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Primary and secondary control in DC microgrids: a review

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Abstract With the rapid development of power electronics technology, microgrid (MG) concept has been widely accepted in the field of electrical engineering. Due to the advantages of direct current (DC) distribution systems such as reduced losses and easy integration with energy storage resources, DC MGs have drawn increasing attentions nowadays. With the increase of distributed generation, a DC MG consisting of multiple sources is a hot research topic. The challenge in such a multi-source DC MG is to provide voltage support and good power sharing performance. As the control strategy plays an important role in ensuring MG's power quality and efficiency, a comprehensive review of the state-of-art control approaches in DC MGs is necessary. This paper provides an overview of the primary and secondary control methods under the hierarchical control architecture for DC MGs. Specifically, inner loop and droop control approaches in primary control are reviewed. Centralized, distributed, and decentralized approach based secondary control is discussed in details. Key findings and future trends are also presented at last.

Keywords Primary control, Secondary control, DC microgrids, Droop control, Power sharing

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1 Introduction

Modern power networks are complex adaptive systems which have undergone extensive changes over the past two decades. Microgrids (MGs), a novel structure of distribution networks, have emerged as a suitable solution for the installation of distributed sources in the grid [1, 2]. Today electrical systems are dominated by alterative current (AC), however, there is a clear tendency that high voltage (HV) and low voltage (LV), have seen the rise of DC systems and its implementation in power transmission and distribution [3]. The rapid development of power electronics technology has allowed the converters to operate at a wide range of DC voltage levels, including transmission, distribution and consumption level. Compared to AC MGs [3, 4], the advantages of DC MGs can be summarized as follows [5]:

1) Most renewable energy resources, such as photovoltaic (PV) panels and fuel cells produce DC power. Even wind turbines, which intrinsically produce AC power, can be more conveniently integrated into a DC grid due to the absence of more power conversions.
2) There is no need for reactive power management and frequency synchronization.

3) Most of energy storage devices are also DC in nature. The battery technologies that are already provided with an internal DC-DC converter would be easily integrated to a DC bus with reduced cost and increased efficiency.

Given the advantages above, DC MGs have been widely accepted not only for utility grids, but also for more electric transportations, such as more electric aircraft [6], more electric ship [7].

Figure 1 shows the number of publications in the DC microgrid field in recent ten years. It is clearly seen that there is an increasing trend on the DC MGs over the past decade. Under such a context, this paper reviews the control strategies in DC MGs.

Figure 2 shows a typical DC MG configuration with a common DC bus. Multiple sources including solar panels, wind turbines, energy storage system (ESS) are connected to a single DC bus via power electronic converters (PEC). DC loads and AC loads are connected via DC/DC converters and AC/DC converters, respectively. It is worth noting that the DC MG topology may differ from radial single feeder configuration to two-pole or ring configuration.

Control strategies in such a multiple source based DC MG need to solve the following issues: 1) DC bus voltage maintenance; 2) Load sharing among parallel sources; 3) Power quality.

To tackle these issues, hierarchical control is often adopted because it introduces a certain degree of independence between different control levels. It is more reliable as it continues to be operational even in the case of failure of the centralized control. This paper is therefore focused on the review of existing hierarchical control techniques.

A hierarchical control architecture consisting of primary, secondary and tertiary control is illustrated in Fig. 3. Primary control copes with the preliminary power sharing control and current/voltage regulations [8]. Secondary control, a higher level than primary, deals with the voltage compensation and sharing performance enhancement [9].

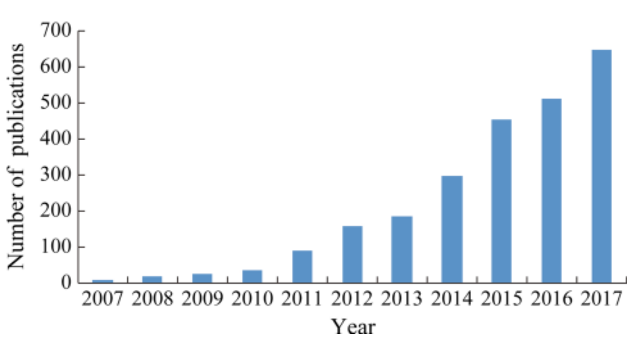
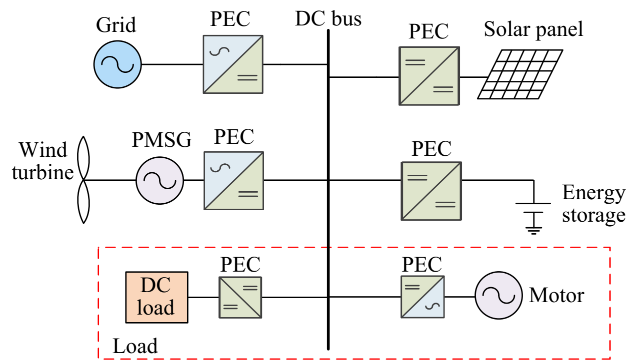


Fig. 1 Number of publications on DC MGs in recent ten years



PMSG: permanent magnetic synchronous generator

Fig. 2 Example of a single bus DC MG

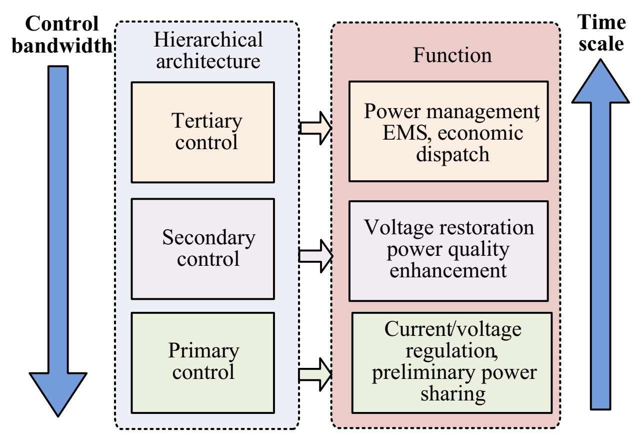


Fig. 3 Hierarchical control architecture

As a highest level in the hierarchical architecture, tertiary control conducts power management [10], energy management [11], system optimization [12] economic dispatch [13, 14, 15]. Hierarchical control is achieved by simultaneously using local converter and digital communication link-based coordinated control, such as novel cloud-based communication platform [16, 17], which are separated by at least an order of magnitude in control bandwidth. From primary control to tertiary control level, control bandwidth decreases while time scale increases.

This paper investigated various techniques applied in the primary and secondary controls as shown in Fig. 4. For each technique, the control principles and relating literatures are reviewed, followed by the detailed discussion in each section.

The rest of this paper is organized as follows: Section 2 presents the state-of-art of the primary control in DC microgrid. Section 3 reviews the existing secondary control approaches which can be grouped into centralized, distributed, and decentralized categories. Section 4 discusses the evolving trends in MGs and finally Section 5 draws the conclusion.

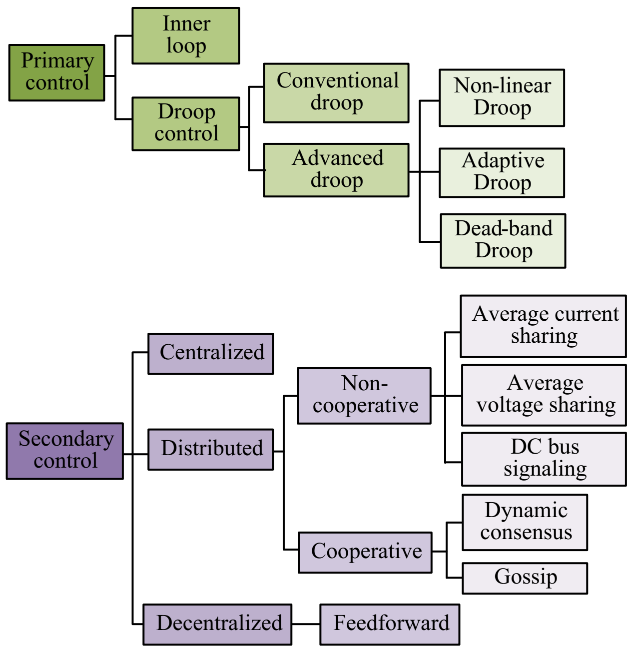


Fig. 4 Schematic overview of the paper

2 Primary control

As one can see in Fig. 2, power electronic converters (including AC/DC converters and DC/DC converters) are essential components in DC MGs to provide controllable interface between loads and sources. From the control perspective in power converters, primary control consists of inner loops (current/voltage regulation) and droop control (preliminary power sharing). This Section shows the state-of-art primary control approaches on three-phase AC/DC converters and DC/DC converters. Section 2.1 discusses the inner loop of the AC/DC and DC/DC converters. Section 2.2 provides an overview of droop control covering the basic concept, conventional droop control applied in DC MGs and its inherent tradeoff, and finally introduces the recent advanced droop control methods.

2.1 Inner loop

2.1.1 AC/DC converter

Taking the three-phase voltage source converter (VSC) as an example, based on the vector control, inner loops regulate the AC current in synchronous rotating frame (*dq* frame), as shown in Fig. 5. After transforming measured currents from three-phase stationary frame to synchronous rotating frame, the linear controllers adjust current in *dq* domain and output *dq* voltage demands. Voltage demands are inversely transformed into three phase modulation indexes for pulse width modulation (PWM). The current

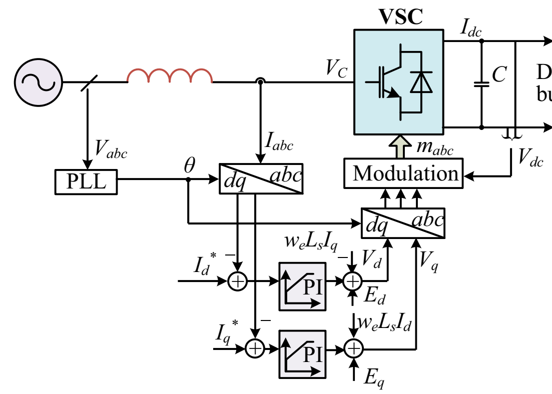


Fig. 5 Inner loop of the three-phase voltage source converter (AC/DC converter)

reference I_d^* and I_q^* are determined by the required active power and reactive power respectively. Therefore, the VSC could control the active and reactive power independently.

2.1.2 DC/DC converter

Types of DC/DC converters [18, 19] may vary but the control can be generalized into two categories: voltage control mode and current control mode (power control mode). The DC/DC converter under voltage control mode sets the voltage reference and operates as a controllable voltage source. Alternatively, the converter under current/power control mode behaves as a controllable current/power source. The output current/power are regulated to follow the given reference. Figure 6a shows a single voltage loop when the converter is working in voltage control mode. The output of the voltage controller G_v is the duty cycle. V_o^{ref} could be given by a *V-I* droop characteristic which will be shown in the next subsection. Figure 6b shows the inner loop when the converter operates in current control mode. The duty cycle is obtained through a current regulator. Current reference I^{ref} could be given by an *I-V* droop characteristic (see next subsection). Figure 6c shows

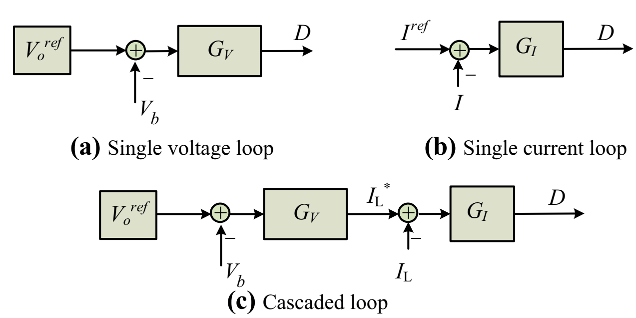


Fig. 6 Inner loops of DC/DC converters

another option of DC/DC converter working in voltage-control mode. A cascaded loop is employed. Given voltage reference, the voltage controller G_v provides the inductor current reference and the switching signals are given by the output of the current controller G_I.

2.2 Droop control

Voltage droop control has been widely accepted since there is no dependency on the communication lines. Usually, “droop control” is realised by adding a “virtual resistance” into the existing system. The “virtual resistance” is an ideal value which will not be affected by its working condition, such as temperature, and no “real” power loss will be produced, whereas the “real resistance” is not a fixed value which could change with the environmental factors and will cause “real” power losses which should be minimised. This virtual resistance is also called droop gain, droop constant or droop coefficient.

Initially droop control was employed in AC systems [20]. In an inductive dominant distribution network, active power is highly dependent on the power angle δ, which is dynamically controlled by the frequency, and the reactive power is mainly determined by the AC voltage V. Figure 7 shows the relationship between the P-Q circle of a distribution generation (DG) unit and P-f/Q-E droops. In AC systems, P-ω and Q-V droop are formulated as follows:

$$\omega = \omega^* - k_{P\text{-}f}(P - P^*) \tag{1}$$

$$V = V^* - k_{Q\text{-}V}(Q - Q^*) \tag{2}$$

where ω and V are the frequency and amplitude of the output voltage measurement; ω^* and V^* are the frequency and voltage references; P and Q are the active power and reactive power measurements; P^* and Q^* are the active and reactive power references; $k_{P\text{-}f}$ and $k_{Q\text{-}V}$ are the proportional gain for the P-f and Q-V droop characteristics, respectively.

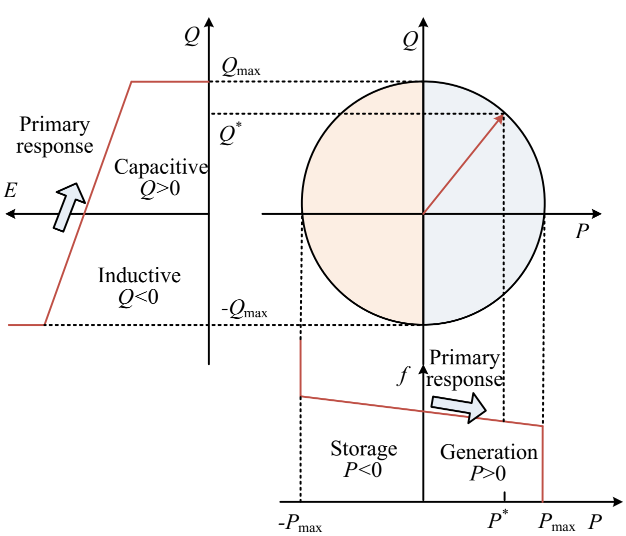


Fig. 7 P-f and Q-V droop control relationship in AC MGs [20]

Similarly, the droop concept has been successfully employed in DC systems. In contrast to the AC systems, the concept “reactive power” is not applicable and only active power can be transferred. The amount of active power transferred in the DC network can be defined by the DC voltage. Therefore, in DC systems a similar droop control can be built by setting a relationship between active power P and DC voltage V in order to achieve the desired load sharing by adjusting the voltage.

2.2.1 *Droop control categories*

In power electronic converters based DC MGs, the basic droop control concept can be implemented either as current/power mode droop, including Current-Voltage (I-V) and Power-Voltage (P-V) strategies or as voltage mode droop, including V-I and V-P strategies [21]. The I-V and P-V droop methods are shown in Fig. 8 [22]. In the implementation of these control methods, the DC voltage is measured and the injected current/power is controlled according to the droop characteristic. Alternatively, for the V-I and V-P methods shown in Fig. 8c, d, current or power is measured and the DC voltage is regulated accordingly [23].

It is shown in [24] that I-V and P-V demonstrated similar performance (both models are almost equivalent with little difference when small voltage errors are considered). Figure 9 shows the voltage-current (or power) characteristics for both P-V and I-V droop-controlled terminals. It is obvious that both models are almost equivalent with little difference when small voltage errors are considered. For this reason, I-V droop can be a representative of the current/power mode strategies. Similarly, V-I droop characteristic can be investigated within the voltage mode methods (V-I and V-P).

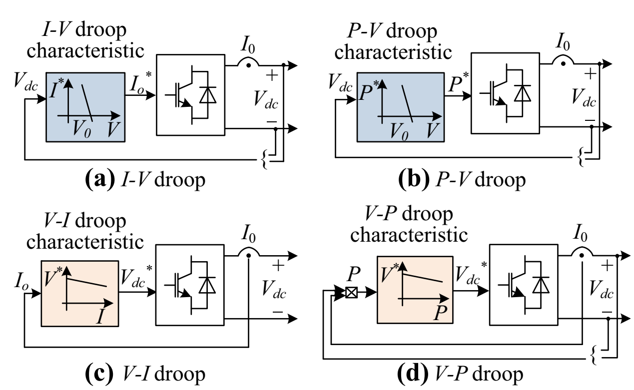


Fig. 8 Droop characteristic employed in power electronic converters [21]

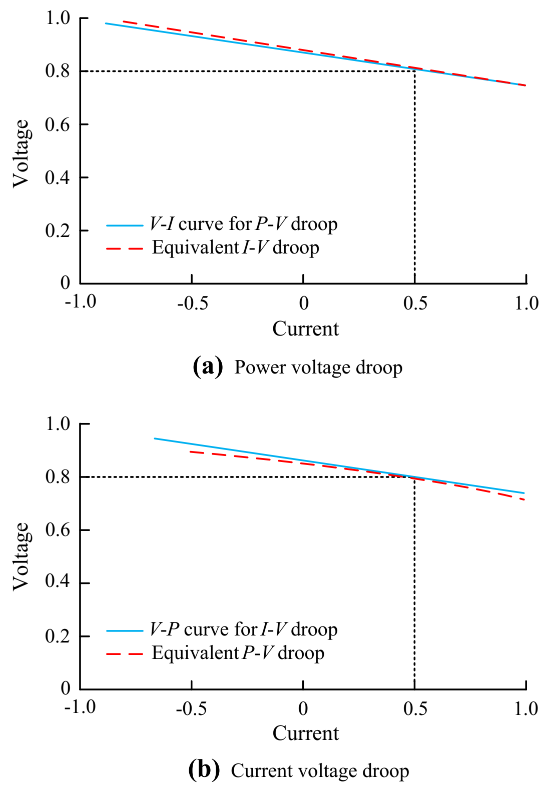


Fig. 9 Comparison of power based and current based voltage droop characteristic [24]

1) Voltage-mode

Voltage-mode approach employs the *V-I* droop characteristic which uses the measured branch current to generate the terminal voltage reference. The control scheme for voltage-mode droop-controlled VSC is shown in Fig. 10. As expressed in (3), the DC voltage reference is generated according to the branch output DC current using the *V-I* droop characteristic:

$$V_{dc}^{*} = V_o - I_{dc}k \tag{3}$$

where V_o is the nominal bus voltage; k is the droop gain; I_{dc} is the DC current measurement; V_{dc}^{*} is the generated DC voltage reference.

2) Current-mode

The current-mode approach uses the measured voltage to calculate the desired injecting DC current. The current-mode droop control scheme is shown in Fig. 11 with the current reference derived from the *I-V* droop characteristic, based on the DC voltage measurement:

$$I_{dc}^{*} = \frac{V_o - V_{dc}}{k} \tag{4}$$

where V_{dc} is the DC voltage measurement and I_{dc}^{*} is the generated DC current reference.

Overall, the current-mode primary control scheme and voltage-mode primary control scheme for parallel VSCs can be presented in Fig. 12a, b, respectively.

2.2.2 *Trade-off*

As a decentralized control method to realize desirable power sharing, droop control increases the system modularity and reliability. However, the impedance on the distribution line will also affect the performance of droop control. Moreover, the cable resistance is subject to changes, such as temperature variation. Also, difference of the nominal voltage will lead to load sharing performance degradation.

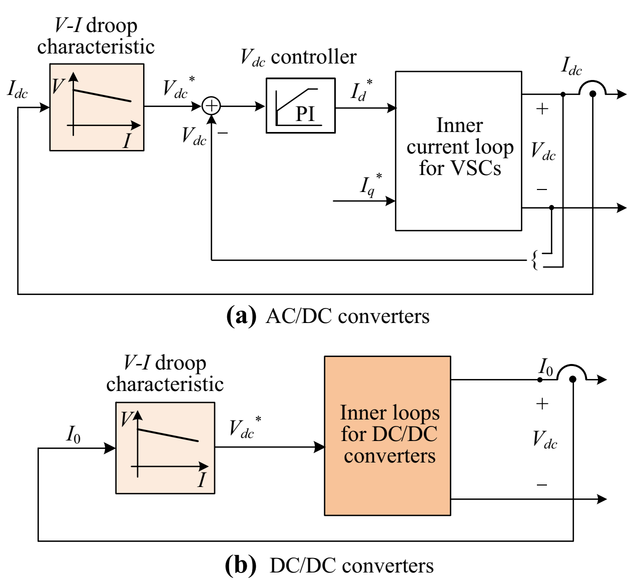


Fig. 10 Voltage-mode droop control scheme

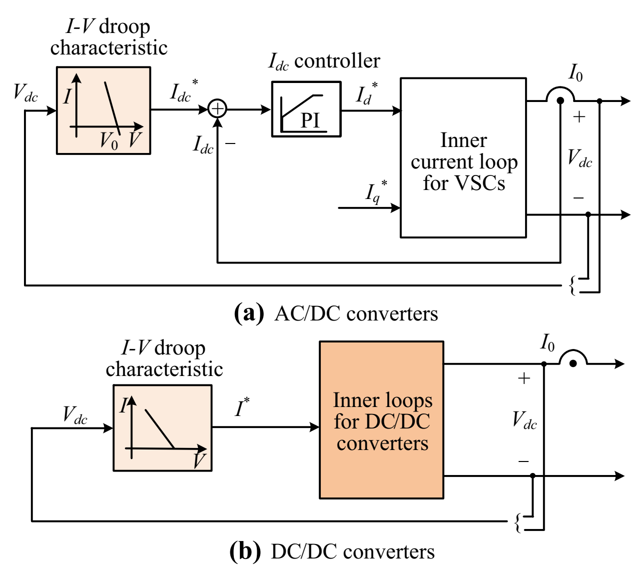


Fig. 11 Current-mode droop control scheme

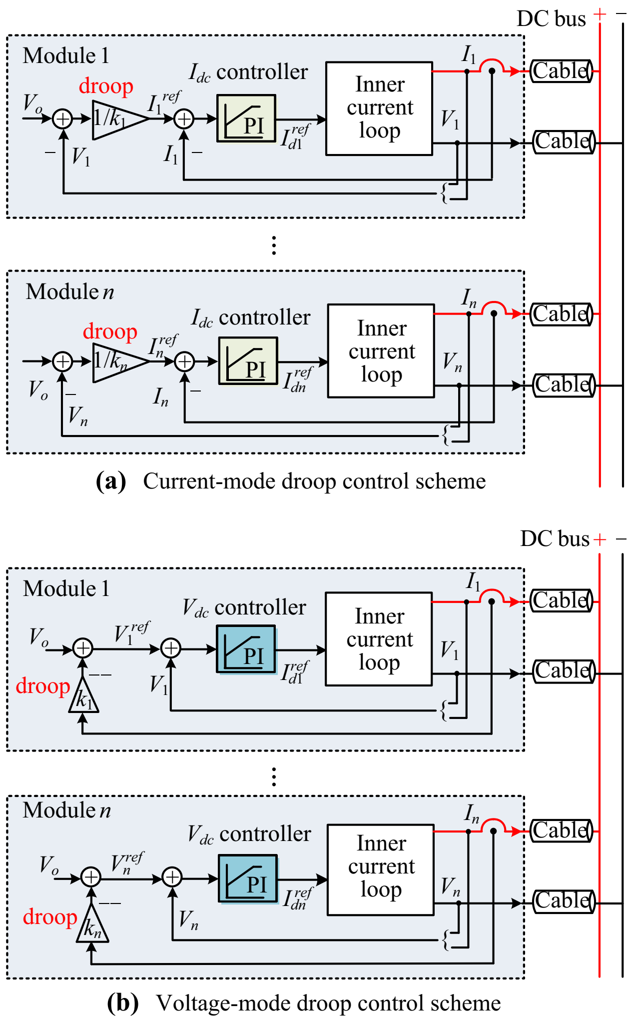


Fig. 12 Primary control diagram

Taking the two parallel connected DC sources as an example, unequal load sharing due to small error in nominal voltages is illustrated by Fig. 13. If a small droop gain k_A is applied, the difference in the twin source currents is $(I_{2o} - I_{1o})$. Alternatively, if a larger droop gain k_B can be used and the difference in the source currents reduces to $(I_2 - I_1)$.

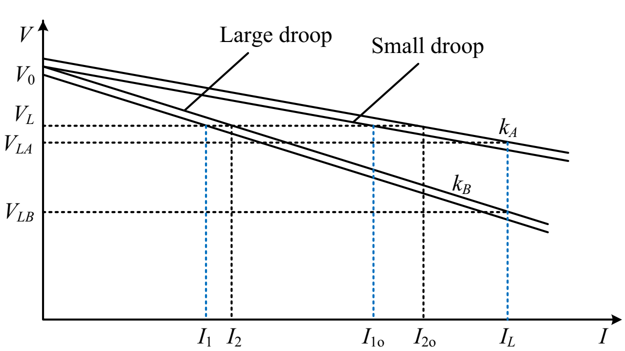


Fig. 13 Principle of secondary control on DC voltage restoration in DC MGs

Thus, it indicates that the system with large droop gains have better current sharing performance.

In addition, under the condition of load I_L, the main bus voltage will reduce to V_{LA} if a small droop gain k_A is applied whilst reduce to V_{LB} if a large droop gain k_B is applied. It implies that voltage regulation performance of the system with small droop gains is superior to the one with large droop gains.

Therefore, for droop control there is an intrinsic trade-off between voltage regulation and current sharing which implies the necessity of secondary control (will be discussed in Section 3).

2.2.3 Advanced droop control

Apart from the conventional linear droop control, different types of droop characteristic (including inversed droop, non-linear droop, and adaptive droop) have been investigated in order to cope with the trade-off and improve the system performance.

1) Inversed droop control

   In [25], an inverse-droop control is proposed to achieve power sharing including input voltage sharing and output current sharing for input-series-output-parallel (ISOP) DC-DC converters. With the proposed inverse-droop control, the output voltage reference rises as the load becomes heavy.

2) Non-linear droop control

   In [26], a nonlinear droop control is proposed in which the droop gain is a function of the output current of the DC/DC converter. The proposed non-linear droop method can increase droop resistance when load increases. Thus, it solves the trade-off in conventional droop methods, i.e., it achieves better load sharing at heavy load and tighter voltage regulation at light load. Reference [27] proposes three novel non-linear droop control algorithms: high droop gain methods (HDG), polynomial droop curve (PDG), polynomial droop curve with voltage compensation (PDCVC). Among all three proposed non-linear droop control methods, HDG offers the best voltage regulation but suffers poor power sharing at light load conditions whilst PDCVC provides the best performance at heavy load conditions. PDC method offers good load sharing and considerable voltage regulation under all loading conditions.

3) Dead-band droop control

   A droop-controlled DC system with the integration of energy storage system is investigated in [28] and [29]. A dead-band droop characteristic is proposed for the battery energy storage system to introduce a "floating" or standby working mode, avoiding the unnecessary repetitive charging and discharging.

4) Adaptive droop control

In [30], a novel droop that controls the nominal voltage is proposed to achieve good load sharing. However, this method only considers the load sharing among sources with same ratings which does not take different capacity of sources into account. In [31], a gain-scheduling technique is proposed which can achieve relative good voltage regulation and power sharing simultaneously by adjusting droop constant rather than simply selecting a large droop at the cost of voltage regulation or selecting a small droop at the cost of load sharing. This method needs to examine the voltage error for different droop gain under various load condition and then derives a certain relationship between load condition and droop constant. Reference [32] proposes State of Charge (SoC) based adaptive droop control to achieve dynamic SoC balancing and appropriate power sharing. In [33], analogue circuit is employed to improve the current sharing performance which actually is scaling up the droop gain, and the larger voltage drop owing to the enhancement of droop gain is compensated by increasing the voltage at a certain interval. In [34], a decentralized power sharing approach is proposed taking the line impedance into account in a low voltage DC MG including a PV, battery ESS. Grid-connected and islanded modes are considered and corresponding droop gains are discussed.

Table 1 lists the state-of-art of the droop based primary control approaches in DC MGs.

3 Secondary control

As discussed in Section 2, there is a trade-off between power sharing performance and voltage regulation. High droop gain can guarantee precise power sharing among the sources while the voltage regulation performance is poor, i.e., voltage deviation is large under high droop gains. In order to maintain the bus voltage for a droop-controlled DC MG at the nominal value, a secondary control level is introduced which sets the reference to the primary control and maintains the controlled parameter within an optimization range [40]. Figure 14 shows the principle of the secondary control in DC MGs. As one can see, when the primary control is implemented, the system operating point will move from v_o (voltage at no load condition) to OP1 under i_{dc1} load condition and from v_o to OP2 under i_{dc2} load condition, respectively. After activating the secondary control, the operating point will shift from OP1 to OP1_new and OP2 to OP2_new, i.e., the system always works at nominal voltage level.

Therefore, unlike the voltage/frequency restoration in AC MGs [41–43], the main task of secondary control is to eliminate the voltage deviation and meanwhile improve the power quality.

From the communication link point of view, the secondary control can be implemented with centralized, distributed and decentralized control policy [44].

3.1 Centralized secondary control

As shown in Fig. 15a, centralized control (sometimes called supervisory control) can be implemented in DG based DC MG by employing a centralized controller and a digital communications network to connect it with sources and loads. Figure 16 shows an example of centralized secondary control in voltage-mode droop-controlled VSCs. Centralized controller, sometimes called supervisory control, will send the voltage adjustment signals to each module via communication networks.

In [45], a multilayer supervision system is proposed to cope with power balancing and energy management in the PV penetrated MG. In [46], a classic hierarchical three level control structure is proposed so that good load sharing and voltage regulation can be achieved simultaneously. Secondary control is implemented via a voltage PI control to eliminate the voltage deviation owing to voltage droop. Reference [47] shows an application of centralized secondary control in DC/DC converters based DC MG. Reference [48] presents a DC-bus signalling secondary control for islanded DC MGs.

3.2 Distributed secondary control

Distributed control indicates the control principle whereby a central control unit does not exist and a communication line exists between the neighbouring modules, as shown in Fig. 15b. The main advantage of this approach is that the system can maintain full functionality, even if the failure of some communication links occurs, provided that the communication network remains connected. Therefore, distributed control is immune to a single point of failure (SPOF) [49–52]. Differently from centralized control, the information directly exchanged between the local controllers contain only locally available variables. In other words, if the two units are not connected directly by the communication link, they do not have direct access to each other's data and their observation of the whole system is limited. To tackle this issue, distributed control can be grouped into three categories: average current or voltage sharing scheme, dc bus signalling scheme, and cooperative control scheme.

Table 1 Features of droop control approaches in DC MGs

Category	References	Feature	Applications
Conventional droop control	[22, 23]	Avoid critical communication link, poor power sharing performance, poor voltage regulation	Multiterminal DC grids and DC MGs
Inversed droop control	[25]	Input voltage sharing and output current sharing	Input-series output-parallel DC/DC converters
Non-linear droop control	[26]	Solves the tradeoff, better sharing at heavy load and voltage regulation at light load	DC/DC converter
Non-linear droop control	[27]	Three non-linear droop control methods (HDG), PDCVC: best current sharing accuracy at all load conditions, PDC: good load sharing and considerable voltage regulation at all load condition	DC/DC converter
Dead-band droop control	[28]	Avoids unnecessary charging/discharging	Bidirectional DC/DC converter for battery
Adaptive droop control	[30]	Sectional linear droop curve depending on the load current, adaptively control the reference voltage	DC/DC converters
	[31]	Fuzzy control with gain-scheduling technique, DC voltage regulation and stored energy balancing control	Multiphase DC/DC converters
	[32]	Adaptive droop gain which is inversely proportional to nth order of SoC	Battery energy storage based DC MG
	[33]	Dynamic droop scaling to increase droop slope to reduce power dissipation	Parallel DC/DC converter
	[34]	Charge and discharge droop gain depending on the ratings and SoC	Battery ESS in a low voltage DC MG
	[35]	Adaptive droop gain depending on the headroom available in addition to the ratings (difference between the rated capacity and present loading); consider actually load condition including power imbalance condition	MTDC grids
	[36]	Adaptive droop gain based on the converters output voltage deviation to minimize circuiting current	DC/DC converters
	[37]	Fuzzy logic to adaptive tune the droop gain to avoid deep charge/discharge of the energy storage	DC MGs with PV, WT and energy storage
	[38]	DC bus signaling for mode selection in DC MGs	DC MGs with PV, WT and energy storage
	[39]	Distributed primary control in which droop gain is based on the distributed communication network; robust to the changes of distributed network	DC MGs with distributed generations

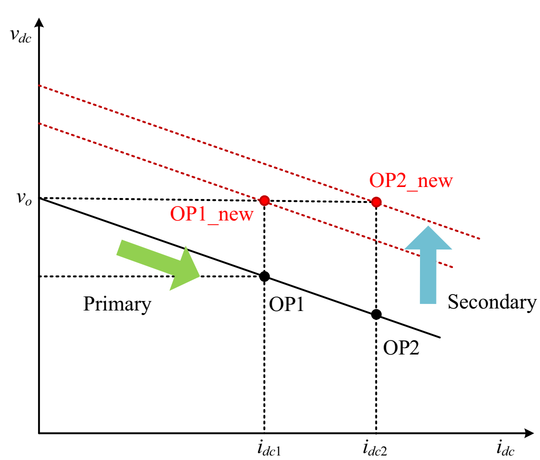


Fig. 14 Principle of secondary control on DC voltage restoration in DC MGs

3.2.1 Average current/voltage sharing

As shown in Fig. 17, an enhanced droop control with improved voltage regulation is proposed in [53]. PI controllers are used to regulate the average voltage and current.

As shown in Fig. 18, in [54] a large droop gain is recommended to overcome the load sharing error caused by line resistance and average current is used to modify every droop characteristic line so that every droop line will be shifted up by a same amount with the increase of the load. The average current needs to be computed and the chosen of shift gain becomes important which is not easily implemented in reality. Reference [55] proposes a secondary control method using three PI controllers. The average voltage, current and droop gain is calculated

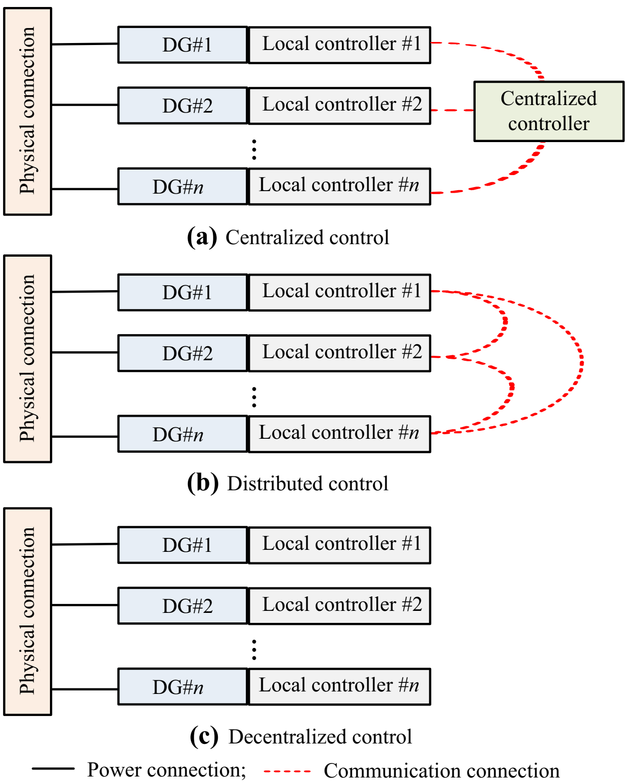


Fig. 15 Control categories based on communication links

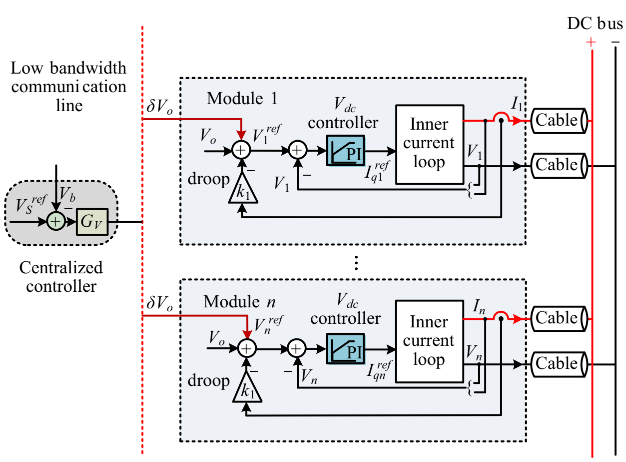


Fig. 16 Example of classic centralized secondary control in voltage-mode VSCs

respectively and the droop gain is tuned by the combination of average current and droop gain controllers. In [56], a unified compensation method is proposed using the common load condition to compensate the voltage drop. Reference [57] shows a distributed secondary control for energy storage units SoC of batteries is estimated. Reference [58] proposed a secondary control scheme while setting a high droop gain in order to ensure appropriate power sharing performance. An average voltage sharing

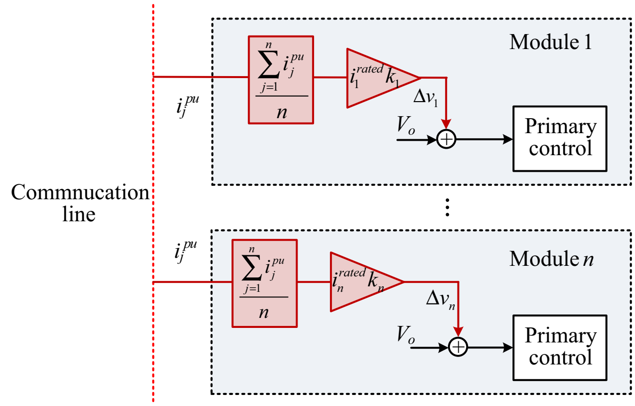


Fig. 17 Secondary control scheme proposed in [53]

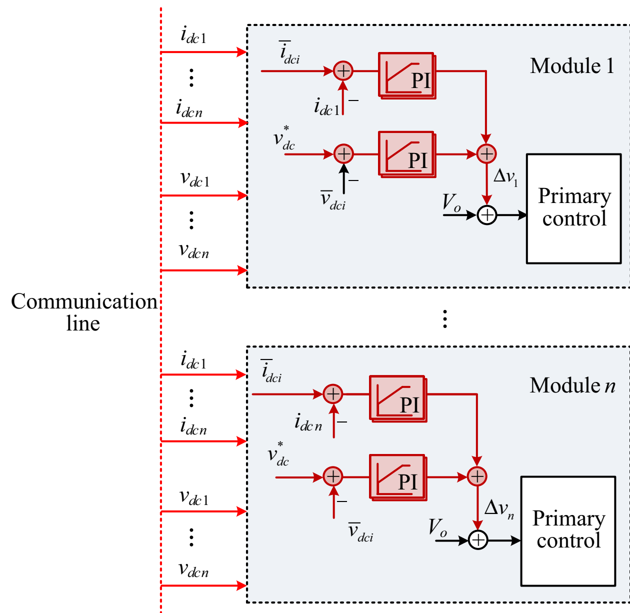


Fig. 18 Secondary control scheme proposed in [54]

control is proposed in [59]. A distributed secondary control utilizes the low-bandwidth communication channel to provide a computed average control signal to its primary controller.

3.2.2 DC bus signaling

References [60] and [61] show distributed secondary control based on DC bus signaling. In [60], the DC bus voltage threshold monitors the action of interface converters of sources and loads in the operation of a DC nanogrid. Four different operation modes of a PV modular system are presented in [61].

3.2.3 Cooperative control

The objective of distributed cooperative control is to find a local control protocol that drives all nodes to have the same constant steady-state values, known as the consensus value. In order to overcome this problem, different distributed control protocols such as consensus algorithm [62–71].

Figure 19 shows the principle of consensus algorithm. The variables can be module current, voltage or SoC if energy storage is integrated. The exchanging variables can be module current or voltage.

In [65] a complete DC MG model using a discrete-time approach with consideration of the consensus algorithm is proposed. The impact of communication topology and the communication speed are studied in detail. In [66], a distributed secondary control using dynamic consensus algorithm is applied in multiple DC electric springs. Reference [67] and [68] show an event-triggered distributed secondary control for DC/DC boost converters based DC MG to deal with average voltage regulation and current sharing. Reference [69] proposes a multi-agent based distributed control of heterogeneous storage devices (ultra-capacitor, battery). The cooperative control could tackle with the SoC balancing between the battery systems and power sharing coordination among multiple energy storage devices. In [70], a consensus algorithm is developed in modular DC-DC converters. The proposed cooperative control is implemented on a sparse communication graph across the MG, reducing the number of communication lines.

Other algorithms such as gossip algorithms are attractive since they are robust to SPOF and unreliable wireless network. Due to its asynchronous property, only one random node chooses other node(s) to exchange their estimates and update them to the global information [72–74].

3.3 Decentralized secondary control

Decentralized control uses local measurement to implement local regulation, as shown in Fig. 15c. Since communication links among the sources and an additional centralized controller are not needed, each parallel module can work independently relying on the local measurements and controllers, which increases the system reliability.

In [75], a proportional controller is proposed and implemented to attenuate the influence of the cable impedance in the secondary control layer. The communication only exists in local distributed sources and all the variables for control are locally measured and transferred. The estimated gain is used to cancel the line impedance in order to achieve better power sharing performance. In addition, [76] presents a decentralized secondary power sharing control in a droop-controlled LVDC MG where a new injected AC frequency-DC current droop characteristic is proposed.

In [77], a feedforward term is added to the terminal voltage reference for each module Similar to the droop characteristic of each individual module at the DC terminal, the DC bus voltage and total load current also follows a droop characteristic. Only the load current needs to be measured and no additional DC voltage controller is in need. If multiple loads are in presence and distributed among the MG, the total load current measurement can be obtained at the main feeders (if this exists) which supplies the power to all loads.

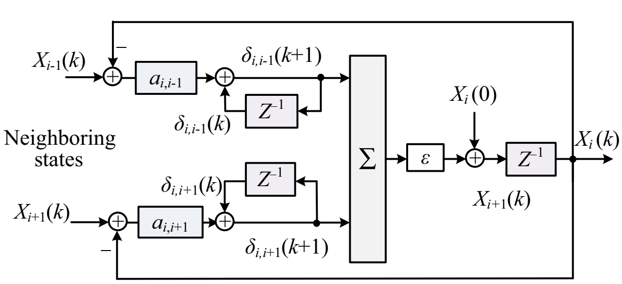


Fig. 19 Consensus algorithm [64]

3.4 Summary of secondary control

Secondary control approaches in DC MGs can be summarized into three categories: centralized, distributed, and decentralized control. Table 2 compares the features of the three abovementioned secondary control categories. As one can see, a digital communication link (DCL) is required for centralized and distributed control. This will reduce the reliability of both control strategies. Especially for the centralised control, the potential single point of failure exists in the centralised controller.

Based on the number of references in each category, it can be seen that distributed control strategies have recently spurred a great amount of interests. Table 3 summarizes the state-of-art distributed secondary control approaches, such as DC bus signaling, average current sharing and cooperative control strategies. The data such as voltage, current or battery SoC are exchanged via communication links to work out the whole network knowledge.

4 Future trends

4.1 Hybrid AC/DC microgrid

The use of low voltage DC to supply information technologies (IT) loads is rapidly becoming standard. In these systems, DC is seen as an opportunity to improve reliability and to reduce energy losses and costs. Today the

Table 2 Features of centralized, distributed and decentralized secondary control approaches in DC MGs

Feature	Centralized control	Distributed control	Decentralized control
Communication medium	DCL	DCL	Power line
Centralized controller	Yes	No	No
Modularity	Low	High	High
Reliability	Low	Medium	High
Single point of failure	Yes	No	No
Advantages	Proper coordination and leadership, global information	Improved immunity to single point of failure	Local measurement and regulation, easy implementation
Disadvantages	Single point of failure	Complex interaction network	Lack of global information
References	[45–48]	[52–71]	[75–77]

Table 3 Distributed secondary control approaches in DC MGs

Reference	Category	Feature	Data exchange	PI controllers	Implementation
[52]	Average current sharing	Low bandwidth communication	Output current	2	Simulation
[53]	Average current sharing	Low speed and low cost communication	Output current and voltage	2	dSpace
[54]	Average current sharing	Digital average current sharing scheme	Current	1	CAN Bus
[55]	Average current sharing	Droop gain averaged as well	Current, voltage and droop gain	3	RS232
[56]	Average current sharing	Average current regulation	Output current	1	CAN Bus
[57]	Average current sharing	Battery SoC balancing	Battery input voltage and current, output voltage and current	1	Experiment
[58]	Average current sharing	Voltage compensation without additional controllers	Current	0	Experiment
[59]	Average voltage sharing scheme	Pilot bus regulation through low bandwidth communication	Current, voltage	1	Experiment
[62]	Cooperative	Dynamic consensus	Average voltage estimation, local voltage, current	2	dSpace
[63]	Cooperative	Dynamic consensus	Average voltage estimation, local voltage, average ES energy	3	MATLAB/ Simulink
[65]	Cooperative	Dynamic consensus	Local voltage, local current	2	PLECS
[66]	Cooperative	Average consensus	Average voltage estimation, SoC	2	RS232
[67]	Cooperative	Voltage observer, average voltage estimation, current regulation	Current and voltage	2	Ethernet
[68]	Cooperative	Finite time tracking protocol	Current	1	Ethernet
[69]	Cooperative	Dynamic consensus	SoC of battery, ultracapacitor voltage	2	Simulation
[70]	Cooperative	Dynamic consensus	Local current	1	RS232
[71]	Cooperative	Dynamic consensus	Average voltage estimation, current in per unit	2	dSpace

market of photovoltaics, batteries, power electronics and IT hardware keeps growing as these technologies become more cost-competitive. The use of DC could be therefore extended to further types of loads, generation and storage which proliferated hybrid AC-DC MGs [78, 79].

In the presence of individual AC and DC grids, the hybrid AC-DC MG facilitates interconnection of various AC and DC-based renewable energy sources which effectively reduces multiple power conversion stages and as a consequence improves system efficiency.

The control in hybrid AC/DC MGs is more complicated due to the absence of a global variable which can be used for power-sharing, voltage and frequency regulation. Control of the interlinking converter such as per unitized voltage and frequency control on both sides are proposed [80–82] and can be further investigated.

4.2 Real-time energy management

Future MGs will be localized distribution systems composed of distributed generators, flexible loads, and energy storage elements that are networked together using advanced communication technologies. Energy management in MGs is usually formulated as an offline optimization problem for day-ahead scheduling. The future challenge is to provide reliable and secure electricity service despite large variation in available generation by rapidly connecting, disconnecting and controlling non-critical loads in a dynamic manner. Under such conditions the management of the embedded stored energy in the MG over timescales of milliseconds (e.g. converter DC link capacitors) to hours (e.g. Li-ion UPS batteries) is of critical importance.

Real-time energy management offers the benefits of being able to detect damaging or potentially dangerous problems as soon as they happen [83–85]. It is clear that future microgrid will contain the following new technologies to ensure reliable operation to provide fundamental electrical controllability, a fast inter-converter communication system to coordinate control and operation of potentially hundreds or thousands of electrical sub systems, a high level energy management system to dispatch embedded generation and optimize operation of in-built storage devices.

4.3 Stability and control

Many loads in DC MGs are tightly controlled by power electronics. These loads often behave as constant power loads (CPLs) and present negative incremental impedance resulting in degrading stability margins. Hence, new control strategies need to be investigated in order to achieve a wide range operation scenario in DC microgrids. Reference [86] proposed a Lyapunov based control approach that compensates for the instantaneous variations of the reference current components of DG units in the AC side. This control approach also addressed the DC voltage variations in the DC side of the system. Similarly, in [87] and [88], a passivity based control approach was proposed to maintain current and voltage stability in the MG's AC and DC side respectively. Another passive control method, which included energy formation and series damping injection, was proposed in [89].

5 Conclusion and future work

Following the hierarchical control structure, this paper provides a comprehensive review of primary and secondary control in DC MGs.

The main findings of this review can be summarized as follows:

1) As the basic level, primary control integrates inner control loops aiming at voltage/current regulation with the preliminary power sharing (droop control). Conventional droop control has the poor voltage regulation at heavy load and poor power sharing performance at light load condition. To overcome this, different droop characteristics including adaptive, inversed, non-linear droop, dead-band droop are presented and elaborated.
2) As a higher level, secondary control improves the power sharing accuracy and meanwhile enhances power quality. Depending on the availability of communication line (or peer-to-peer communication network) and centralized controller, secondary control layer is further classified into centralized, distributed and decentralized secondary control methods.
3) Centralized control schemes are based on a centralized controller which communicates with all other units through dedicated DCLs. Supervisory system is deployed to realize global optimization or to determine proper operation modes for each unit in DC MGs. Centralized control offers the highest level of flexibility for achieving advanced functionalities, but renders the system suffering an inherent single point of failure (SPOF).
4) Decentralised control can achieve high reliability, modularity and only depends on the local variables. It is perceived to be a highly effective methodology for mitigation of source contingencies and communication breakdown. The disadvantage is that it lacks of global information of the network indicating difficulty in system optimization.
5) Distributed control methods (e.g., DC bus signaling, MAS including dynamic consensus, gossip algorithms

are discussed) can achieve similar functions as centralized methods but eliminates the SPOF. They collectively gather data among themselves and process it either through consensus-based or gossip algorithms. In general, distributed control has enhanced reliability compared to centralized control, since there is no SPOF. However, rigorous mathematical analysis of distributed control strategies remains a challenge. The proper selection of the communication step-size and convergence time is critical.

Considering the future work, distributed control strategies need to continue developing. From the standpoint of control protocols, diffusion algorithms [90] can be a good candidate given the better performance over consensus in terms of the convergence speed and mean stability of the distributed network. Also, successful laboratory scale experimental demonstrations are inevitable steps forward before commercialization.

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