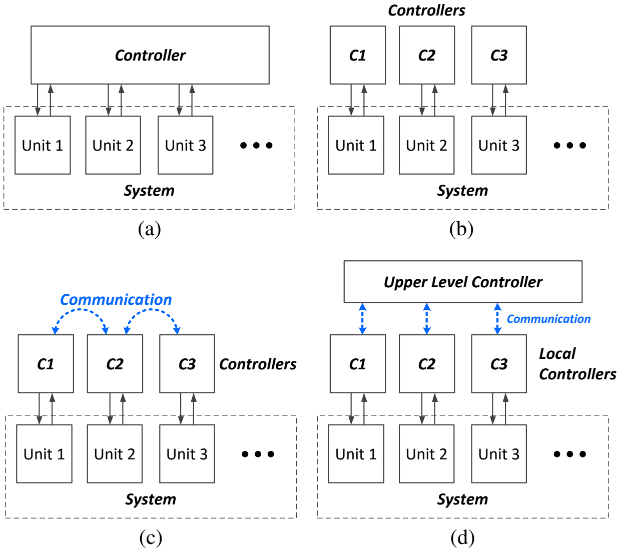


Fig. 1. Hierarchical control scheme.



(a) (b) (c) (d)

Fig. 2. Basic control structures: (a) centralized; (b) decentralized; (c) distributed; (d) hierarchical.

Recent progress in communication technologies [37] (WiFi, Zigbee, etc.) and information exchange algorithms [38]–[42] (P2P, gossip, consensus etc.) enable the possibility of distributed control and management in practical applications [43]–[45]. In that sense, functions provided by centralized control scheme can also be realized in a distributed way as shown in Fig. 2 (c). The controllers ‘talk’ with each other through communication lines so that essential information is shared among each local system in order to facilitate a coordinated behavior of all the units. The main challenge of a fully distributed control scheme is the coordination among distributed units to fulfill either the control or optimization objectives, which necessarily require proper communication and information exchange schemes. In recent years there had been a major trend to integrate distributed algorithms into the control and management of MGs. Consensus algorithms [46]–[48], as they offer a simple and straightforward implementation, are widely applied. The general purpose of consensus algorithms is to allow a set of agents to reach an agreement on a quantity of interest by exchanging information through a communication network. While associated information is limited to only a few quantities in case of secondary control, tertiary control may need to exchange a number of different signals with neighboring agents. The consensus algorithm either fetches essential global information [49], [50] or can be well integrated into control layers [51], [52] to help the local control system perceive the 'outer' environment.

Actually as the modern energy systems are becoming more complex and require higher intelligence, not all the functions can be achieved in a distributed or decentralized manner, especially when the system involves a complicated decision-making process. A hierarchical control structure, as shown in Fig. 2 (d), is thus widely used. Simple functions can be implemented in the local controllers to guarantee a basic operation of the system. Advanced control and management functions can be implemented in the central controller. Hierarchical control is thus becoming a standardized configuration in MGs. The primary control, including basic voltage/current regulation and power sharing, is usually implemented in local controller. The secondary and tertiary functions are conventionally realized in a centralized manner as they require global information from all the essential units.

III. PRIMARY CONTROL

Primary control is the first layer in the hierarchical control scheme shown in Fig. 1. It is responsible of local voltage and current control to meet the operation and stability requirements. Meanwhile, decentralized load power sharing methods are also commonly implemented in this layer to achieve proper source and load power management.

A. Active Current Sharing

In DC MGs or DC distribution systems, multiple power electronic converters commonly coexist as the interfaces of DERs. Hence, it is necessary to achieve proper load sharing among them following their current or power ratings. This is the similar concept proposed years ago for DC-based server system with paralleled DC/DC converters.

Master-slave control is a common approach used for active current sharing among multiple converters [53]. In this scheme, one converter is selected as the master unit that operates in voltage controlled mode to establish the DC bus voltage, while the other converters are configured as slave converters operating in current controlled mode. Hence, multiple slave converters operate in DC-bus-feeding mode while the voltage is stabilized by the master converter. Since the output signal of the DC voltage controller in the master converter is transferred to each of the slave converters, the current sharing among slave converters can be achieved.

In order to enhance the resilience and reliability of DC system, circular chain control (3C) is proposed, where circular communication architecture is employed to enhance fault isolation and detection [54]. The reference current in each DC/DC converter is generated based on the measured output current of the adjacent converter. Hence, a communication loop is established. If a fault occurs, the related converter is disconnected to isolate the fault and a new communication loop with the rest of the converters is reorganized to maintain proper load current sharing. It should be noted that high bandwidth communication network is required in these control strategies.

B. Droop Control and Virtual Impedance

As aforementioned, most of the current sharing methods paralleled DC/DC converters are based on high bandwidth communication network. Accordingly, they are mostly used in centralized DC systems with relatively small scale, e.g., DC server system, DC electrified aircraft, etc. However, in DC MGs, since the DERs and loads are connected to the point of common coupling (PCC) dispersedly, it can be unsuitable or costly to use high bandwidth communication network considering the data reliability and investment cost. Hence, droop control as a decentralized method has drawn increasing attention.

Droop control was also regarded as adaptive voltage positioning (AVP) method in analog circuit design and the control diagram is implemented as shown in Fig. 3 [55]. The principle of droop control is to linearly reduce the DC voltage reference with increasing output current. By involving the adjustable voltage deviation, which is limited within the acceptable range, the current sharing among multiple converters can be achieved. In most of the cases, the current sharing accuracy is enhanced by using larger droop coefficient. However, the voltage deviation increases accordingly. Hence, the common design criterion is to select the largest droop coefficient while limiting the DC voltage deviation at the maximum load condition:

$$v_{\mathrm{dci}}^{*} = v_{\mathrm{dc}}^{*} - r_{\mathrm{i}} \cdot i_{\mathrm{oi}} \tag{1}$$

$$\Delta v_{\mathrm{dc}} = \left| v_{\mathrm{dc}}^{*} - v_{\mathrm{dc}} \right| \le \Delta v_{\mathrm{dcmax}} \tag{2}$$

where v_{dci}^{*}, i_{oi} and r_{i} are the reference DC voltage, output current and droop coefficient of converter #i (i = 1, 2, 3, …), respectively, v_{dc}^{*} is the reference DC voltage, Δv_{dc} is the DC voltage deviation and $\Delta v_{\mathrm{dcmax}}$ is its maximum value.

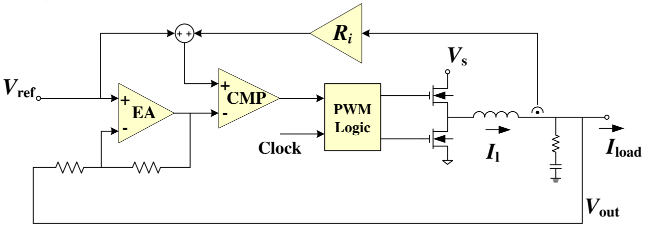


Fig. 3. Analog implementation of AVP current sharing method.

It is seen from (1) that the droop coefficient r_{i} can be regarded as a resistor since it represents the relationship between DC voltage and current. Therefore, this droop coefficient r_i is also named as virtual resistance in droop-controlled DC MGs. The interface converter with droop control can be modeled by using Thévenin equivalent circuit, as shown in Fig. 4. This virtual resistance allows additional control flexibility of DC MGs.

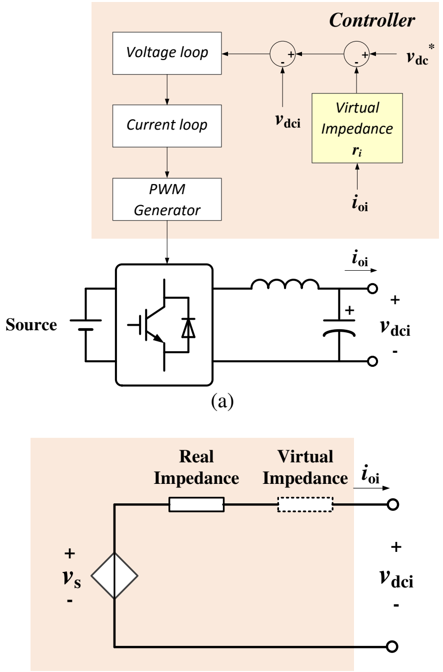


Fig. 4. General control diagram and equivalent circuit model of droop-controlled interface converter. (a) general control diagram; (b) thévenin equivalent circuit

C. Non-linear Droop Control

The community has also proposed different nonlinear control techniques at different levels. One of the techniques in decentralized control is nonlinear droop. It has been an established fact that the linear droop technique cannot ensure low voltage regulation and proportional current sharing [100], [101]. To achieve acceptable voltage regulation at full load and to ensure proportional current sharing, nonlinear and adaptive droop techniques are proposed in [102]–[106]. A recent review on droop control techniques is reported in [107]. The generic droop can be given by the following equation:

$$V_{ref_j} = V_j^0 - k_j(i_j) i_j^{\alpha} \tag{3}$$

where k_j is a positive function, α is a positive constant, V_{refj} is reference setting and i_j is the current supplied by the j^{th} source, respectively. For constant values of k_j, the above characteristics represent the linear droop. Nonlinearity in droop characteristic ensures that droop gain is high at full load and has a low value at light loading conditions.

Fig. 5 shows improvement in current sharing with nonlinear droop controller when two sources are considered. There have been some proposals where shifting of droop characteristic is done to ensure better regulation and current sharing [100]. In [108], [109], an optimal control framework is proposed for DC MGs. The proposed controllers require full state information and therefore demand proper communication among the sources. The same paper also proposes different variants of optimal control which require less communication and/or no communication. It has been proposed that droop controller is a special case of the proposed optimal control law. The droop control computes references for different power converters which provide an interface for sources.

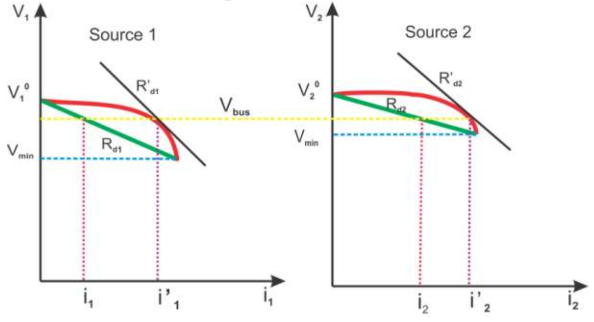


Fig. 5 . Nonlinear droop control for two sources

D. DC Bus Signaling

Besides droop control, DC bus signaling is another useful distributed method for power management among sources and loads [67], [68]. It is implemented by measuring the DC voltage at the local coupling point. Multiple DC voltage ranges are pre-defined to determine the operation modes. Particularly, when the DC voltage falls into a certain range, the corresponding operation mode is selected. Considering the sources that are responsible of establishing DC bus voltage, three operation modes are commonly employed, i.e., utility dominating mode, storage dominating mode and generation dominating mode, as shown in Fig. 6 (a), (b) and (c). In these operation modes, utility grids, ESSs and DGs, e.g., photovoltaic (PV) panels, wind turbines (WT), etc., dominate the DC MG and are responsible of establishing DC bus voltage, respectively. Meanwhile, different operation modes are selected depending on local DC bus voltage level, as shown in Fig. 6 (d).

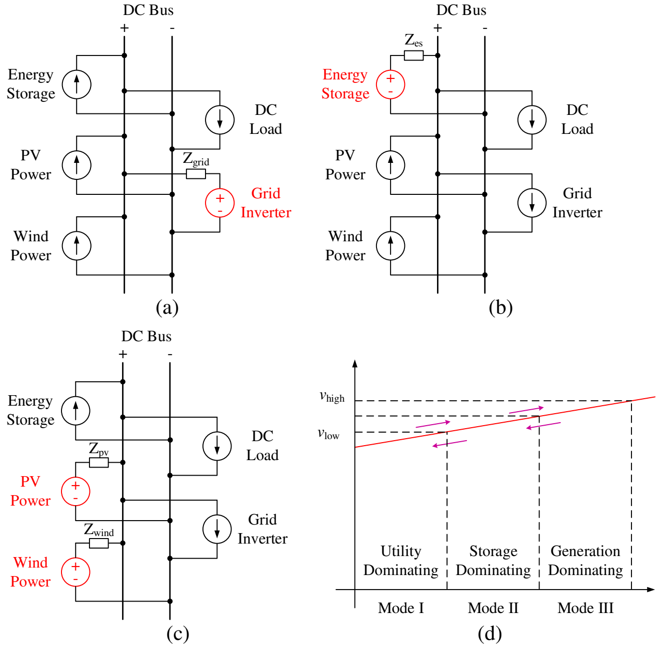


Fig. 6. Different operation modes in DC bus signaling method. (a) Utility dominating mode; (b) ESS dominating mode; (c) generation dominating mode; (d) operation mode selection based on local DC bus voltage.

IV. SECONDARY CONTROL

The concept of secondary control, under the name of automatic generation control (AGC) or load frequency control (LFC), has been used in large power systems to address the steady-state frequency drift caused by the droop characteristic of generation sites. It is conventionally implemented via a slow, centralized PI controller with low bandwidth communication [69]. In AC MGs, however, the name of ‘secondary control’ has been utilized not only for frequency regulation, but also for voltage regulation, load power sharing, grid synchronization, and power quality issues[14], [70].

Similar fundamental has also been utilized for voltage regulation [14], [51], [71]–[73], current sharing [52], [74], [75], and energy storage management [76]–[79] in DC MGs.

A. *Voltage Boundary/Restoration Control*

Despite the aforementioned benefits, the conventional droop method suffers from poor voltage regulation and load sharing, particularly when the line impedances are not negligible [56], [71], [80]. Voltage drop caused by the virtual impedance in droop mechanism, and voltage mismatch among different converters are the main reasons [51].

To eliminate voltage deviation induced by droop mechanism, a voltage secondary control loop is often applied to the system. This controller assigns proper voltage set point for primary control of each converter to achieve global voltage regulation. The secondary control effort (δv_i^v) changes the voltage reference of local unit(s) by shifting the droop lines up (or down), regulating the voltage to the nominal value:

$$v_i = v^{ref} - r_i i_i + \delta v_i^v \tag{4}$$

where v^{ref} is the global reference voltage, v_i is the local voltage set point for i^{th} converter, i_i is the output current injection, and r_i is the droop coefficient. In the islanded mode of operation, the global reference voltage, v^{ref}, is typically the rated voltage of the MG. However, in the grid-connected mode, a new reference voltage may be set by the tertiary control in order to exchange power between grid and MG [51]. It should be noted that secondary control should be designed to operate on a slower time frame (e.g., 10 times slower) than that of the primary control to decouple these two control loops.

The concept of voltage secondary control is illustrated in Fig. 7, where, for simplicity, a MG consists of two parallel converters with the same power ratings is examined. As in practice, the lines connecting the converters to the common bus are considered to have different impedances; it is assumed here that $Z_1 > Z_2$. As Fig. 7 depicts, the primary control imposes different voltage levels at the converter terminals, i.e., $v_1 \neq v_2$. This is because of the unequal current injection ($i_1 < i_2$) due to the line impedance difference. Once the voltage secondary controller is applied, voltage at the converter terminals is restored to the nominal value v^{ref}. However, application of this controller for voltage regulation may deteriorate the current sharing between converters, i.e., $i_2^s - i_1^s > i_2 - i_1$. This is due to the fact that the voltage regulation procedure is in a direct conflict with current sharing among converters.

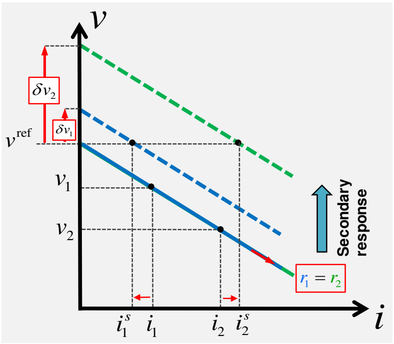


Fig. 7. v-i droop characteristics of a DC MG consists of two parallel converters with the same power rates (converter 1 (blue) and converter 2 (green)), but different line impedance ($Z_1 > Z_2$); before (solid lines) and after (dashed lines) applying voltage secondary control (eq. (4)).

B. *Current Sharing Control*

Proper current sharing is a highly desirable feature in MG’s operation, e.g., to prevent circulating currents [81] and overloading of the converters [82]. In droop-controlled DC MGs, load power is shared among converters in proportion to their rated power. Since voltage is a local variable across the MG, in practical applications where line impedances are not negligible, droop control itself is not able to provide an accurate current sharing among the sources. In the other words, the line impedances incapacitate the droop mechanism in proportional sharing of the load.

To improve current sharing accuracy, another secondary control loop is employed [72], [73], [83]. This current regulator generates another voltage correction term, δv_i^c, to be added to the droop mechanism, i.e.,

$$v_i = v^{ref} - r_i i_i + \delta v_i^c \tag{5}$$

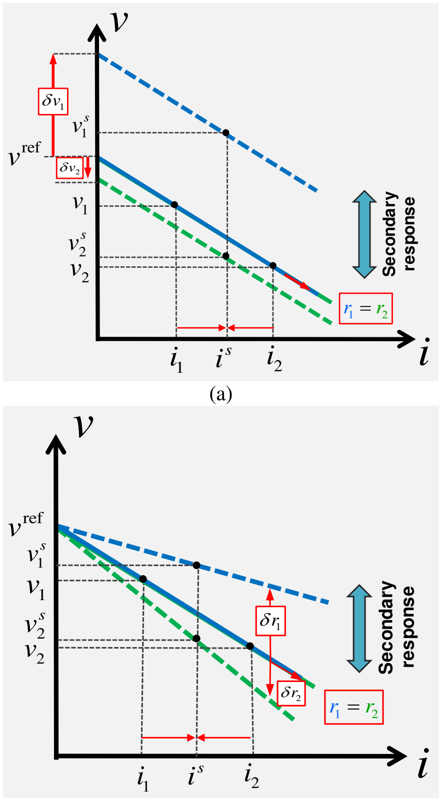
The correction term forces the system to accurately share the currents among the MG according to, for instance, the power rate of the converters. As an alternative [52], the current sharing module can update the virtual impedance, r_i, to manage the current sharing (see Fig. 8 (b)). In this approach, the droop correction term generated by the secondary controller, δr_i, adjusts the droop mechanism as:

$$v_i = v^{ref} - (r_i - \delta r_i) \cdot i_i \tag{6}$$

Fig. 8 illustrates the v-i droop characteristics before and after applying the secondary controllers, based on (5) and (6), where i^s is the shared current and v_i^s is the local voltage after applying the secondary controller. Although the secondary control ensures proportional current sharing i^s, it might inversely affect the voltage regulation. Therefore, there is an inherent trade-off between these two control objectives, i.e. voltage regulation and current sharing.

C. *Centralized vs Distributed Secondary Control*

As mentioned, primary control is principally operated locally, in a decentralized manner, and does not require communication. For the higher control levels (i.e., secondary and tertiary control), however, communication plays an essential role. These communication-based control levels can be implemented with either centralized or distributed architectures [84].



(a)

(b)

Fig. 8. v-i droop characteristics of a MG consists of two parallel sources with the same power rates (converter 1 (blue) and converter 2 (green)), but different line impedance ($Z_1 > Z_2$); before (solid lines) and after (dashed lines) applying secondary control: (a) eq. (5); (b) eq. (6).

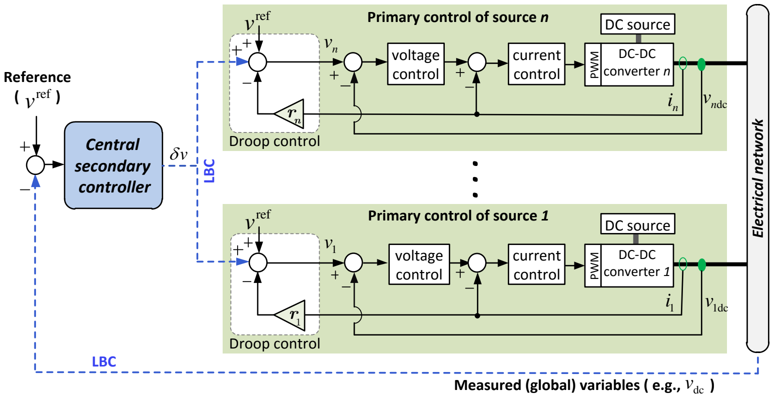


Fig. 9. Centralized secondary control of a DC MG consisting of sources.

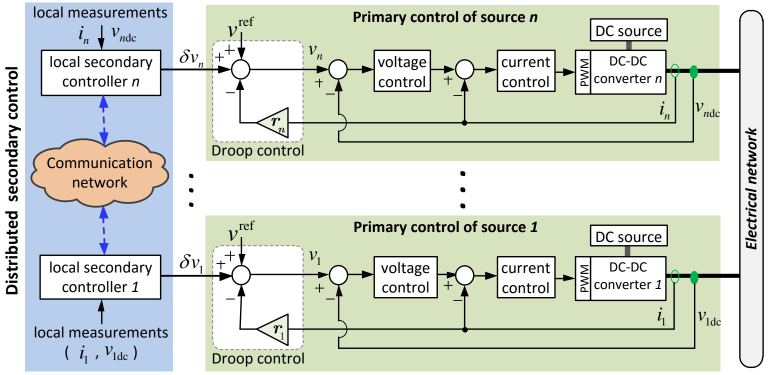


Fig. 10. Distributed secondary control of a DC MG consisting of n sources.

Conventional secondary controller is unique for the whole MG. It relies heavily on centralized communication infrastructure and is usually implemented in the MG central controller (MGCC) [14], [85]. Some other functions mostly related to the tertiary control may be implemented in MGCC. Fig. 9 shows conventional secondary control architecture for a DC MG consisting of n sources controlled by local primary control and one central secondary controller, which collects remotely measured variables (e.g., MG voltage) transferred by means of a low bandwidth communication (LBC) system. Those variables are compared with the references (e.g., MG rated voltage) in order to calculate appropriate compensation signals by secondary controller, which sends them through dedicated communication channels back to the droop controller of each source.

Distributed secondary control (DSC), as a new control strategy, takes all responsibilities of the centralized controller with less communication and computation costs, while being resilient to faults or unknown system parameters [51]. Moreover, it offers scalability, and improved reliability. The idea is to merge primary and secondary control together into one local controller. Unlike the decentralized primary control, for proper operation, embedded secondary controllers need to "talk" with their companions, as highlighted in Fig. 10. In this paradigm, each agent (i.e., converters) exchanges information with other agents on a sparse communication network (see Fig. 10.). Thus, every local secondary controller makes its decision in accord with its neighbors' information.

The basic working principle of DSC is to exchange the information through the neighboring communication, by utilizing a distributed protocol and achieving a consensus, e.g. on the average value of measured voltages [56], [71], [73]. Since voltages are local variables, their restoration can be done either in selected critical buses, or on the total average level. In the latter case, DSC can be exploited to generate a common signal, i.e., the average voltage, to be compared with a reference and passed through a local PI controller [56], [71]. For current sharing, however, the consensus is either on the averaged current [56] or the loading mismatch (i.e., current sharing mismatch) in the system [51], [52]. In the former case, the averaged current is compared with a reference first. In the latter, the loading mismatch is directly fed into a local PI controller to generate the correction term. Ultimately, the appropriate control signal produced by DSC is locally sent to the droop control of each converter for removing associated steady state errors.

It should be noted that the type of protocol, which is essential for making the secondary control distributed, influences the feasibility and performance of the DSC. Earlier works, e.g., [56], [71], propose distributed secondary control for load current sharing and voltage regulation of DC MGs using normal averaging technique. In this approach, however, all units (e.g., converters) require to communicate with all others directly in order to achieve a satisfactory performance. Recently, consensus-based algorithms have received significant attention for secondary control of DC MGs [51], [52], [86]–[90]. Consensus protocols [47], [91], [92] ensure that agents converge to a consistent understanding of their shared information in a distributed manner. They are classified to unconstrained algorithms and constrained algorithms [93]. A consensus-based approach achieves global optimality using possibly time-varying communication between neighbor units, without needing a dedicated unit.

In summary, centralized secondary control suffers from reliability risk since it exposes a single point-of-failure, i.e., any failure in the controller renders the entire system inoperable. This is because a single central controller is utilized for secondary control of the whole microgrid. In addition, it requires two-way communication links between the central controller and the sources (see Fig. 9), which adds complexity to the system. In addition, the centralized architecture conflicts with the MG paradigm of distributed generation and autonomous management, i.e., when some sources are newly plugged in/out, the central controller settings require to be updated. Alternatively, distributed methods, due to their attractive features, have recently drawn a lot of attention in secondary control of DC MGs [51], [52], [56], [71], [75], [87]. In the distributed strategy, however, each converter uses a local secondary controller where a sparse communication is often used between the neighboring units. Such a strategy can provide a satisfactory performance so long as the communication network used among the neighbors carries a minimum connectivity requirement. Therefore, loss of communication links cannot affect the operation if the communication graph remains connected. In addition, unlike the centralized architecture, when one local controller (or one converter) fails only the associated source is affected and the other controllers (converters) can still remain operational.

V. TERTIARY CONTROL

The main function of tertiary control, as illustrated in Section III, is to manage the power and energy with specified objectives, i.e. balanced energy storage, reduced power flow losses and minimized operation costs. Power flow management and energy scheduling are usually treated separately [33], [94]. Energy scheduling is issued for longer time range operation, providing optimal setting points for controllable units including DGs, loads and ESSs. Then, by following the optimal setting points, power flow management finds the best routine of power delivery with consideration of stochastic events as well. In certain cases, energy scheduling is not necessary, since power management is developed to guarantee a continuous operation by properly coordinating the generation and storage. Furthermore, in order to adapt to the distributed fashion of power generation, distributed optimization and management methods are becoming popular, a general review is also given in this section.

A. *Power Flow Analysis and Control*

Although an MG system is usually of smaller size than conventional power grids, power flow issues exist when generation sites and consumers are dispersed. *Newton-Raphson* method and its extended versions are still widely used and demonstrated effective for either pure DC network or hybrid DC/AC systems [95]–[97]. Featured power flow analysis can be found in HVDC systems, where the DC grid is created by voltage-sourced-converters formulating a multi-terminal DC transmission system. Power in the DC system is calculated and controlled according to terminal voltages and AC side power injections. Similar method can be applied to DC MG systems, while researchers have made adaptations according to specialized type of DG control methods, such as virtual impedance/droop control as shown in Fig. 11, in order to improve the calculation accuracy [98], [99].

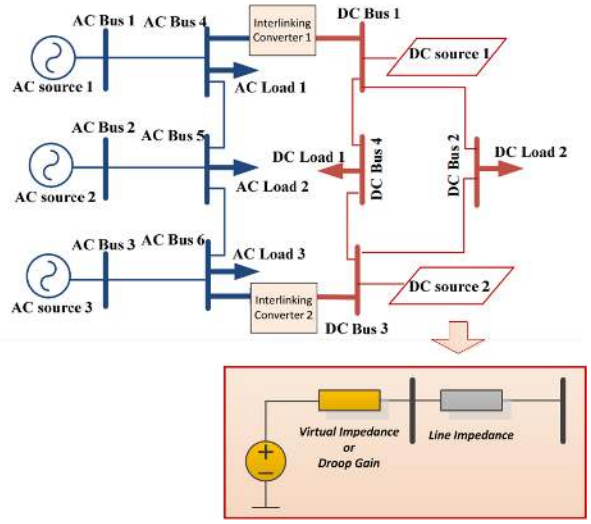


Fig. 11. Power flow analysis considering virtual impedance/droop gain in DC.

Also, power flow analysis is considered a necessary step for the design and planning of an MG system in order to facilitate power flow control and protection purposes. It even becomes critical when we consider applications in vehicles, such as shipboard and aircraft power systems. A power flow study is conducted in [100] aiming to compare two typical ways of generation system arrangement in ship power system, Unit-connected or Group-connected. The results indicate a better system voltage performance and power delivery in the unit-connected case, since the generators are sort of distributed with independent voltage regulation scheme and power delivery routine. Although it was not mentioned, another advantage of unit-connected scheme is that the system is naturally much easier for protection and more robust to failures, since the separated generator units and power delivery routines are mutual backups. In [101], the power flow analysis is applied for security assessment in a MVDC shipboard power system considering the power line capacity limit. Based on the analysis, critical power lines under certain loading conditions are identified, providing necessary guidelines for system operator to avoid failure or damage. Furthermore, the power flow analysis also assists the application of optimization algorithms, realizing power loss minimization [78], [102], [103] or energized loads maximization [104].

Although power flow analysis provides essential knowledge for system operator to ensure safe operation, the calculation usually requires collection of global information and extensive computation. Accordingly, some autonomous power management strategies are proposed based on the energy balance between energy storage systems. The power flow between energy resources can be regulated according to the state-of-charge conditions either by varying the voltage control references [60] or by adaptive droop methods [105].

B. Power and Energy Management

As off-grid operation capability is usually desired for MGs, the pre-store of energy and a well scheduled utilization of different energy resources are necessary. The power and energy scheduling is inherently an optimization based decision-making process considering a rough prediction of future conditions, e.g. weather, energy availability, and consumption levels. Taking inspiration from conventional power systems, a multi-level management is usually adopted with Unit Commitment (UC) and Economic Dispatch (ED) function differentiated [22], [29], [32], [35], [106]–[110] as shown in Fig. 12. According to the time scale of the management cycle, UC provides day-ahead solutions based on 24-hour generation and consumption forecasting aiming to find the most cost-effective combination of generating units to meet forecasted load and reserve requirements. This commitment schedule takes into account the inter-temporal parameters of each generator (minimum run time, minimum down time, notification time, etc.) but does not specify production levels, which are determined a few minutes before delivery by the ED function. The solution of ED problem is actually the cost-minimized usage of the committed assets during a single period to meet the demand, while adhering to generator and transmission constraints.

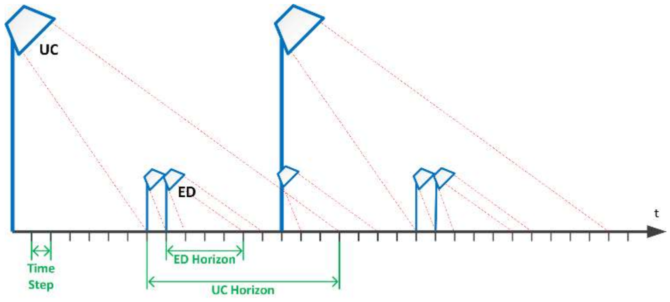


Fig. 12. Unit commitment and economic dispatch.

DC MGs, advantageous with nature interface to renewable energy and storage systems, are attracting research efforts for their future application in efficient buildings and homes [111]–[115]. A scheduling and coordination between RES, ESS and EV charging in an efficient building is presented in [111], where the optimal solution is essentially to find the proper time for absorbing grid power and charging EVs in order to minimize the operation cost. Similarly, a tariff driven gain scheduling approach is shown in [114], where the droop gain is regulated to modify the generation level according to time-of-use electricity tariff. Taking into consideration of battery lifecycle, a multi-objective optimization problem is formulated in [116] aiming to find a balance between battery usage and grid electricity purchasing. An online adaptive EV charging scheduling method is proposed in [117] in order to coordinate the charging operation and avoid detrimental impact caused by peak demand.

In case of vehicle application, DC MGs also easily find their suitability especially in More/All Electric Aircraft/Ship power systems. Strict system operation requirements and special types of loads ask for the seamless coordination between energy storage and generation. A fine schedule of power generation and an optimized storage utilization is critical for the mission success and voyage safety. Applications of multi-agent system [104], fuzzy logic [118], and model predictive control [119], [120] have been found in those systems for scheduling and management purposes. In [104], a reduced order agent is formulated to model a zonal area with controllable loads, and an optimization problem is formulated to maximize the load energization in all agent areas. In [118], an energy management approach based on fuzzy logic is utilized to achieve multi-objective management aiming to maintain voltage stability, enhance efficiency and ensure storage availability in an all-electric-aircraft. Model predictive control, which has been widely applied in process management, also has promising applications in DC systems with clearly defined objectives, such as dynamic power balance and sharing between energy resources [119] and power flow regulation of single generation devices [120].

C. Distributed Optimization and Scheduling

Recent years consensus algorithms have been extensively studied and applied for secondary functions, such as voltage/frequency regulation and current sharing control, while the applications to tertiary optimization and scheduling are relative limited because of higher complexity and larger amount of information needed for those purposes. However, some research works are carried out to solve this issue either with proper formulation of optimization problem or by using modified version of parallel computing algorithms [121]–[125]. A generalized issue in DC power conversion system is presented in [49], where the efficiency of paralleled converter system can be enhanced by using proper number of converters and keep their efficiency at optimal point. Dynamic consensus algorithm is used for essential global information sharing in order to assist the optimization. Similarly, a consensus algorithm based distributed management approach is proposed in [125], a cost minimization optimization problem is formulated and implemented in a multi-agent scheme realizing a fully distributed control over the system. The generalized scheme is shown in Fig. 13, in which the upper level consists of four modules: *initialization and measurement module* provides start-up/updated local information, *communication module* exchanges essential global information with neighbors, *objective function discovery module* finds the objective function value, and finally the *local information update module* sends the optimal solution to control level. In [121], a game theory based distributed energy management strategy is proposed for a DC home application, where MG management system acts as the leaders deciding a minimum generation level to maximize the profit, and on the other hand the consumers act as the followers making local decisions about consumption level.

In general, the control and management structures found in above applications, as that was shown in Fig. 13, can be summarized by the agent based hierarchical control structure proposed in Section III. Through the above examples, it is obvious that the distributed management and scheduling are also essentially consensus problems demanding an iterative calculation process. While the system flexibility is largely improved, information security issue is another practical challenge.

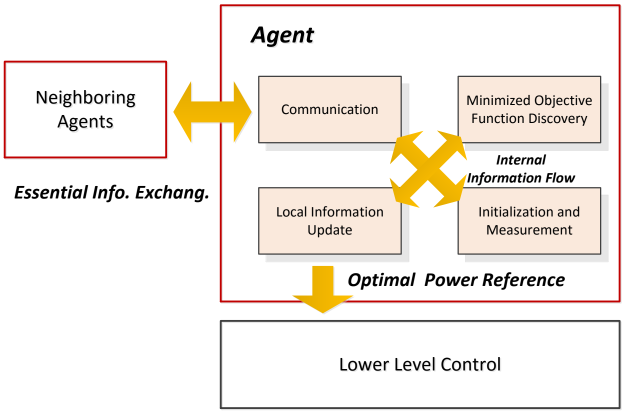


Fig. 13. Agent based distributed optimization example structure.

VI. COORDINATED CONTROL FOR DC MICROGRIDS

Considering the drawbacks of conventional droop control methods, coordinated control among different units in DC MGs are necessary to maintain system stability, enhance power quality and achieve some additional control functionalities. In order to avoid single point failure, distributed control methods with complementary communication network are preferred for these coordinated control algorithms.

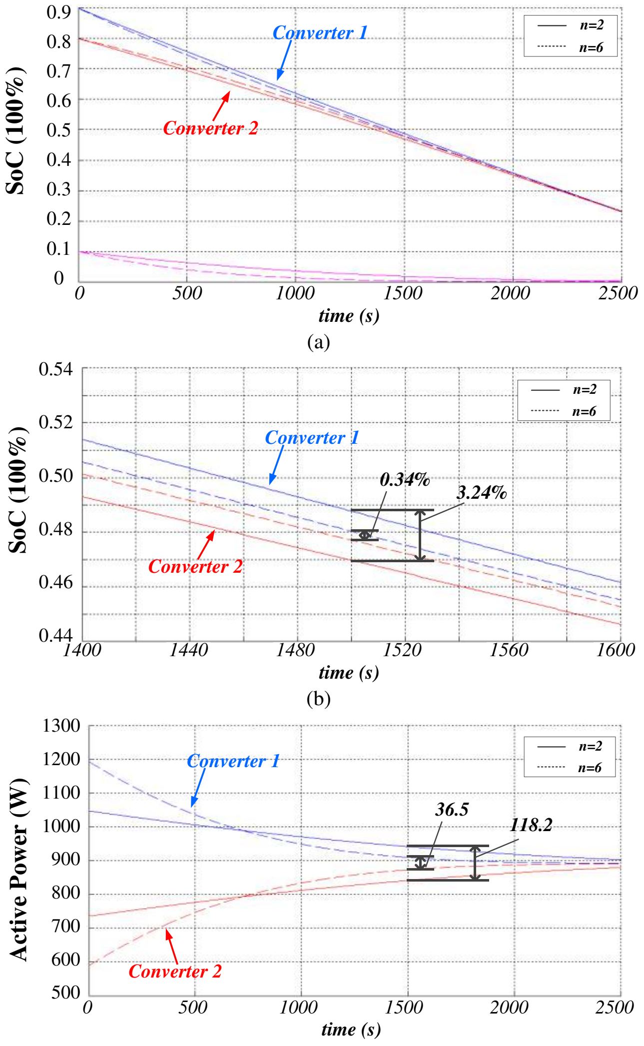
A. State-of-Charge Equalization Strategies

ESSs are frequently used in DC MGs to mitigate the intermittence of DERs and load variations. An optimal operation mode for distributed ESSs is that their state-of-charge (SoC) can be balanced in both charging and discharging process automatically. In the meantime, the injected or output power can be equalized accordingly. Hence, a coordinated operation among multiple distributed ESSs can be achieved. In [64] and [126], the above coordinated operation is realized by modifying the droop coefficients. In particular, in charging process, the droop coefficient is set to be proportional to the nth order of SoC, while in discharging process, it is set to be inversely proportional to the nth order of SoC, as shown below:

$$\begin{cases} v_{\mathrm{dc}i}^{*} = v_{\mathrm{dc}}^{*} - m_0 SoC_{\mathrm{i}}^{\mathrm{n}} \cdot p_{\mathrm{oi}} & \text{(charing)} \\ v_{\mathrm{dc}i}^{*} = v_{\mathrm{dc}}^{*} - \dfrac{m_0}{SoC_{\mathrm{i}}^{\mathrm{n}}} \cdot p_{\mathrm{oi}} & \text{(discharging)} \end{cases} \tag{7}$$

where SoC_{i} is the SoC of ESS #i, n is the order of SoC, m_0 is the initial droop coefficient when SoC equals 100%, p_{oi} is the output power of converter #i.

By using the above method, the SoC balancing and injected/output power equalization can be achieved automatically in both charging and discharging process, as illustrated in Fig. 14.



(a)

(b)

(c)

Fig. 14. SoC balancing and power equalization using the SoC-based droop control method. (a) SoC balancing results (original size); (b) zoom-in result of the square area in (a); (c) output power equalization results.

B. Frequency Coordinated Virtual Impedances

As shown in (7), when output current is selected as the feedback variable, the droop coefficient can be used as a virtual resistance. Meanwhile, this virtual resistance can be used to implement some additional functionalities. This is a flexible way for DC MG to involve an additional degree of freedom into its control scheme. However, it should be noted that the virtual resistance in (7) is only implemented as a DC term. The concept of virtual impedance in DC MGs can be further expanded in a wider frequency range. In [127], a frequency coordinated virtual impedance is proposed to achieve autonomous operation of DC MGs. Especially for hybrid ESSs, by manipulating and reshaping the virtual impedances in different frequency ranges, the autonomous operation of battery and super-capacitor can be achieved simultaneously.

C. Combined Voltage-Shifting and Slope-Adjusting Strategy

Although load power sharing can be achieve by using conventional droop control method, there are still two drawbacks that need to be noticed [71]. First, since conventional droop control is realized based on adjustable voltage deviation, the power quality of DC bus voltage is influenced to some extent. Second, when considering line impedance in DC MGs, the DC voltage at each DG terminal cannot be exactly the same. The voltage across line impedance impacts the DC bus voltage. Furthermore, it degrades load power sharing accuracy.

In order to cope with the above two drawbacks of conventional droop control, several approaches are proposed to eliminate the voltage deviation and enhance current sharing accuracy. In [14], a centralized secondary control method is proposed to restore the PCC voltage, while in [71] and [56], the DC voltage deviation at each DG terminal is eliminated by controlling the average voltage. In the meantime, current sharing accuracy is enhanced by involving an additional compensating term generated by average output current control. In [51], [52], [74], besides the voltage compensating terms that are used to restore DC voltage and improve load current sharing accuracy, the droop coefficient is also dynamically adjusted to regulate the output impedance of each DG converter. Hence, the dynamic sharing performance can be further enhanced.

VII. PLUG AND PLAY OPERATION IN DC MGS

In recent years, the words "Plug and Play" (PnP) have become increasingly popular in the context of MGs. Borrowed from Communication and Computer Science, PnP refers to the possibility of adding or removing DGs with minimal effort or human intervention. PnP is therefore related to the concept of flexible MG structures that can be adapted over time in a seamless way. Often, it also implies a degree of modularity in the interconnection of MG components. These features, have motivated the study of MGs since their early days [128] and are still central in the area of agile power systems [129]. However, PnP has been used in various publications with very different meanings. Next, we review the main contributions on PnP in the field of DC MGs.

In some works, PnP refers to hardware design with the goal of reducing integration costs when new DGs are added or removed. As an example, [130], describes the design of DC/DC converters that synchronize automatically when added to an MG. In the large majority of papers, however, PnP is related to features of the control system. More precisely, it conveys the idea that the control layers of the MG can be updated easily, in order to accommodate for the addition and removal of DGs. Features of PnP control schemes can be classified according to the following criteria:

- *The control layer.* As shown in the previous Sections, controllers of DC MGs are usually structured into hierarchies. PnP operations can concern a specific layer (e.g. primary, secondary, tertiary) or more layers simultaneously.
- *The MG topology.* Some PnP controllers are tailored to specific structures of the electrical graph. For instance, MGs with a bus-connected topology are often assumed. So far, only few approaches have been developed for MGs with more general, meshed topology.
- *Centralized vs. decentralized/distributed control.* As described in Section II, these architectures differ for the presence of a unique controller (centralized schemes) or a local controller for each DG (decentralized/distributed). In order to ease the addition/removal of DGs, PnP approaches often assume decentralized controllers. However, for achieving advanced behaviors, such as current sharing, distributed architectures have been considered. In this case, in order to avoid burdensome communication that might spoil scalability of the MG, it is implicitly assumed that the communication graph is sparse.
- *Centralized vs. scalable control design.* In some approaches, the off-line design phase requires to use a model of the whole MG. In these cases, control synthesis is centralized [16] and the main problem is that design complexity can increase tremendously with the MG size. Furthermore, even if decentralized or distributed controllers are used, the addition/removal of DGs requires to update all local controllers. In order to overcome these issues, one must add constraints on the information flow in the design phase. For instance, on might require that the synthesis of a local controller can be based on a model of the corresponding DG only or, at most, on the model of its neighbors, i.e. DGs directly connected through power lines. When the complexity of local control synthesis is independent of the number of DGs in the MG, the design becomes scalable [16].

Primary controllers with PnP features have been proposed in [131]–[134]. These papers focus on decentralized architectures where local controllers act on converters interfacing individual DGs. The goals of control design are to guarantee voltage stability in the MG and suitable levels of performance (e.g. fast enough compensation of load steps). In [131], the authors study DC MGs connected with constant power loads and provide local controllers that are implemented through passive circuits connected to the inverter terminals. PnP means that voltage stability is guaranteed irrespectively of parameters of electrical lines. However, no explicit design procedure is provided for MGs with more than two converters. In [133] the authors consider MGs composed by elementary DGs given by the parallel combination of a fuel cell, a photovoltaic system and a supercapacitor. The primary controller of each DG is obtained by combining a voltage controller with a virtual impedance using a dynamic droop gain. As in [131], PnP denotes robustness of stability against uncertainty affecting the MG parameters. Stability analysis is conducted using a specific MG with 4 DGs and a meshed topology. In particular, control design is centralized, as it is based on the characteristic polynomial of the linear time-invariant closed-loop MG model.

Primary control schemes for MGs with more general topologies are presented in [134]. More precisely, [134] considers load-connected MGs, meaning that loads are connected only to the output terminal of inverters. This is however a mild restriction because arbitrary interconnections of DGs and load nodes can be always mapped into load-connected MGs through Kron reduction [135], [136]. In [134], PnP refers to a scalable control synthesis method where (i) local optimization is used for testing whether the addition of a DG will spoil voltage stability of the overall MG; (ii) when a DG is plugged in or out, at most neighboring DGs have to update their controllers and (iii) the synthesis of a local controller uses only models of the DG and lines connected to it. The synthesis procedure is illustrated in Fig. 15. Recently, in [137] the method has been extended to avoid the use of power line parameters, hence improving robustness of the controllers. For general linear systems, control design procedures with similar features have been proposed in [138], [139] (see also [140], [141] for related approaches).

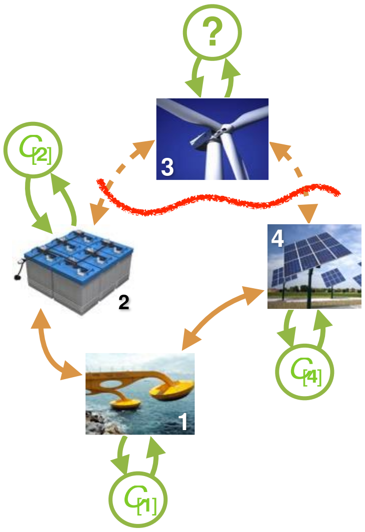


Fig. 15. Example of the PnP design method in [134] for an MG composed by DGs 1,2 and 4 connected by electric lines (orange arrows). DG 3 issues a plug-in request to its future neighbours (DGs 2 and 4). A plug-in test is executed and, if passed, new stability-preserving controllers are designed for DGs 2, 3, and 4.

Design procedures for decentralized primary controllers have been also proposed for HVDC systems. In particular, the approach in [142] guarantees stability after the plug-in and out of DGs in a bus-connected topology, even though the word PnP is not explicitly used.

Secondary controllers allowing for PnP operations have been analyzed in [88]–[90], [132], [143], [144]. As reviewed in Section IV, one goal of secondary control is to compensate for deviations of voltages from reference values, which might be caused by primary controllers, and to achieve advanced behaviors such as current sharing and voltage balancing. To this aim, distributed control architectures based on consensus algorithms are often used.

Consensus algorithms were originally proposed for achieving desired emergent behaviors in physically decoupled multi-agent systems, independently of the number of agents and under very mild assumption on the topology of the communication network among agents [46], [47]. Therefore, the design of consensus-based controllers is expected to be scalable and to lend himself to PnP operations. However, in the context of MGs, consensus algorithms are coupled with primary-level controllers and stability of the overall closed-loop system cannot be given for granted.

In [143], [144] bus-connected MGs with ideal power lines are considered. The topology of the communication network linking DGs can be general, albeit connected. Current sharing is realized through a secondary-level consensus scheme that allows for PnP operations, in the sense that DGs can be plugged-in or out without disrupting system operation. Stability of the closed-loop MG is analyzed in [143] even in presence of communication delays and finite bandwidth of channels. This is achieved using the characteristic closed-loop polynomial of the whole system. However, the design of local regulators, based on this criterion, must be conducted in a centralized fashion. The design procedure in [144] suffers from a similar drawback. Bus-connected MGs are also considered in [89], with the goal of analyzing the impact of the network topology and communication non-idealities (e.g time discretization) on performance. In particular, a simulation study shows that parameters of secondary controllers, as well as the communication rate, might destabilize the system, if not carefully chosen. However, when the secondary layer is properly tuned, the control scheme realizes a PnP function, in the sense that it is robust to changes in the topology of the communication network. Secondary consensus-based controllers for MGs with more general topologies are presented in [88]. They are coupled with primary-level adaptive droop regulators accounting for battery state of charge. Stability however, is analyzed only for specific MGs using the root locus or through simulations.

Systematic methods for the scalable design of secondary controllers in MGs with general topologies are proposed in [132] and [90]. In [132], the authors present primary droop regulators tightly coupled with secondary consensus filters for guaranteeing voltage stability and current sharing. Stability of the overall MG is rigorously shown under the assumption that inner voltage and current loops can be treated as unitary gains. For this approximation to hold, the interconnection of DGs, equipped with inner loops only, must be asymptotically stable.

Voltage stability can be guaranteed using the primary controllers in [134]. This observation motivated research on how to couple them with a consensus-based secondary layer [90]. The consensus-on-current scheme in [90] is accompanied with a proof that, when a DG enters or leaves the MG, current sharing and voltage balancing are preserved by updating secondary controllers of the DG and of its neighbors in the communication network.

In the tertiary level of the control hierarchy, contributions on PnP methods are much more scarce. In general, different DGs, such as PV panels or batteries, can work in different modes of operation, each characterized by a different local controller. For instance, batteries can be in charging mode or contribute to regulation of voltages in the MG. The tertiary layer performs unit commitment and decides the operation mode of different DGs, ensuring that there are always sufficient DGs to meet the consumption demands and guarantee voltage stability. In [145], PnP denotes the possibility guaranteeing this behavior through communication in bus-connected MGs. Furthermore, an experimental validation of the proposed protocol is provided. A more general tertiary layer, accounting for heterogeneous DGs, is studied in [146]. Although computation of the discrete control actions is centralized, in [146] PnP refers to the fact that the supervisor can be easily updated when DGs are plugged in or out.

VIII. ACTIVE DAMPING IN DC MGS

Electric loads in conventional distribution system can be regarded as a combination of power loads, current loads and impedance loads. For current and impedance loads, they normally do not induce stability degradation. However, power loads, also known as constant power loads (CPLs), refer to the loads which consume constant amount of power regardless of their input voltage. The CPLs degrade system stability due to their negative incremental impedance. The effect of CPL can be expressed as:

$$\frac{\partial v_{\mathrm{o}}}{\partial i_{\mathrm{o}}}\bigg|_{(V_{\mathrm{o}},I_{\mathrm{o}})} = \frac{\partial}{\partial i_{\mathrm{o}}}\left(\frac{P_{\mathrm{o}}}{i_{\mathrm{o}}}\right)\bigg|_{(V_{\mathrm{o}},I_{\mathrm{o}})} = -\frac{P_{\mathrm{o}}}{I_{\mathrm{o}}^{2}} \tag{8}$$

where v_{o} and i_{o} are the instantaneous load voltage and current, respectively, and P_{o}, V_{o} and I_{o} are the steady-state load power, voltage and current at a given operating point. Based on the derivation in (8), it is observed that the incremental impedance is negative, which degrades the system damping and may impose stability issues. In DC MG, the most typical CPLs are the loads interfaced through tightly regulated power converters, e.g., electronic devices and electric drives, as shown in Fig. 16.

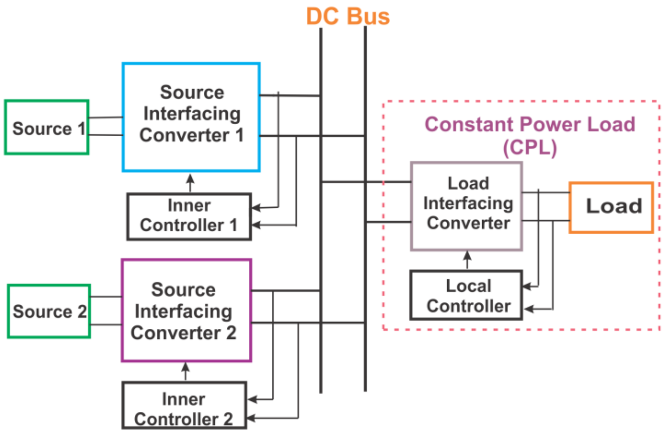


Fig. 16. DC MG with constant power load

The instability due to input filters of the closed-loop converters was first experienced in 1970's [147]. To overcome the stability problems (power oscillation) caused by the CPLs, passive methods have conventionally been introduced [148]–[150]. However, such methods may introduce power losses and reduce the efficiency [151]. Due to the aforementioned limitations of the passive damping methods, feedback control based methods have been proposed. These methods, also known as active power damping methods, offer enhanced efficiency. The instability due to the CPLs inclusion is inherently a nonlinear phenomenon, and therefore a few solutions employ nonlinear control techniques to overcome such instability problems [152]–[154]. In 1998, Ciezki and Ashton have introduced a nonlinear control law for a DC/DC buck converter to ensure the asymptotic stability and to eliminate the nonlinearity imposed by the CPL using a pseudo-linearization technique [152]. However, the proposed feedback linearization method works properly for a limited range of CPLs, i.e., it provides the local stability.

Kondratiev et al. have used the synergic control theory to stabilize parallel connection of some DC/DC buck converters supplying resistive loads [153]. A general nonlinear synergic PI controller is applied to the average model of the converter. The simulation results demonstrate that the constant disturbances are suppressed, the errors of the current sharing among parallel converters are eliminated, and exponential asymptotic stability is ensured. However, the paper lacks a detailed analysis for CPLs and input filters.

The large-signal dynamics and control of a buck converter supplying a downstream DC–DC converter have been studied in [154]. The proposed controller includes an instantaneous current feedback loop which employs a hysteresis control augmented with a PI controller to adjust the output voltage of the converter. The large signal averaged model of the DC/DC buck converter is used to verify its robust stability around the operation point.

In [155], the authors address the instability issue using a nonlinear feedback loop referred to as the loop cancellation. The proposed method can theoretically compensate for any amount of CPL and can be implemented on different types of converters. The CPL is modeled by an internal loop whose impact can be removed by introducing an outer loop to the open-loop converter. This stabilizing controller moves the poles of the open-loop system to the stability region. Then, a servomechanism feedback controller is designed for the stabilized converter. The paper requires a robust stability analysis to show its robust performance with respect to the unknown CPLs.

In [156], the authors propose three structurally simple active damping methods based on linear feedback loops to stabilize the voltage source converter (VSC) interfacing a DC MG to an external ac system. The active damping methods inject a signal, referred to as internal-model active damping signal, to adjust the VSC impedance. The damping signal can be applied either to the outer, the intermediate or the inner control loops of the interface VSC. The outer and the intermediate loop compensators provide the system with more damping factor. However, the inner loop compensator offers a better voltage control performance while its damping factor is not as high as the other two loop compensators. The main drawback of the proposed methods is that they only guarantee the stability for a small neighborhood of the operating points.

The stability analysis of cascade converters with CPLs in current controlled mode has been discussed in [157]. The stability about the equilibrium point is investigated using the Lyapunov linearization method (indirect method). A small-signal criterion is proposed and using the mixed potential theory, the region of attraction for the equilibrium point is estimated. A general stability criterion in terms of system parameters is finally proposed which can be used to design the controller. The main drawback is the conservativeness of the proposed criterion.

In [158], the authors have introduced self-disciplined stabilization concept using passivity control. The stabilization technique ensures the stability of the overall DC MG provided that each individual converter satisfies the proposed stability discipline. In fact, the design process is carried out individually for each converter, and there is no need to derive the entire MG model. This provides robustness against any change in the structure of the overall MG system. To improve the stability margin of the proposed self-disciplined criterion, a passivity criterion with more restrictive phase condition is proposed. The passivity margin criterion presents explicit phase margins and overcomes the transient oscillations. To improve the passivity of the converter, a control algorithm is introduced which is implemented through a voltage feedforward control.

The authors of [159] propose two active compensation methods for Line Regulating Converter (LRC) in a DC MG with high penetration of power electronic converters. The MG is modeled by a simplified transfer function. The transfer function is then used to design two different control systems using Compensation Transfer Function and Codesign methods. In the first method, the controller transfer function is shaped such that the adverse effect of the CPLs is eliminated. The CPL often imposes some limitations when the network input impedance is non-minimum phase. In the Codesign method, the LRC controller is designed considering DC MG properties. Both methods have been experimentally implemented and tested.

In [160], a fault tolerant multi-agents stabilization system (MASS) is implemented to ensure the stability of the DC MG. The main advantage of the proposed method is that it guarantees the robust stability even when a converter is suddenly shut down (loss of operation) or in case that the MG system is subject to reconfiguration or development. In the proposed MASS approach, to attenuate the impact of the CPLs on the system stability, the CPL set-points are modified during fluctuations of the power. In order to optimize the effect of each stabilizing agent on the system stability, an objective function is defined which results in design of the agent itself.

In many active damping methods, a stabilizing current component is injected into the CPLs to achieve an input impedance with stable characteristic. However, the injected current component may result in undesired performance of the loads, e.g., the fluctuation in rotating speed of tightly regulated motors. In order to avoid such shortcoming, a method that stabilizes the system from source-side converters rather than the CPLs side has been proposed in [161]. A virtual resistance is built in the source-side converter which is operational around the resonant frequency of the LC input filter and thus can ultimately reduce its output impedance to satisfy Middlebrook's stability criterion [147]. In the proposed method, to preserve system stability, the resonant frequencies of different LC filters of parallel CPLs must differ from each other.

The virtual-impedance based stabilizers are used to improve damping in DC MGs with CPLs, and guarantee the stable operation [162]. The virtual impedances are incorporated in the output filters of the interface converters in the second stage of a multistage configuration. One of the virtual impedances is connected in series with the capacitive filter, and the other one is connected to the output of the converter. The unstable poles due to the CPLs are then moved to the left-half s-plane resulting in a closed-loop stable system. Introduction of virtual resistance in droop control also improves CPL stabilization; this interesting link is recently established in [105].

A control strategy for damping of power oscillations in a multi-source DC MG with a hybrid power conversion system (HPCS) is proposed in [133]. The HPCS controller includes a multi-loop voltage controller and a virtual impedance loop for stabilizing the system. The virtual inductive impedance loop, whose gain is determined using small-signal analysis and pole placement method, applies a dynamic droop gain to damp the low-frequency oscillations of the power management control unit. The robust stability analysis shows that the closed-loop system is robust against uncertainties imposed by MG parameters. The authors have verified the performance of the proposed method using hardware-in-the-loop (HIL) tests carried out in OPAL-RT technologies.

The CPL has inherent nonlinear characteristic and therefore it is necessary to establish the overall stability of DC MG in presence of such loads [193]–[196]. The problem is further aggravated by the interaction among different subsystems and the uncertainties associated with renewable power sources (if present). Therefore, the overall system stability cannot be guaranteed, even if the individual subsystems are stable. There have been several tools proposed by the researchers to assess the stability in such situations [164], [167], [168]. CPL may also cause total voltage collapse. Some researchers have proposed the use of LC input filter to stabilize CPL [169]. Authors in [170] have used feedback linearization technique for DC/DC buck converter loaded with a pure CPL to obtain its linear model. Furthermore, a reduced order observer is used to estimate the CPL power and its derivative, and to ensure the accuracy of linearization in entire operating range, i.e., to improve the transient performance. A full-order state feedback controller is proposed for the feedback linearized converter model. In [171] a technique referred to as Synergetic Control, similar to Sliding Mode Control, is proposed. The technique requires selection of desired dynamics and a control law to ensure that desired dynamics is reached. Passivity based technique to mitigate destabilizing effect of CPL is proposed in [172], [173]. This technique works on principle of energy conservation i.e. energy supplied is equal to sum of energy stored and energy dissipated. The passivity based controller modifies energy dissipation function though introduction of virtual impedance matrix. A coupling based technique or amplitude death is coupling induced stabilization of the equilibrium points of an unstable system. The sufficient strength of coupling and different natural frequencies of the systems being coupled, are the two requirements for stabilization through amplitude death. The technique originally belongs to nonlinear dynamical systems and has recently been applied for open-loop stabilization of the DC/DC converters in a DC MG in the presence of CPLs. In reference [163], authors have proposed a heterogeneous and time-delay coupling to stabilize a DC/DC Buck converter supplying a CPL. Sliding mode control approach is also proposed to ensure robust stabilization of DC MGs in presence of CPL [174].

IX. CONTROL ALGORITHMS FOR ISLANDING DETECTION AND PROTECTION IN DC MGS

A. Islanding Detection

Islanding is a condition in which one or more DG units and their dedicated loads, usually at a distribution voltage level, are disconnected from the utility system and remain operational. Accidental formation of an island, e.g. due to a fault, may result in a number of issues [175], [176], e.g. protection and safety aspects. Thus, under the current standards, accidental islanding is not permitted and upon islanding detection, the DG units are required to be disconnected and shut down. Such a process is also known as anti-islanding [177]. If autonomous operation of an island is permitted [178], [179], fast islanding detection is required for appropriate decision making to manage autonomous operation of the island. Thus, in either case, islanding detection is a requirement for utilization of DG units. There have been several methods developed and tested for islanding detection of DG units interfaced to the AC networks [179]–[188]. In AC MGs, any measured abnormalities in the voltage, frequency, or phase-angle of the PCC voltage can be used for detection of islanding, whereas in DC MGs, voltage is the only parameter that can be employed for islanding event detection. This makes the islanding detection in DC MGs more challenging.

Very few islanding detection methods have been proposed for DG units within the context of DC MGs [189], [190] and there still remain so much room to research on this subject. The proposed algorithm of [189], [190] injects a disturbance current through the PV converter to create an abnormality in the DC link voltage upon the islanding event. The proposed method combines a passive and an active algorithm to minimize its Non-Detection Zone (NDZ). The PV converter is modeled by a current source with a capacitive output, and the load is modeled by an equivalent resistance. In this case, the DC link is considered as an ideal voltage source. The injected disturbance current is a periodic pulse whose duty cycle is determined according to the DC link voltage ripples and the speed of detection. In the grid-connected mode, the DC link voltage is not perturbed since the voltage controller is in service. However, in the islanded mode, the DC link voltage control is lost and the DC voltage deviates from its nominal value. If the voltage drift exceeds a certain threshold, the algorithm increases the amount of the disturbance current which can be considered as a positive feedback loop. The positive feedback accelerates the voltage drift and thus, the islanding event is quickly detected. The authors have verified the performance of the proposed method by both using simulations and experiments. The results show that the islanding event is detected in less than 0.2 seconds. The authors have shown that their proposed method does not degrade the power quality of the overall system, and the MPPT efficiency has not significantly been affected.

B. Protection of DC MGs

Different from AC systems, since DC current does not have zero crossing point, it is more difficult to be extinguished, especially under fault conditions. In order to effectively protect DC MGs, some approaches are proposed in the existing literature. In [191], the conventional AC circuit breakers and fast DC switches are coordinated to cut off DC fault current. Particularly, since most of DC systems are interconnected with the external AC system by using AC-DC rectifiers, the AC circuit breakers at the AC sides of these rectifiers are used in the protection scheme of DC system. In [192], a ring-bus power architecture is proposed to enhance the reliability of DC MGs. Rather than integrating the DERs and loads using a radial configuration, in this ring-bus architecture, the DG terminals are connected to a circular common bus via intelligent electronic devices (IEDs). Since circular configuration is used, the DG output power can flow in two directions. Meanwhile, the IEDs are used as smart switches to detect and isolate the fault. Hence, the protection scheme for DC MGs can be enhanced. In [193], differential protection is used to achieve high-speed fault isolation. Compared to conventional protection schemes mainly based on over-current detection, the proposed differential protection scheme can significantly reduce the fault detection time.

It should be noted that for the protection schemes of DC MGs, a common issue is the malfunction of conventional protective devices. This is usually induced by relatively low fault current contributed by DER interface converters, and it is a similar problem also met in AC MGs. In order to tackle the obstacle of limited fault current contribution of converter interfaced DERs, the relay settings can be updated according to the present operation mode of DC MG. In particular, during grid-connected operation, the DC MG is interconnected to the external AC grid. Since larger fault current can be contributed by the AC grid, higher level fault current thresholds can be used in the protective relays. However, during islanded operation, when a fault occurs, the fault current is solely contributed by the DERs. Hence, the settings of the protective relays should be updated with smaller fault current thresholds.

X. MULTIPLE DC MICROGRID CLUSTERS

In the islanded mode of operation, MGs, especially the ones highly dependent on renewable resources, may fail to support their individual loads, and become unstable in the face of large sudden load/generation changes. Interconnection of MGs has been recognized as a solution, in the literature [14], [194], and real applications [195], to enhance reliability, stability, supply security, and resiliency to disturbance.

MGs can be connected to each other and form a cluster. A MG cluster, as shown in Fig. 17, refers to a group of MGs, in a close vicinity, physically interconnected via DC (or AC) buses. This concept enables maximum utilization of energy sources, improves reliability, and suppresses stress and aging of the components, e.g., power electronic converters, in the MGs. Moreover, it may reduce the maintenance costs, and expand the overall lifespan of the network availability [123]. It should be noted that when the inertia of interconnected MGs is relativity high, this concept may also improve the system stability. In other words, connecting the MGs with low inertia may lead the whole cluster toward instability [194]. Despite all these benefits, economical issues and marketing is still unsolved for the MGs owners. [196].

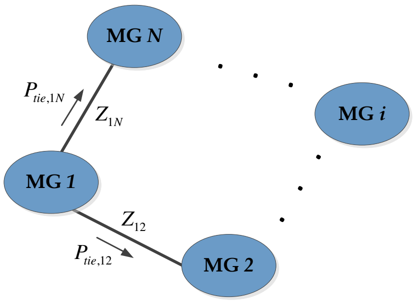


Fig. 17. General structure a MG cluster.

To achieve a higher quality of service, e.g. global voltage regulation, and power flow control, communication-based higher control layers must be applied to these systems. In autonomous mode, each MG has its own control layers to supports its local loads. While connected, the power/current flow among MGs may be controlled to optimize the utilization of their energy sources. It is obvious that power flow control among MGs can be achieved by adjusting their bus voltages. Thus, a trade-off needs to be taken into account between the conflicting goals of voltage regulation and power flow control.

Recently, a few works have been presented in the literature to address challenges in DC MG clusters, e.g., modeling and stability [194], [197], voltage regulation [87], [88], and power management [123], [198]. Small signal modeling and stability issues of DC MG clusters has been addressed in [197], considering impact of different parameters of the system and the loads. A distributed two-level tertiary control system is proposed in [123] to handle load sharing in a cluster of DC MGs. It uses a cooperative approach to adjust voltage set points for individual MGs and, accordingly, manage the power flow among them. Reference [87] introduces a hierarchical control framework to ensure reliable operation of DC MG clusters where distributed policies are employed to provide global voltage regulation and manage the power flow among the MGs according to the capacity of their local energy storage systems. Although some researches have been carried out, controlling such systems still requires more attention.

XI. CONCLUSIONS AND FUTURE TRENDS

This paper provides an extensive review on the control of DC MGs and related issues. The control system structure under a general hierarchical scheme is presented along with the discussion on centralized, distributed and decentralized organizations. The choice of the structure depends on the type and feature of respective applications. Under the paradigm of distributed generation and active consumer participation, distributed schemes are becoming popular since they naturally satisfy the flexible and autonomous operation requirements in both generation side and consumer side. However, control system design, communication, stability and information security will be the main research challenges in this regard.

Concerning hierarchical control, a great number of research works have been published recent years on the different layers from primary to tertiary. Primary control as the basic layer integrates control loops aims at proper voltage, current and power regulation and defines the dynamic performance of the local unit. Secondary and tertiary control provides advanced functionalities such as voltage quality maintenance, current sharing improvement and optimized operation. Based on this well-defined structure, the future efforts are expected to improve the intelligence of the system achieving an actively integrated coordination between generation, storage and consumers.

Plug-and-play capability, from component level to system level, is a critical objective for future energy system. In component level, the converters and DG units need to be able to seamlessly connect and disconnect from a MG. In the system level, similarly, a MG should have the possibility to connect and disconnected with external grid at any time. A proper control design has to guarantee not only the coordination between components and systems, but also maintain the stability of the system.

Furthermore, as CPLs are prevalent in modern electric power systems, the system stability can be largely affected especially in case of small scale islanded MG, such as vehicle applications and MGs in remote areas. Active damping methods and nonlinear control algorithms provide the possibility to alleviate this problem. A global stability will be the main goal in future study since conventional small signal based local stability may not be suitable for MG applications.

Based on the MG concept, the future energy system is expected to be a combination of many MGs formulating a fully flexible and reliable grid. Additional regulation is also necessary in operational levels, which are upon the existing hierarchical control scheme and regulate the interaction between MGs. Control, management and stability in multi-MG systems introduce a number of interesting issues and start to attract more and more researchers.

MG and MG clusters, as the main building block for future energy system, will formulate a loosely but flexibly integrated grid. A well-designed control and management scheme is necessarily the key to this achievement, but still and always calling for more research and development efforts.

XII. REFERENCES

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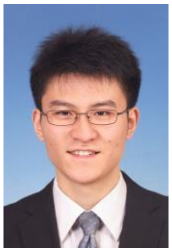
XIII. BIOGRAPHIES



Lexuan Meng (S'13, M'15) received the B.S. degree in Electrical Engineering and M.S. degree in Electrical Machine and Apparatus from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2009 and 2012, respectively. In 2015, he received the Ph.D. degree in Power Electronic Systems from Department of Energy Technology, Aalborg University, Denmark. He is currently a post-doctoral researcher in the same department working on flywheel energy storage and onboard electric power systems.

Qobad Shafiee (S'13–M'15–SM'17) received the B.S. degree in electronics engineering from Razi University, Kermanshah, Iran, in 2004, the M.S. degree in electrical engineering-control from Iran University of Science and Technology, Tehran, Iran, in 2007, and the Ph.D. degree in electrical engineering-microgrids from the Department of Energy Technology, Aalborg University, Aalborg, Denmark, in 2014. He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, I ran, where he was a Lecturer, from 2007 to 2011. He is Vice Program Leader of the Smart/Micro Grids Research Center at University of Kurdistan. He was a Visiting Scholar with the Electrical Engineering Department, University of Texas-Arlington, Arlington, TX, USA, for 3 months, in 2014. He was a Post-Doctoral Fellow with the Department of Energy Technology, Aalborg University, in 2015. His main research interests include modeling, energy management, control of microgrids, and modeling and control of power electronics converters. He has been a Guest Associate Editor of the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS Special Issue on structured dc microgrids. He is a member of PELS, IAS, and PES Societies.

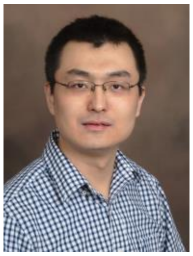
Giancarlo Ferrari-Trecate (SM'12) received the Ph.D. degree in Electronic and Computer Engineering from the Universita' degli Studi di Pavia in 1999. Since September 2016 he is Professor at EPFL, Lausanne, Switzerland. In spring 1998, he was a Visiting Researcher at the Neural Computing Research Group, University of Birmingham, UK. In fall 1998, he joined as a Postdoctoral Fellow the Automatic Control Laboratory, ETH, Zurich, Switzerland. He was appointed Oberassistent at ETH, in 2000. In 2002, he joined INRIA, Rocquencourt, France, as a Research Fellow. From March to October 2005, he worked at the Politecnico di Milano, Italy. From 2005 to August 2016, he has been Associate Professor at the Dipartimento di Ingegneria Industriale e dell'Informazione of the Universita' degli Studi di Pavia. His research interests include decentralised and networked control, plug-and-play control, scalable control of microgrids, modelling and analysis of biochemical networks, hybrid systems and Bayesian learning.

Prof. Ferrari-Trecate was awarded the "assegno di ricerca" Grant from the University of Pavia in 1999 and the Researcher Mobility Grant from the Italian Ministry of Education, University and Research in 2005. He is currently a member of the IFAC Technical Committee on Control Design and he is on the editorial board of Automatica and Nonlinear Analysis: Hybrid Systems.

Houshang Karimi (S'03-M'07-SM'12) received the B.Sc. and M.Sc. degrees from Isfahan University of Technology, Isfahan, Iran, in 1994 and 2000, respectively, and the Ph.D. degree from the University of Toronto, Toronto, ON, Canada, in 2007, all in electrical engineering. He was a Visiting Researcher and a postdoctoral Fellow in the Department of Electrical and Computer Engineering, University of Toronto, from 2001 to 2003 and from 2007 to 2008, respectively. He was with the Department *of* Electrical Engineering, Sharif University of Technology, Tehran, Iran, from 2009 to 2012. From June 2012 to January 2013, he was a

Visiting Researcher in the ePower lab of the Department of Electrical and Computer Engineering, Queens University, Kingston, ON, Canada. He joined the Department of Electrical Engineering, Polytechnique Montreal, QC, Canada, in 2013, where he is currently an Assistant Professor. His research interests include control systems, distributed generations, and microgrid control.

Deepak M. Fulwani is working as an assistant professor in Department of Electrical Engineering at Indian Institute of Technology Jodhpur (IITJ). He also worked at IIT Guwahati and IIT Kharagpur. He obtained his PhD from IIT Bombay in 2009. His research fields include Control of DC micro-grids and network control systems.



Xiaonan Lu (S'11-M'14) received the B.E. and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 2008 and 2013, respectively. From Sep. 2010 to Aug. 2011, he was a guest Ph.D. student at Department of Energy Technology, Aalborg University, Denmark. From Oct. 2013 to Dec. 2014, he was a postdoc researcher in the Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville. In Jan. 2015, he joined the Energy Systems Division, Argonne National Laboratory. He is also a Member of Northwestern-Argonne Institute of Science and Engineering (NAISE).

His research interests include modeling and control of power electronic converters in AC and DC microgrids, hardware-in-the-loop real-time simulation, distribution automation, etc. Dr. Lu received Outstanding Reviewer Award for IEEE Transactions on Power Electronics in 2013, Outstanding Reviewer Award for IEEE Transactions on Smart Grid in 2015, and Outstanding Postdoctoral Performance Award in Argonne National Laboratory in 2016.

Dr. Lu is the Guest Associate Editor of the Special Issue entitled "Structured DC Microgrids" in the IEEE Journal of Emerging and Selected Topics in Power Electronics. He is a member of IEEE Power Electronics Society (PELS), Industry Applications Society (IAS), Power and Energy Society (PES) and Industrial Electronics Society (IES).

Josep M. Guerrero (S'01-M'04-SM'08-FM'15) received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, in 1997, 2000 and 2003, respectively. Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Denmark, where he is responsible for the Microgrid Research Program (www.microgrids.et.aau.dk). From 2012 he is a guest Professor at the Chinese Academy of Science and the Nanjing University of Aeronautics and Astronautics; from 2014 he is chair Professor in Shandong University; from 2015 he is a distinguished guest Professor in Hunan University; and from 2016 he is a visiting professor fellow at Aston University, UK, and a guest Professor at the Nanjing University of Posts and Telecommunications.

His research interests is oriented to different microgrid aspects, including power electronics, distributed energy-storage systems, hierarchical and cooperative control, energy management systems, smart metering and the internet of things for AC/DC microgrid clusters and islanded minigrids; recently specially focused on maritime microgrids for electrical ships, vessels, ferries and seaports. Prof. Guerrero is an Associate Editor for the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and the IEEE Industrial Electronics Magazine, and an Editor for the IEEE TRANSACTIONS on SMART GRID and IEEE TRANSACTIONS on ENERGY CONVERSION. He has been Guest Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS Special Issues: Power Electronics for Wind Energy Conversion and Power Electronics for Microgrids; the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS Special Sections: Uninterruptible Power Supplies systems, Renewable Energy Systems, Distributed Generation and Microgrids, and Industrial Applications and Implementation Issues of the Kalman Filter; the IEEE TRANSACTIONS on SMART GRID Special Issues: Smart DC Distribution Systems and Power Quality in Smart Grids; the IEEE TRANSACTIONS on ENERGY CONVERSION Special Issue on Energy Conversion in Next-generation Electric Ships. He was the chair of the Renewable Energy Systems Technical Committee of the IEEE Industrial Electronics Society. He received the best paper award of the IEEE Transactions on Energy Conversion for the period 2014-2015, and the best paper prize of IEEE-PES in 2015. As well, he received the best paper award of the Journal of Power Electronics in 2016. In 2014, 2015, and 2016 he was awarded by Thomson Reuters as Highly Cited Researcher, and in 2015 he was elevated as IEEE Fellow for his contributions on "distributed power systems and microgrids."