IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received September 6, 2019, accepted October 2, 2019, date of publication October 11, 2019, date of current version October 24, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2946706

Review of Power Sharing, Voltage Restoration and Stabilization Techniques in Hierarchical Controlled DC Microgrids

YANG HAN[1], (Senior Member, IEEE), XING NING[1], PING YANG[1], AND LIN XU[2]
[1]School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
[2]Sichuan Electric Power Research Institute, Sichuan Electric Power Company, Chengdu 610072, China

Corresponding author: Yang Han (hanyang@uestc.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 51977026, in part by Natural Science Foundation of Guangdong Province under Grant 2018A030313494, and in part by the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources under Grant LAPS18007.

ABSTRACT In order to overcome the problem of power generation in distributed energy, microgrid(MG) emerges as an alternative scheme. Compared with the ac microgrids, the dc microgrids have the advantages of high system efficiency, good power quality, low cost, and simple control. However, due to the complexity of the distributed generation system, the conventional droop control shows the drawbacks of low current sharing accuracy. Therefore, the improved primary control methods to enhance current sharing accuracy are systematically reviewed, such as particle swarm optimization programming, probabilistic algorithm and voltage correction factor scheme. However, it is difficult to achieve stable and coordinated operation of the dc microgrids by relying on the primary control. Hence, the various secondary control approaches, such as dynamic current sharing scheme, muti-agent system (MAS) control and virtual voltage control methods have been summarized for voltage regulation. Furthermore, the energy management system (EMS), modular-based energy router (MBER) and other coordinated control methods are reviewed to achieve power management. Besides, various control methods to compensate the effect of communication delay are summarized. Moreover, linear matrix inequality (LMI), Lyapunov-Krasovskii functional stability and Takagi–Sugeno model prediction scheme can be adopted to eliminate the influence of communication delay. In addition, due to the constant power loads (CPL) exhibit negative impedance characteristics, which may result in the output oscillation of filter. Thus, various control approaches have been reviewed to match the impedance, such as the nonlinear disturbance observer (NDO) feedforward compensation method, linear programming algorithm, hybrid potential theory and linear system analysis of polyhedral uncertainty. The merits and drawbacks of those control strategies are compared in this paper. Finally, the future research trends of hierarchical control and stability in dc microgrids and dc microgrid clusters are also presented.

INDEX TERMS DC microgrid, nonlinear droop control, multi-agent system, consensus control, communication delay, constant power load, hierarchical control.

I. INTRODUCTION

In recent years, in order to solve the problem of environmental pollution and reduce the demand of fossil fuels for conventional power generation, distributed generation (DGs) including renewable energy (RES) and energy storage systems (ESS) have been widely developed [1], [2]. Moreover, to coordinate the contradiction between the conventional grid and the DG units, while exploiting the advantages of the distributed power source, the concept of the microgrid (MG) have emerged at the beginning of this century [3]. MG can be divided into dc MG and ac MG, compared to ac MG, dc MG possesses the advantages of high efficiency, more natural interface with various RES and ESS, and in compatible with the requirements of consumer electronic products, thus dc MG has been widely applied [4]. Furthermore, dc MG can be adopted to renewable energy (photovoltaic arrays, wind turbines, etc.), aerospace equipment, ship electrical systems,

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Masood.

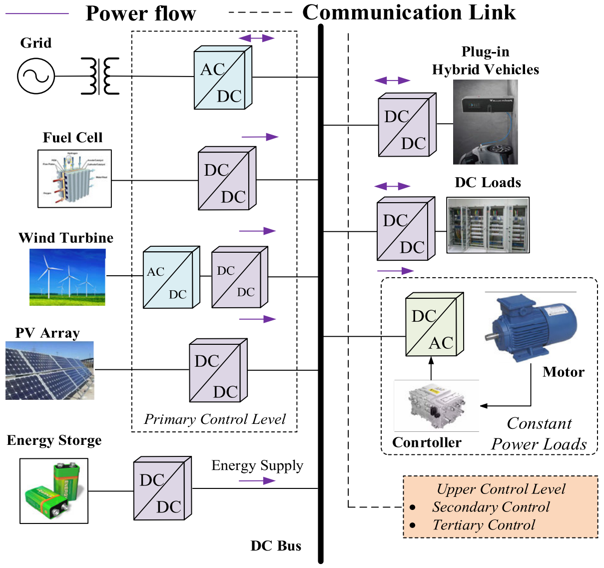

FIGURE 1. Architecture of the dc microgrid.

energy storage equipment, electric vehicles, data centers, telecommunication systems [5]–[9]. In addition, when components are coupled around a dc bus, there are no issues with reactive power flow and frequency adjustment [10]–[12]. Therefore, dc MGs are increasingly attracting considerable attention.

Fig.1. shows the basic architecture of a dc MG system, which consists of various micro sources, ESSs, energy conversion devices and load control equipment. DC MG can be operated in islanded or grid-connected mode. Therefore, the dc MG is a complex multi-target control system, which shows multiple time-scale property, deals with the issues of load sharing (LS), voltage restoration, power regulation, etc. The hierarchical control of dc MG can be divided into three layers: primary control, secondary control and tertiary control. The primary control is used to handle the load sharing among the DGs, the secondary control is responsible for the regulation of the voltage fluctuation, and the tertiary control is to set the power flow between the dc MG and the upper grid. The secondary and tertiary levels of control are combined for upper-level control.

Droop control is a popular current sharing method in primary control, and its improved method has been widely studied. In the conventional droop control, the output impedance of various converters would be unequal due to the uncertainty of line impedances, which results in unbalanced output power. Furthermore, the line impedance can be identified by active pulse injection method to ensure the control effect [13]. However, the line droop parameter design method is influenced by the accuracy of mismatched line impedance and sensing problems. In addition, a nonlinear droop method such as high-order polynomial can be employed to eliminate the current sharing deviation among the microgrid units. Instead of the linear droop formula, the nonlinear droop with slope of the droop curve can be adjusted to enhance the current sharing accuracy effect of dc MG [14], [15]. Nevertheless, a tradeoff between voltage management and current sharing accuracy may still exist.

In order to solve the problem in the primary control of the dc MG, the secondary control can be used to reduce the voltage deviation and improve the current sharing accuracy simultaneously, such as distributed control, coordinated control, etc. Essentially, the secondary control is an improved solution to droop control. The conventional solution adopts the centralized control method [16], [17]. However, the problems of centralized control structure are as followed: 1) only the accurate adjustment of single bus voltage is achieved, 2) poor plug-and-play capability, 3) more DGs leads to increased demanding for computing and communication bandwidth, 4) the dependence on centralized controllers (MGCC) may cause low reliability of the system [18], [19]. Thus, an improved secondary compensation control strategy such as the distributed multi-agent system (MAS) control structure can be adopted to solve the above problems [20], [21], which has been widely used to establish optimal model to enhance reliability and energy management, optimization, and improve the performance of ancillary services. Furthermore, to eliminate the problem of large load variation, the dynamic load sharing control method can be adopted [22], and low voltage management of the system can be ensured by digital average current sharing (DACS) control [23].

By implementing a distributed MAS control method, global voltage management and current sharing could be ensured. Compared with diverse distributed control methods, distributed secondary control can be used to reduce the dc bus voltage fluctuation [24]. Furthermore, the dynamic consensus algorithm can be utilized to reduce the communication congestion of the system [25], [26]. Moreover, to match the line impedance and output voltage among the DER units, a two-stage MAS method based on the switched topology communication network control scheme can be applied [27]. In addition, a virtual voltage control strategy can be applied to achieve coordinated control among multiple sources [28].

Compared with the coordinated management of a single MG, the coordinated control of the microgrid clusters (MGC) is more complicated. It is necessary to evaluate the allocate energy of distributed power sources and the optimization power in each sub-microgrid, thus, tertiary control should be applied to ensure the stable and reliable operation of the dc MG. In addition, in order to achieve economical energy coordinated control of the MGC [29], [30], adaptive energy management system (EMS) and modular-based energy router (MBER) can be applied to adjust power set point and power direction of the MGC [31], [32]. Furthermore, tie-line internal control can be used to ensure constant power of the MGC [33], [34], and the energy storage system (ESS) is coordinated with each other to maintain the bus voltage [35].

However, it takes the certain time to perceive mutual communication and signal processing among the dc MGs and each layer of the hierarchical structure in the dc MGC, which may lead to delay and influence the overall control effect, even cause communication failure in severe cases. In order to reduce the communication congestion among internal converters, a consensus-based distributed control method can be employed [36]. Furthermore, noise resilience observation can be used to facilitate the study of the dynamic performance of the system [37], [38]. In addition, for the stability problem of dc MGs, in order to determine the delay boundary and eliminate the influence of communication delay on system stability, linear matrix inequality (LMI) and Lyapunov-Krasovskii functional stability methods can be utilized [39]–[41]. Furthermore, as an active nonlinear method, Takagi–Sugeno's (TS) fuzzy model and model prediction scheme can be employed to mitigate the network-induced delays from the sensor-to-controller in case of the large-scale distributed energy systems [42].

Moreover, along with precise voltage and current regulation, the stable operation of the dc MG should be ensured under all operating conditions. Especially, the power converter is strictly controlled, these points of load (POL) converters and their associated loads are generally assessed to be constant power loads (CPL) [43]. However, with the negative impedance characteristics of CPLs, dc MGs are easier to be unstable due to the reduced system damping [44]–[46]. Thus, the system damping can be elevated by applying virtual impedance [47], model prediction [48], feedback control [49], [50], etc. Moreover, a linear programming algorithm can be applied to enhance the system robustness. Besides, in order to analyze the influence of system parameters on system stability, the hybrid potential theory can be established [51]. In addition, when the system is under large disturbance, the algorithm of estimating the attraction domain and the linear system analysis method of polyhedral uncertainty can be used to achieve the ideal robustness index and ensure the stability margin of the system [52], [53].

Recently, a review of dc MG control, dynamic stability analysis and stabilization techniques are presented in [45]. Through the communication among various units in the MG, three main coordinated control methods are distinguished: decentralized, centralized and distributed control. Moreover, several important impedance specifications and stability principles are reviewed. However, the problems of the primary control in the hierarchical control have not been elaborated. In [54], to enhance the control ability of the primary control level, the two-layer and three-layer control structures of the dc MG are reviewed respectively. The dc bus voltage control strategy and its improved method are introduced to elevate the energy efficiency and reliability of the system. Nonetheless, for the larger and more flexible microgrid system, the problem of the voltage restoration could not be solved in the secondary control.

The control, management, stability and active damping design of dc MG are presented in [55], which include the coordinated control schemes, islanded protection approaches and control of the MGC, but the communication delay problem in the multi-layer control of the MG and the MGC is not considered. The modeling, behavior and effects of CPLs in dc MGs are reported in [56], which combine the advantages and disadvantages of existing standards for small signal stability and large signal stability of dc power systems. The instability effects of CPLs and stable analytical methods are studied. Nevertheless, it did not mentioned how to enhance the stability margin of system, and there was no prediction of instability and stability margin of the system.

For the shortcomings of the above literatures, this paper will combine the previous research and the latest advances, the main contributions can be summarized as follows. Firstly, the active pulse injection is used to eliminate the problem of mismatched line impedance in the primary control. Furthermore, the particle swarm optimization programming method, the probabilistic algorithm, the voltage correction factor approach, etc, are employed to derive the optimal droop parameters. Moreover, nonlinear droop method such as higher order polynomials are utilized to enhance the current sharing effect. Secondly, in order to reduce communication congestion of dc MG and MGC, such as adaptive energy management system (EMS) scheme, modular-based energy router (MBER) approach, tie-line internal control method, noise resilience observation control, etc, are used to ensure global voltage management, power set point and power direction of the MGC.

In addition, linear matrix inequality (LMI) method, Lyapunov-Krasovskii functional stability analysis approach, Takagi–Sugeno fuzzy model and model prediction scheme can be applied to provide a basis for dc MG stability domain selection. Finally, to deal with the problem of negative impedance of CPLs, the feedforward compensation method of nonlinear disturbance observer (NDO), linear programming algorithm, hybrid potential theory, algorithm of attracting domain estimation, polyhedron uncertain linear system analysis and other methods are adopted to track the CPL power variation and ensure system stability margin.

The aim of this paper is to provide an overview of power sharing, voltage restoration and stabilization techniques in hierarchical controlled dc microgrids. The overall broad categorization block diagram of dc MG control strategies and stability issues are shown in Fig. 2. The structure of this paper is organized as follows: In Section II, the line impedance, current sharing accuracy and control problems under complex load conditions are analyzed. Section III introduces the secondary compensation control for the voltage drop caused by the primary control, the distributed multi-agent control and coordinated control of the dc MG are summarized and the communication delay problem based on this hierarchical structure are discussed. Besides, a corresponding solution to the negative impedance problem caused by CPLs are reviewed in Section IV. Finally, concluding remarks and future research trends of dc MG are presented in Section V.

II. PRIMARY CONTROL STRATEGY OF DC MICROGRIDS

The droop control strategy can be used to achieve power sharing by imitating the behavior of virtual synchronous

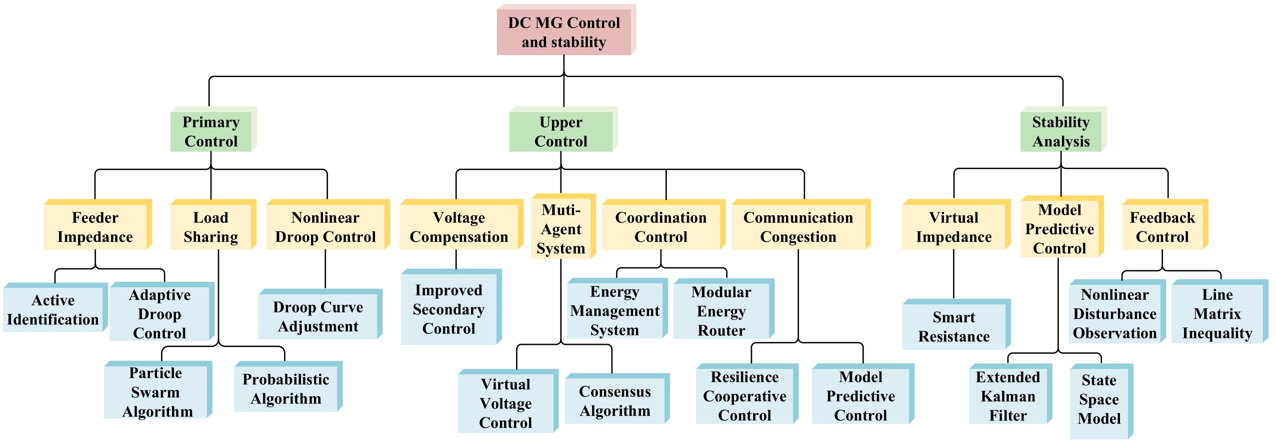

FIGURE 2. Broad categorization of dc MG hierarchical control and stability techniques.

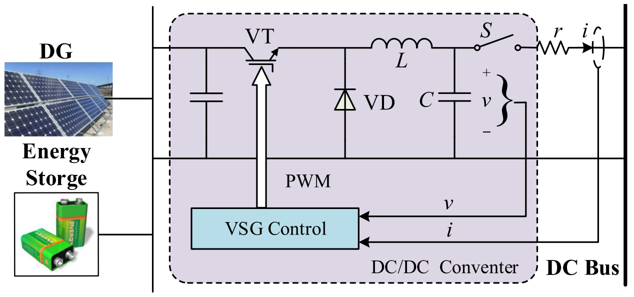

FIGURE 3. Block diagram of virtual synchronous generator.

generator (VSG), as shown in Fig. 3. And the control methods of traditional power grids can also be extended to microgrids. In order to overcome the instability problems of the renewable energy generation system, it is generally necessary to increase the energy storage unit on the DC side to maintain the stability of the DC sources. Nevertheless, the output impedance of various converters would be unequal due to the uncertainty of line impedances [57], [58], which results in unbalanced output power [59]. Furthermore, to ensure the control effect, the optimal droop parameter can be determined by optimizing the line impedance and introducing the optimization programming [60], thereby improving the current sharing accuracy [61], [62]. However, the linear droop parameter design method is influenced by the accuracy of line impedance and sensing problems. In order to eliminate the current sharing deviation among the microgrid units in time, a nonlinear droop method such as high-order polynomial and piecewise quadratic polynomial descent curve (PQPDC) can be employed. In view of the aforementioned problems, in this section, the line impedance issues and current sharing accuracy in the droop control are discussed in detail. Nonlinear droop control for primary control is reviewed.

A. PROBLEMS OF LINE IMPEDANCE IN THE DROOP CONTROL

The principle of droop control can be represented by the equivalent schematic of two parallel-DGs. As shown in Fig. 4,

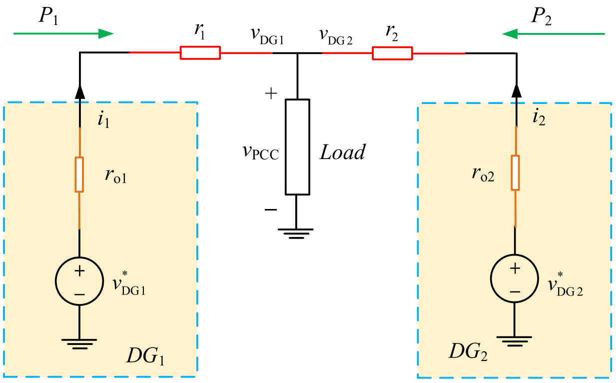

FIGURE 4. Equivalent schematic of two parallel-DGs in an islanded dc MG [63].

the relationship between current and voltage of DG_1 and DG_2 at the point of common coupling (PCC) of the system is given as follows:

$$v_{DG1} = v^*_{DG1} - (r_{o1} + r_1)i_1 \tag{1}$$

$$v_{DG2} = v^*_{DG2} - (r_{o2} + r_2)i_2 \tag{2}$$

The voltages of the two DGs at the common point are equal due to the parallel topology, since the reference values of the two DGs are $v^*_{DG1} = v^*_{DG2}$. By combing (1) and (2), the output currents of the two converters can be described as

$$\frac{i_1}{i_2} = \frac{r_{o2} + r_2}{r_{o1} + r_1} \tag{3}$$

where r_1 and r_2 are the equivalent resistances between the corresponding converters and the common point, respectively, r_{o1} and r_{o2} are the output impedance of DG_1 and DG_2 respectively, and v_{DGi} indicates the voltage of DG_i. It can also be deduced that the ratio of the output current of the converter is proportional to the sum of the respective output impedances of the converters and the corresponding line impedances.

Due to the large variation of the line impedance, the current sharing accuracy and the dc bus voltage of the droop control would be decreased. Thus, in order to measure the line

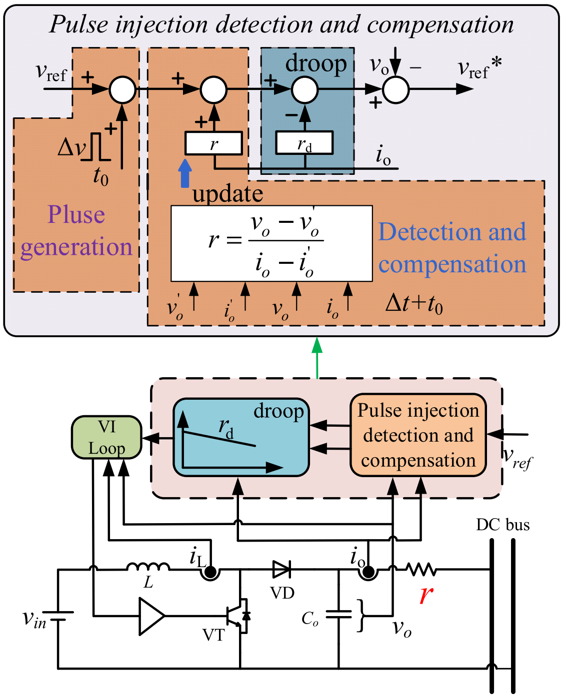

FIGURE 5. Control scheme of the active identification method for line impedance [13].

impedance accurately, a line impedance active identification method based on a specific system structure of dc MG is proposed in [13]. Fig. 5 shows the control scheme of the active identification method for line impedance, it mainly consists of a pulse generation, line impedance detection, compensation and droop control. The output voltage and current are $v_{\rm o}$ and $i_{\rm o}$ at t_0 when the system is in steady-state conditions. The output voltage $v_{\rm o}'$ and current $i_{\rm o}'$ are measured at the $t_0+\Delta t$.

By injecting pulse actively and detecting the change of output voltage and current, the line impedance r between the parallel converters and the dc bus can be obtained as

$$r=\frac{v_{\rm o}-v_{\rm o}'}{i_{\rm o}-i_{\rm o}'} \tag{4}$$

Compared to conventional droop control method and its improvements, the effects of mismatched line impedance on voltage quality and load sharing are eliminated. In addition, to eliminate the deviation of the power distribution among the sources caused by the difference of the line impedance, the droop coefficient can be adjusted to perceive effective power sharing accuracy, voltage regulation and restoration of the dc bus voltage [62].

In summary, by identifying the line impedance actively and adjusting the droop coefficient, the current sharing accuracy can be enhanced. The deviation in dc bus voltage is restored and the effects of line impedance on voltage quality and load sharing are eliminated. However, due to the existence of cable impedance and internal coupling, the problem of current sharing accuracy needs to be further discussed in the large-scale dc MGs.

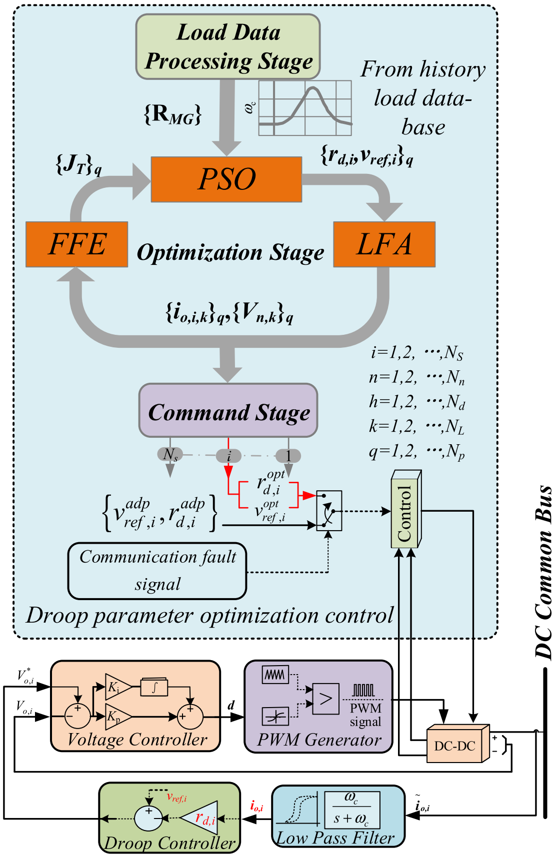

FIGURE 6. Overall droop selection concept with the particle swarm optimization structure [60].

B. PROBLEMS OF CURRENT SHARING IN THE DROOP CONTROL

Proper current sharing is a highly desirable feature in MG's operation to prevent circulating currents and overloading of the converters. Since voltage is a local variable across the MG, in practical applications where line impedances are not negligible, conventional droop control is not able to provide an accurate current sharing among the sources. Hence, the improved droop control such as the optimization programming method [60], probabilistic algorithm [64], equal voltage correction factor algorithm [61], TS fuzzy model and sliding mode control algorithm [65], piecewise linear form adaptation approach [66], I-V decentralized control scheme based on observer-based control methods [68], etc, are applied to enhance the current sharing performance of the droop control.

Furthermore, an optimization programming can be utilized to derive the optimum parameters of the droop mechanism [60]. As shown in Fig. 6, the overall optimization structure consists of three stages: load data processing stage, optimization stage and command stage. The loading data processing stage is first performed: the load flow analysis of each particle is performed. Then the optimization stage is entered, which is composed of three steps: particle swarm optimization (PSO) algorithm, particle swarm optimization load flow analysis (LFA) and fitness function evaluation (FFE). Finally, the execution stage is entered: through the load data processing stage and the optimization stage, these optimal droop parameters are assigned to the corresponding converters. Thus, the current sharing accuracy can be increased and the voltage drop of the droop control is reduced.

Although the particle swarm optimization algorithm modifies the problem of selecting the optimal parameters, when the external disturbance is not negligible, such as the variation of output power in the renewable DG unit. To solve this problem, a probabilistic algorithm can be applied to determine the optimal droop parameters of a single DG in a distributed network [64]. Furthermore, a communication-based technique for an equal voltage correction factor algorithm can also be employed to provide fault tolerance and scalability characteristics for the system [61]. However, it is still difficult to design a programming algorithm that can accelerate the computing and processing speed in the complex microgrids.

Moreover, a new droop control method is proposed to enhance the current sharing performance [65], which is based on the TS fuzzy model and the sliding mode control algorithm, due to the usage of time-stamp technique and network delay compensator, the presented approach is robust against the network delays with small computational burden. However, the nonlinear relationship between the output power of DGs and the voltage magnitude may not be solved due to the uncertainty and disturbance of renewable resources and loads. Furthermore, a new dc MG load sharing control strategy is adopted to eliminate the uncertainty and disturbance problem in dc MG [66]. Moreover, the control strategy of the equal-current of the I-V decentralized control can be used to modify the tradeoff between current sharing accuracy and voltage drop [67]. Compared to $V-I$ control method, $I-V$ droop control method has better dynamic response. In addition, the dynamic response and the robustness stability are enhanced by the observer-based current feedback control method when the system parameters are modified [68]. However, the current sharing of islanded MG might be poor under unbalanced and nonlinear load conditions.

It can be concluded that, to avoid the current sharing error, the particle swarm optimization programming can be used to derive the optimal parameters of the droop mechanism. Furthermore, a probabilistic algorithm can be applied to select the parameters of the operating range planning of the IMGs when the microgrid configuration is complex and there is external disturbance. Moreover, the TS fuzzy model and the sliding mode control algorithm can be applied to satisfy fault tolerance and scalability requirements for the system. However, above the droop control method faces a tradeoff between voltage regulation and load sharing accuracy.

C. CURRENT SHARING STRATEGIES BASED ON NONLINEAR DROOP CONTROL

Due to the linear droop parameter design method is influenced by the accuracy of line impedance and sensing problems, which may cause the tradeoff between voltage regulation and load sharing accuracy. To deal with the problem, the nonlinear droop control method is applied in [14], [15], [69], where the droop coefficient is a function of the output current of the converter, and its value is enlarged as the output current increases. Therefore, the effects of sensors and cables are reduced.

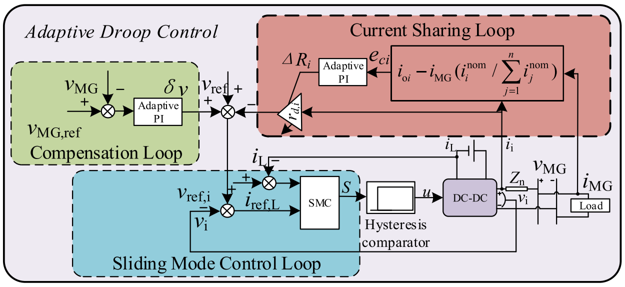

FIGURE 7. **Adaptive droop control system for dc microgrids [14].**

As shown in Fig. 7, an adaptive droop control is proposed in [14], which is regulated and compensated by two PI controllers. One adaptive PI controller is utilized to perform droop control for current sharing deviation elimination. Another adaptive PI controller is adopted to adjust the dc bus voltage of the microgrid by modifying the droop curve of the microgrid. The sliding mode control circuit is applied to control the output voltage and input current of each converter synchronously.

The adaptive PI controller is adopted to adjust the droop coefficient to eliminate the current sharing deviation in each unit of the dc MG:

$$e_{ci} = i_{oi} - i_{\mathrm{MG}}(i_i^{\mathrm{nom}} / \sum_{j=1}^{n} i_j^{\mathrm{nom}}) \tag{5}$$

where i_{oi} is the output current of the ith converter, i_{MG} is the load current, and i_i^{nom} is the nominal current of the ith converter, n is the number of converters, and another PI controller compensates the dc bus voltage of the control microgrid by moving the droop curve. Unlike conventional adaptive droop control, sliding mode control is utilized to control the output voltage and inductor current. Hence the fast dynamic response and good robustness can be realized. However, a poor current sharing may exist when MGs operate on mismatched feeder impedance, nonlinear and unbalanced load conditions.

Furthermore, the conventional droop control can be enhanced by adjusting the curve coefficient, which could be adjusted from no load to full load [69]. Specifically, the sag curve with elliptical and anti-parabola has a smaller output impedance in case of light loads, inversely, it has an infinite output impedance at full load. Since the constructor of curve fitting method between the start point and the end point is infinite. For the sake of simplicity, the conventional droop control in (6) is replaced by the polynomial equation (7):

$$v_{\mathrm{o}} = v^{*} - r_d \cdot i_{\mathrm{o}} \tag{6}$$

$$v_{\mathrm{o}} = v^{*} - \sum_{n=1}^{N} r_n \cdot i_{\mathrm{o}}^{n} \tag{7}$$

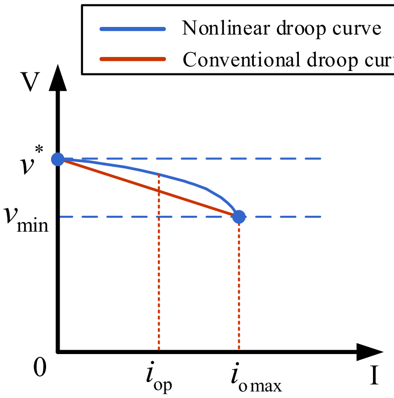

FIGURE 8. Conventional droop control and nonlinear droop control curve design [15].

where v_o and i_o are the output voltage and current, v^* is the no-load voltage set point, and the droop coefficient in (7) is the sum of the Nth power functions of the current i, r_d is the droop coefficient, r_n is the proportional coefficient of the droop coefficient of each segment output. By increasing the current order in the droop equation to increase the impedance at full load, the study shows that the droop coefficient of the fifth-order polynomial equation achieves five times the droop resistance than the linear droop and minimizes the load sharing unbalance, hence the accuracy of load current sharing is effectively enhanced. However, the power function may be difficult to be computed in the droop equation.

Moreover, considering that the droop coefficient of the power function is relatively weak within the starting range, a piecewise quadratic polynomial descent curve (PQPDC) method can be employed to fulfill the current sharing requirements for low load conditions [15], as shown in Fig. 8. The red line is the conventional linear droop curve and the blue line is the nonlinear droop curve. The nonlinear droop formula can be rewritten as

$$v_o = \begin{cases} v^* - a_1 i_o^2 - b_1 i_o & 0 < i_o \leq i_{\mathrm{op}} \\ v^* - a_2 i_o^2 - b_2 i_o - c & i_{\mathrm{op}} < i_o < i_{o\max} \end{cases} \tag{8}$$

where i_{op} is the split point output current of the converter, i_{omax} is the maximum output current of the converter, and the accuracy of current sharing among inverters is guaranteed by the configuration of the curve parameters a_1, a_2, b_1, b_2, c. Therefore, the division point i_{op} is selected according to the range of the low droop coefficient condition, where dividing the function into two parts is the most efficient, and the current sharing precision could be ensured.

To conclude, in order to achieve the tradeoff between voltage regulation and load sharing, an adaptive nonlinear droop control method can be adopted. Furthermore, the parameters of modifying the droop polynomial and adjusting the slope of the droop curve can be applied in case of the large load variation. Moreover, the piecewise quadratic polynomial descent curve (PQPDC) method can be used to enhance the real-time performance of the controller when the high-order polynomial calculation is complex. However, if scenarios are more complex, such as including dynamic (inductive) lines and loads are considered, the primary control need to be further improved. Therefore, the real-time implementation of nonlinear control strategies needs to be further explored [70]. The advantages and disadvantages of primary control and voltage compensation methods in dc microgrids are summarized in Table 1.

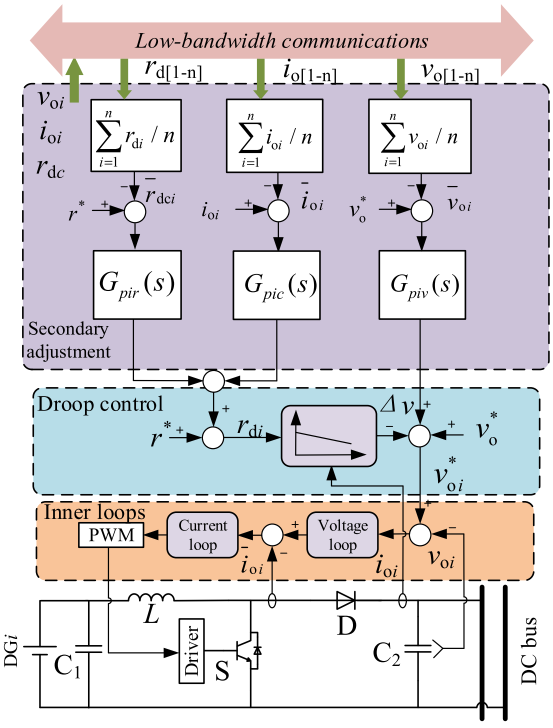

FIGURE 9. Control diagram of the dynamic load current sharing secondary control method [22].

III. UPPER-LEVEL CONTROL STRATEGY FOR DC MICROGRIDS

In order to overcome the problem of the output voltage with large variation range in the primary control, the upper-level control can be used to correct the output voltage on the basis of the current sharing accuracy [22], [23], [71]. The secondary control is responsible for the regulation of voltage fluctuation [25]–[27], and the tertiary control sets the power flow between the dc MG and the upper grid to maintain the power balance among each energy source [32]–[34], energy storage device and load. The following second-level and tertiary-level control are discussed together as upper-level control in this section, secondary compensation control, distributed multi-agent control, tertiary control, and communication delay issues will be discussed.

A. SECONDARY CONTROL STRATEGY

The voltage compensation can be participated by the secondary control to solve the voltage deviation caused by mismatched line impedance. Concretely, the output power information of each DG is exchanged through the communication link to correct the output voltage and ensure the current sharing accuracy [20]. Furthermore, the dynamic load equalization secondary control method can be adopted to converge droop coefficient with a reasonable value [22]. As shown in Fig. 9, the dynamic current sharing scheme is composed of an inner loop controller, a droop controller and a secondary controller. The inner loop controller consists of a voltage and current loop for controlling the output voltage of each converter. The reference value of the inner loop dc voltage controller is generated by the droop controller. The secondary adjustment consists of local average voltage controller, local average current controller and average droop coefficient controller.

The entire secondary control loop can be expressed as follows:

$$v_{oi}^* = v_o^* - (r_d^* + G_{\mathrm{pir}}(r_d^* - \bar{r}_{\mathrm{d}ci}) - G_{\mathrm{pic}}(i_{\mathrm{o}i} - \bar{i}_{\mathrm{o}i})) \cdot i_{\mathrm{o}i} + G_{\mathrm{piv}}(s) \cdot (v_o^* - \bar{v}_{\mathrm{o}i}) \quad (9)$$

where G_{piv}, G_{pir}, and G_{pic} are the transfer functions of the average voltage, the average droop coefficient and the average management current, respectively, $\bar{r}_{\mathrm{d}ci}$ is the average value calculated by the ith converter droop coefficient, v_o^* is the nominal voltage, $\bar{v}_{\mathrm{o}i}$ is the average value of the output voltage, $i_{\mathrm{o}i}$ and $\bar{i}_{\mathrm{o}i}$ are the output current and average output current of the ith converter, respectively.

Therefore, the average current and the droop coefficient, the equivalent output impedance of each converter is controlled to be identical by compensation controller, and the average value $\bar{r}_{\mathrm{d}ci}$ of the droop coefficient is adjusted to its reference value r_d^*. It shows that the dc voltage deviation and the current sharing accuracy are improved by voltage shifting and slope removing. However, the LBC delay are not considered in the aforementioned methods.

Moreover, a shift control called digital average current sharing (DACS) control can be utilized to maintain low voltage management of the system [23], as shown in Fig. 10. Low-bandwidth communication (LBC) is applied to determine the average current from all source converters in the conventional droop equation, and the voltage offset of each source converter is calculated by Δv_j^0.

Firstly, the controller of each source converter communicates with the controllers of other source converters and transmits the magnitude of the current supplied by it, which is used to determine the average current of all convertors:

$$i_j^{\mathrm{avg}} = \frac{\sum_{m=1}^{n} i_{om}}{n} \quad (10)$$

where i_{om} is the output current of the mth source converter.

The voltage offset of each source converter is set according to its calculated average current as follows:

$$\Delta v_j^0 = r_{\mathrm{d}j} i_j^{\mathrm{avg}} \cdot i_j^{\mathrm{nom}} \quad (11)$$

where $r_{\mathrm{d}j}$ and i_j^{nom} are the droop coefficient and the nominal current of the source converter j, respectively, the average current of all converters is i_j^{avg}. In fact, due to the variation of the source converter current, the system voltage may be varied from its nominal value. Thus, once a new current value is transferred among the converters, the new value of the restoration voltage offset Δv_j^0 would be calculated to compensate the system voltage. Moreover, the method solves the distribution of nominal voltage and load sharing, with the advantages of high reliability, low voltage management, and current sharing accuracy are also achieved. However, current sharing accuracy is difficult to be maintained if the distance among the source converters is considered.

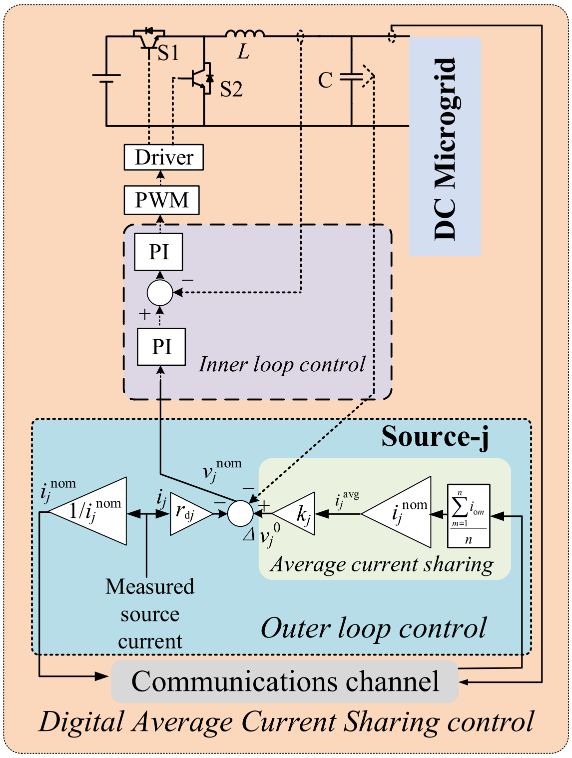

FIGURE 10. Scheme of digital average current sharing control [23].

Therefore, regarding the secondary control method of the dc MG, in order to solve the problem of large load variation, a dynamic load sharing based on secondary control method can be adopted to ensure accurate load sharing and voltage management. The current reference value can be modified by current source to enhance the power quality and voltage management. In addition, to maintain low voltage management of the system, digital average current sharing (DACS) control can be applied. Although the above-described secondary control method ensures voltage management, it may cause huge communication pressure when the scale of the microgrid is expanded, which might influence the overall control effect.

B. IMPROVED SECONDARY CONTROL METHOD

Since the conventional distributed secondary control is required to communicate with all the unit modules to obtain the average value (such as voltage, current average) [84], and this method is only static averaging, poor flexibility, large communication pressure. In order to solve the above problems, the communication topology of distributed secondary control can be enhanced by multi-agent consensus

TABLE 1. Advantages and disadvantages of primary control and voltage compensation methods in dc microgrids.

Specific problems and methods		Advantages	Disadvantages	Communication requirement
Load current sharing problem	Particle swarm optimization algorithm [64], [72], [73]	• Improve the current sharing accuracy	• Not suitable for complex loads • Not suitable for discretization problems	• No communication required
	Low bandwidth average voltage management technology [23], [57], [58], [74], [75]	• Achieve voltage management and load sharing	• Communication delay exist in the LBC lines • The algorithm is complex • Noise in the power coupling	• Low bandwidth communication required
	Improved droop control [76]	• Achieve voltage management and load sharing	• Not suitable for complex load problems	• No communication required
Line impedance problem	Droop coefficient adaptive modification [77]	• Restore dc bus voltage and enhance current sharing accuracy	• Adaptive coefficients are difficult to achieve	• No communication required
	Line impedance active identification [13]		• The algorithm is complex	• No communication required
Nonlinear droop	Nonlinear adaptive droop control [14], [69], [78], [79]	• Improve the load sharing accuracy	• Mode switch is easy to cause transients and oscillations	• No communication required
DC bus voltage compensation	Average voltage equalization control algorithm[22], [80]	• Achieve voltage management	• Not suitable for complex loads	• No communication required
	Bus voltage autonomy control [11], [81], [82]	• Enhance transient response	• Noise in the power coupling	• No communication required
	Dynamic gain droop control [83]	• Achieve voltage management and load sharing	• Not suitable for large scale MGs	• Low bandwidth communication required
	Proportional load sharing control [23], [71]	• Improve transient response	• Not suitable for complex load problems	• No communication required

algorithm [20], [21], which has been widely used to establish optimal model to enhance reliability and energy management, optimization, and improve the performance of ancillary services [27], and consensus means that the state information of all agents in the system can eventually converge to the same value [25], [26], hence all information can be averaged by distributed methods. In this section, other improved secondary control methods such as the pinning secondary control method, the two-level multi-agent system method based on the switched topology communication network control scheme, the virtual voltage-based control strategy can be applied to achieve power sharing and restore the dc bus voltage to the normal value simultaneously.

1) DISTRIBUTED MULTI-AGENT CONTROL

Fig. 11 shows a multi-agent communication network diagram, each unit is composed of a device layer, a main controller layer and an agent layer. The device layer is located at the lowest level of the platform for physical electrical component connections. The main controller is located in the middle layer and directly controls the power output of the corresponding device. This layer usually implements droop control, top-level agents and communication layer provide secondary and tertiary control, which mainly adopts distributed control circuit with consensus algorithm, only requires the neighbor information among the agent units, and iteratively evaluates the global average value to perform compensation. Moreover, consensus protocol is the rule of interaction among multiple agents in the complex systems, which describes the process of information interaction among agents and their neighbors. The realization of consensus in MAS is one of the most important direction to achieve the cooperative control. In this part, the MAS-based consensus control schemes are systematically reviewed [21], [24]–[26].

To maintain the dc bus voltage at the reference value, a distributed secondary control based on consensus algorithm is presented in [21], which adopts one of three control modes for each microgrid: power control, voltage control and droop control. However, the tie-line limitation problems are seldom fully considered when large-scale disturbances occur. In order to achieve power sharing and restore dc bus voltage, a dynamic consensus algorithm for enabling adjacent unit communication is applied in [25], [26], the pinning secondary control method can be applied to achieve power distribution and voltage restoration [24], which only sends voltage feedback information of the dc bus to one DG, without the knowledge of the global voltage information.

2) MULTI-AGENT SYSTEM COOPERATIVE CONTROL

In practical applications, to achieve coordinated control among multiple power sources for maintaining the stability of dc bus voltage, a dynamic consensus-based control strategy based on virtual voltage is presented in [28], which track the bus voltage and converge the output consensus value. As shown in Fig. 12, the local controller is composed of a bottom control layer, a compensation layer and an agent layer respectively, the local controllers communicate with adjacent controllers through distributed low-bandwidth communication and obtains corresponding voltage information.

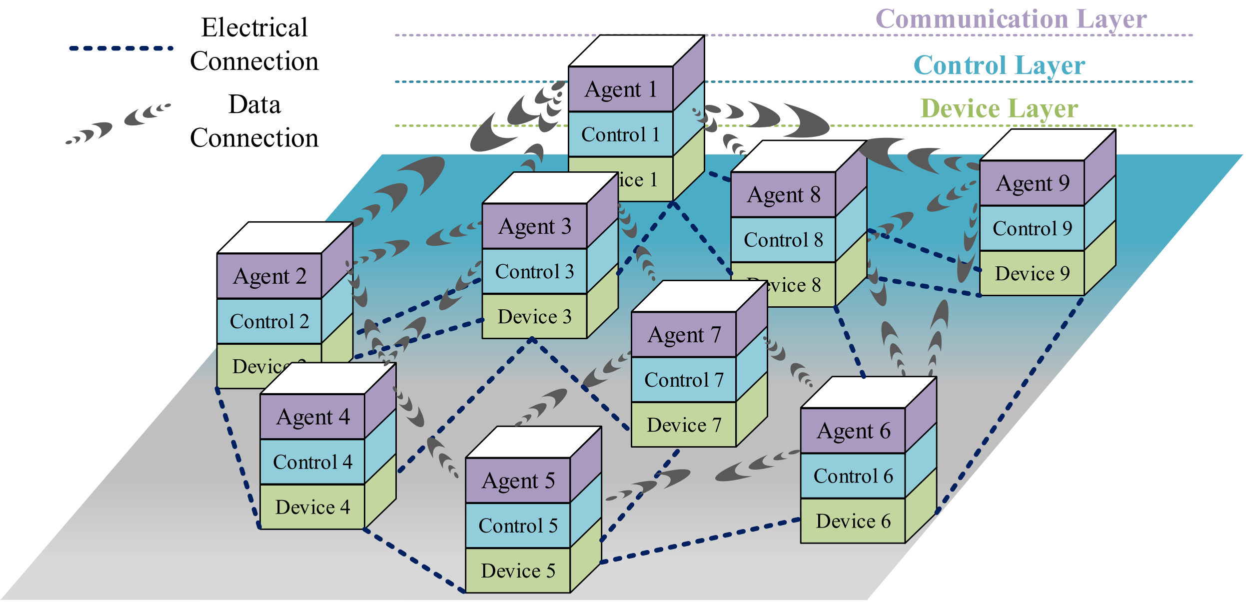

FIGURE 11. Multi-agent network communication diagram [85].

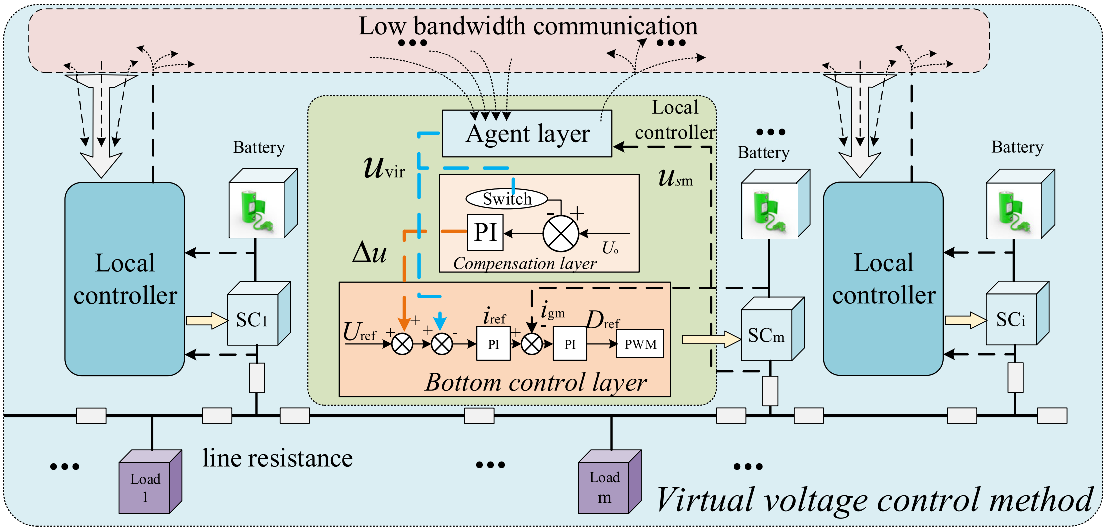

FIGURE 12. Virtual voltage control method for current sharing [28].

The multi-agent layer collects the neighboring stable controller (SC) and local SC voltage information to calculate the virtual output voltage, and the voltage of the DC bus can be represented:

$$\boldsymbol{X}(k+1)=\boldsymbol{S}(k)-\boldsymbol{S}(k-\tau)+\boldsymbol{W}\cdot\boldsymbol{X}(k) \tag{12}$$

where $\boldsymbol{X}(k)$ is the value of the kth iteration for each node voltage, $\boldsymbol{W}$ is the weight matrix of the communication network, $\boldsymbol{S}(k)$ is the response of the control system to $\boldsymbol{X}$(k), τ is time extension. Since the same reference input for each SC can be provided by the virtual voltage, the virtual voltage convergence is determined by switching function in the compensation layer, and the bus voltage level is improved by providing a compensation intercept for the bottom layer. However, it is still difficult to reduce the LBC delay among the local controllers.

To conclude, compared with various distributed control methods, in order to reduce dc bus voltage fluctuations, consensus distributed secondary control can be adapted. Furthermore, the pinning secondary control method can be applied to achieve power sharing simultaneously and restore the dc bus voltage to the normal value. In addition, to match the line impedance and output voltage among the DER units, a two-level multi-agent system method based on the switched topology communication network control scheme can be employed. Besides, a virtual voltage-based control strategy can be utilized to achieve coordinated control among multiple sources when the capacity of the dc MG is further expanded. Nevertheless, it is necessary to coordinate and control the

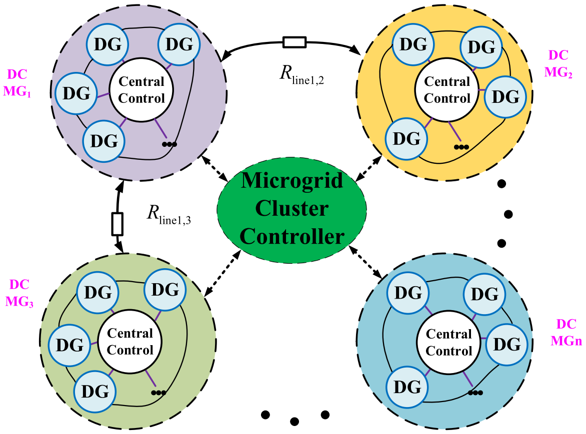

FIGURE 13. **Schematic diagram of dc microgrid cluster communication structure [34].**

global optimal power scheduling within the clusters to ensure stable and reliable operation of the dc MG.

C. TERTIARY CONTROL FOR MICROGRID CLUSTERS

Fig. 13 shows a schematic diagram of a communication structure of a microgrid cluster (MGC), and a dotted circle in the figure represents a power generation system, which is formed by connecting n DGs in parallel. The power generation units are interconnected to form a cluster system, which is abbreviated as the dc MGC [86]. Compared with the coordinated management of a single microgrid, the coordinated control of the MGC is more complicated. Hence, it is necessary to evaluate the coordinated allocation and the power optimization of energy of distributed power sources in each sub-microgrid [29], [30].

1) COORDINATED CONTROL

In order to isolate the dc fault and ensure the stable operation of the local dc bus, an islanded bidirectional dc-dc converter (IBDC) is proposed in [29], the grid-connected mode and islanded mode can be transformed automatically and seamlessly. In addition, to realize the plug-and-play function in islanded and grid-connected mode, two-layer hierarchical control of the MGC is presented in [87]. However, the communication data drop between the two-layer may not be considered. Moreover, a new plug-and-play voltage/current controller is developed to ensure the passivity and asymptotic stability of the power system and seamless plug-and-play can be achieved in each microgrid.

Furthermore, to ensure the economic operation and effective power adjustment of each microgrid, the upper control based on the hierarchical control architecture is introduced in [88]. Compared with the existing control method, this method is convenient to calculate average voltage without collection of central voltage information. However, the convergence may not be guaranteed. In addition, the multi-microgrids internal control of the tie-line restriction can be achieved by decentralized control when the power of the microgrids is excessive or deficient [33], [34]. However, this method may fail to the optimal control of the internal power flow of dc MG.

On the other hand, to buffer the energy fluctuation of the DG and control the power balance of the source load, an improved state of charge (SoC) control method can be used [35]. Specifically, consensus algorithm is employed to estimate the local average state of charge to compensate the state of charge equalization, the SoC error signal must be modified with the tertiary control:

$$SoC_{er,i}(t) = SoC_i - SoC_m - (SoC_{ref,i} - SoC_{ref,m}) \tag{13}$$

where the state of charge value and the state of charge reference value of each microgrid i are SoC_i, $SoC_{ref,i}$ respectively. The average of these values are SoC_m and $SoC_{ref,m}$ respectively. When the SoCs of the microgrid are unbalanced, the microgrid with higher SoC will increase its voltage to transfer power to those with lower SoC. Hence, the dynamic response of this method is fast in practical applications, over-discharge and over-charge of the energy storage system are avoided through energy management and energy coordinated control among microgrids can be realized. However, the storage capacity of the microgrids may not be fully considered.

2) POWER SHARING AND MANAGEMENT

In order to adjust the power setting of small MGC and realize power flow control, an architecture of a resilient small community including a distributed adaptive energy management system (EMS) of microgrids is presented in [31]. However, note that an economic dispatch type of formulation is applied for the EMS instead of optimal power flow (OPF). In addition, to fulfill the requirements of different voltage levels of dc MG and isolate fault in islanded operation, a modular-based energy router (MBER) method is presented in [32], which realizes the power flow direction of the energy router. However, it is noteworthy that, the condition for unity power factor might be violated.

In [91], a coordinated control strategy of intelligent power function is proposed, the fuzzy droop control of voltage feedback compensation is adopted to distribute the load power.

Furthermore, to eliminate the average voltage deviation on the MGs and perceive the power flow control, a distributed hierarchical control framework is adopted to ensure the reliable operation of the MGC [30]. As shown in Fig. 14, the distributed hierarchical control framework consists of two independent modules: a voltage regulator and a power flow controller, the voltage regulator is designed to regulate the average voltage of the entire cluster, and the power flow controller is used to monitor SoC of the battery in the MGs and adjust the power parameters accordingly. The local common voltage of each microgrid is determined by the SoC of the battery. The average voltage of each microgrid i can be expressed as

$$\dot{v}_i^{avg}(t) = \sum_{j \in N_i} a_{ij}(v_j^{avg}(t) - v_i^{avg}(t)) + \dot{v}_i(t) \tag{14}$$

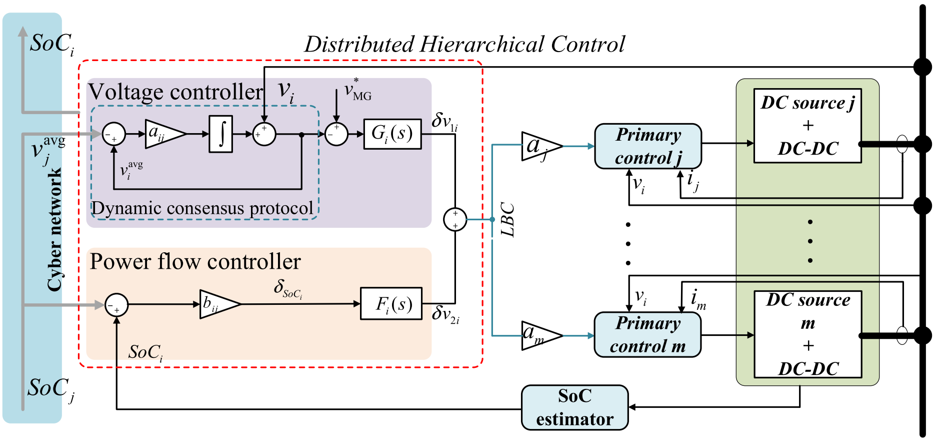

FIGURE 14. **Distributed hierarchical control framework for dc microgrid clusters [30].**

where v_i is the voltage of the ith microgrid, v_i^{avg} is an estimate of the average voltage provided by the node i estimator, the microgrid received voltage estimate of the adjacent unit v_j^{avg} is used to implement voltage regulation. The cooperative strategy is applied to compare the local SoC with the SoCs of the MG neighbors in the power flow controller, and then compared the estimated voltage with the reference value v^*_{MG}, which feedback to the PI controller to generate the voltage correction term δv_{1i} to adjust the voltage drop set value, then secondary voltage correction term generated by the local SoCs. δv_{2i} is applied to adjust the power flow among the MGs, hence, global voltage regulation is achieved. However, the storage capacity of the microgrids may not be fully considered.

In summary, for the coordinated control method of the dc MGC, in order to perceive the tertiary control of the dc MGC, the adaptive energy management system (EMS) and the modular-based energy router (MBER) can be adopted. Moreover, tie-line internal control can be utilized to ensure the constant power of the MGC, and the energy storage system (ESS) can coordinate with each other to maintain the bus voltage within a certain range. Furthermore, since the power management and control of the dc MG considering the transmission line loss is a common problem encountered in practical system, it is necessary to implement further in-depth research on the SoC of the microgrids. In addition, the communication delay effect in the overall control should be considered. The advantages and disadvantages of the various upper-level control strategies of dc MG and MGC are summarized in Table 2.

D. COMMUNICATION DELAY RESTRICTION FOR MICROGRIDS AND MICROGRID CLUSTER

Indeed, there may exist multiple time delays in different exchange channels. Once any coupling happens among those multiple delays, unrevealed risks might occur and even affect the stability of the whole cluster [37], [38]. Fig.15 shows the Schematic diagram of dc microgrid cluster communication delay propagation, the red dotted line may cause multiple delay couplings, which influences the overall control effect. However, most of the existing distributed control strategies may not evaluate the impact of delay on system stability when designing the controllers. Thus, this section analyzes the delay stability problem, which provide a basis for the system to reduce the communication congestion and select the stability domain [41], [42].

1) COMMUNICATION CONGESTION PROBLEM IN THE UPPER CONTROL

In general, most of the existing technologies rely on the communication values of the terminal voltage and output current of each source. However, when the size of the microgrid is expanded, huge data exchange would result in exhaustion of network resources quickly, which may cause serious communication burden and unreliable operation.

In order to reduce the communication congestion. In [96] , an online algorithm based on the quality index is employed to derive the optimal droop coefficient. Compared with the centralized controller, as only output current information is exchanged among sources, it does not require the knowledge of the system parameters. In addition, an event-based consensus distributed control method is proposed in [36], the proportional power flow among sub-microgrids can be achieved. Furthermore, a distributed consensus control method for achieving power sharing among dc MGC is presented in [97]. However, it is still difficult to design a good consensus protocol that can realize the optimal power flow [98].

It is noteworthy that, the existing cooperative control of dc MG relies on the communication network, which makes them vulnerable to cyber attacks. To mitigate the adverse effects of such attack communication chain and controller hijack, the global trust-based resilience cooperative control can be applied [37], [38], as shown in Fig. 16, it consists of a physical layer, a control layer and a cyberspace layer. When an external attack is coming, the trust values of the faulty unit and the adjacent unit is indifference, then the distributed cooperative control is adjusted to reduce the adverse effects of attacks on communication links and controller hijack.

TABLE 2. Advantages and disadvantages of the various upper-level control strategies in dc microgrids and microgrid clusters.

Upper-level control method	Major technologies	Advantages	Disadvantage	Application
Secondary control of dc microgrids	Flexible coordination control [29]	• Electrical isolation • High reliability	• Total generation cost of MGs is not considered	• Operation mode is switched
	Energy continuous power control [89], [90]	• DC bus voltage fluctuations are reduced	• Without considering frequently charging and discharging	• Operation mode is switched
	Modular energy tracker control [32]	• Multi-directional energy exchange	• Complex line impedance conditions is not considered	• Low voltage microgrids
	Tie-line internal chain control [33], [34]	• DC bus voltage fluctuations are reduced	• Not satisfied with plug and play • Transmission power limitation	• MG for without communication requirement
Tertiary control of dc microgrids	EMS power control[31]	• Voltage deviation is reduced • Power flow control is achieved	• Lack of operation and control of internal MGs	• Small low voltage MGC
	Adaptive control [35], [91]	• Power flow control is achieved	• Voltage deviation exist in the system	• Small MGC
	Finite time consensus algorithm method [88], [92]	• Convenient calculation • Good robustness	• Need to determine the convergence factor to determine convergence	• Load variation conditions
	Power flow control [30], [93]	• Good robustness • Plug and play	• Complex MGC is not considered	• Internal voltage deviation exists
	Plug and play control [87], [94], [95]	• Good robustness	• Complex MGC is not considered	• Small MGC

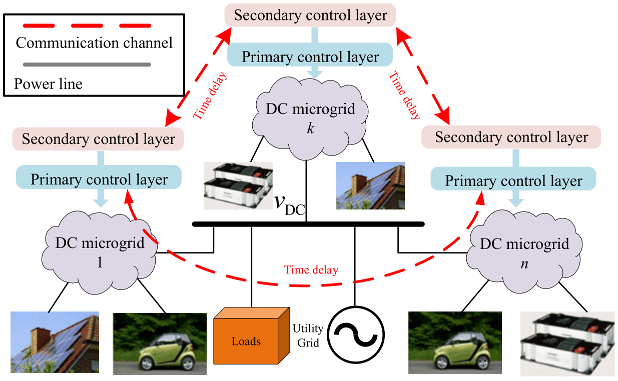

FIGURE 15. Schematic diagram of dc microgrid cluster communication delay propagation [39].

As shown in Fig. 16, during the external attack of the converter 1, whose trust value assigned to the converters 2, 4 drop and the weight associated with the neighbor information decreases, thereby the propagation of the attack is limited. The trust value of the kth conventer is assigned by the jth conventer:

$$T^i_{jk} = \max(C^i_j(t), b^i_{jk}(t)) \tag{15}$$

where $C^i_j(t)$ is the local trust value of converter j, $b^i_{jk}(t)$ is the proximity trust value of converter j, if the trust value of any converter is less than the minimum trust value $T^i_{jk} < \tau_j$, the information received from converter k will be from converter j removed from the control structure, the larger the adjacent information difference, the lower the value of T^i_{jk}. Thus, in order to guarantee the attack restoration capability, damaged converter can be recognized in case of more than half of the adjacent converters, the adverse effects of attacks on communication links and controller hijacking are mitigated.

2) COMMUNICATION DELAY COMPENSATION FOR DC MICROGRID STABILITY IMPROVEMENT

As discussed in part D1, the distributed control method involves the communication delay problem in the communication network. It is noteworthy that, the delay caused by communication lines is mainly divided into fixed communication delay and random communication delay. The fixed delay usually depends on the hardware and software performance of the equipment, the bandwidth of the communication network and transmission distance, while random delay usually relies on the protocol of the MAS layer, connection type and network load. Therefore, it is a crucial issue to maintain the stability of the dc MG under fixed delay and random delay conditions.

In order to eliminate the influence of fixed communication delay on system stability, a distributed quadratic control algorithm is proposed in [39], and the fixed delay correlation stability criterion using linear matrix inequality are discussed. However, this scheme is rather complex, which cannot handle the random delay determined by the protocol in the MAS layer. Moreover, to eliminate the influence of random communication delay on system stability, a new method based on the distributed control strategy is presented in [40], which

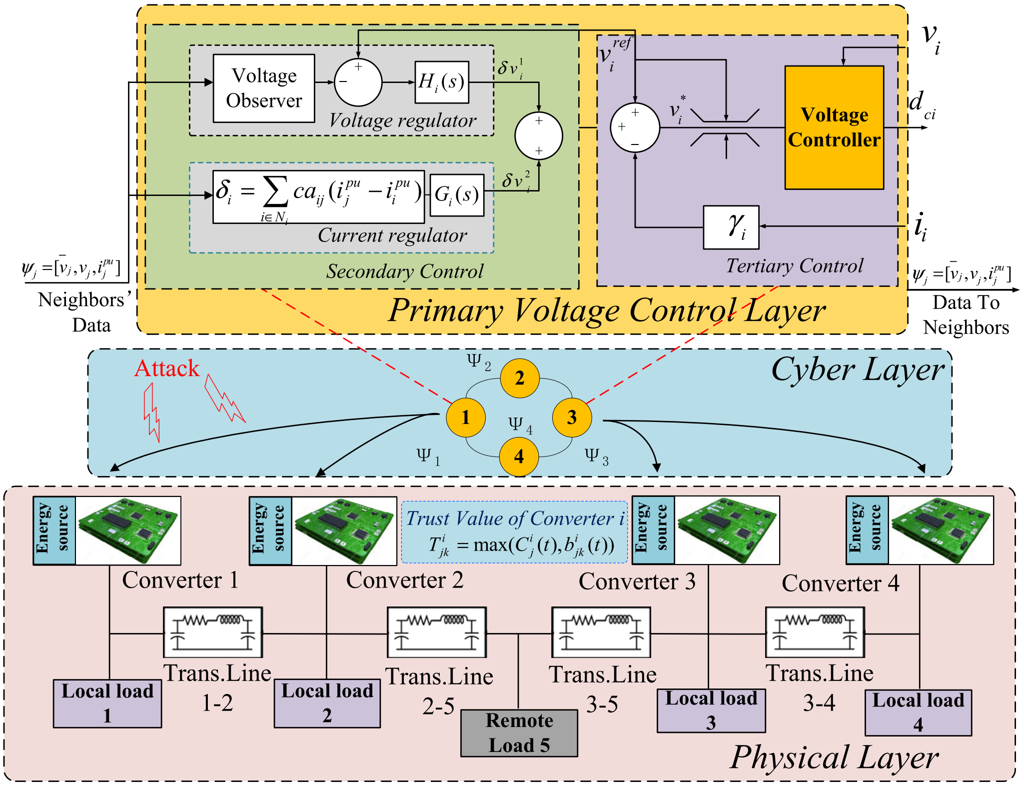

FIGURE 16. Trust-based resilience distributed cooperative control method [37].

transforms the transcendental characteristics equation of the microgrid model into the Nyquist stability problem, and the upper bound of the delay is analyzed.

Furthermore, to overcome the effects of multiple delay coupling, a distributed control framework based on dc MG is proposed in [99], and the delay stability of the dc MGC is improved by setting strict constraints on a channel or using a non-uniform network. In addition, Takagi–Sugeno's fuzzy model and model predictive scheme is studied to mitigate the communication network delays from the sensor-to-controller and controller-to-actuator links [42], it can be applied to large-scale distributed energy systems with small computation load. However, for the system with a large time constant, the calculation and execution of control algorithm will be huge and dynamic response of the system would be sluggish. In [41], for the secondary control of distributed cooperation of dc MG, the Lyapunov-Krasovskii functional stability analysis method is also used to ensure the system stability [41].

It can be concluded that, a consensus distributed control method can be adopted to reduce the communication congestion among internal converters. In addition, in order to determine the delay boundary and eliminate the influence of communication delay on stability, linear matrix inequality (LMI) and Lyapunov-Krasovskii functional stability methods can be used, where Linear matrix inequality (LMI) can be applied to study the stability of time-varying delays. Takagi–Sugeno's fuzzy model and model prediction scheme can be used to provide selection of dc MG stability domain in the large-scale distributed energy systems. Moreover, with the development of communication, the boundaries of each control layer show a weakening trend. Due to the limitation of existing communication rate and reliability, real-time control of various time scales in dc MG is worthy further study.

The advantages and disadvantages of various dc MG hierarchical control methods considering communication delay are summarized in Table 3.

IV. LOAD STABILITY ANALYSIS IN THE DC MICROGRIDS

In order to achieve safe and reliable MG performance, its dynamic stability needs to be ensured in all operating conditions. Especially when the load side power converter is strictly controlled, these point of load point (POL) converters and their associated loads are generally considered to be constant power loads. However, the dc MG would become unstable due to the negative impedance characteristics introduced by CPLs [44]–[46]. Thus, to solve the problem of system instability caused by large-scale access of constant power load in dc MG, various strategies for enhancing the system stability is reviewed in this section: applying a virtual impedance to cancel out the negative impedance [47], employing model prediction to counteract the negative impedance [48], utilizing feedback control to cancel out the negative impedance [49], [52].

TABLE 3. Advantages and disadvantages of layered control in dc microgrids under communication delay.

Communication delay problems	Major technologies	Advantages	Disadvantages	Application
Current sharing problem	Low bandwidth distributed control [61], [84]	• Precise load power distribution • Stable dc bus voltage	• Load variation is not considered	• Low voltage microgrids
	Adjust voltage set point consensus algorithm [27], [28], [97]	• Plug and play • Improve the load current sharing accuracy	• Good algorithm are difficult to design	• Physical and cyber attacks
	Internal microgrids link power allocation [36]	• Reduce the communication congestion between internal converters	• Not suitable for complex microgrids	• Microgrids with large communication demand
Voltage deviation problem	Voltage noise resilience observation control[37], [38]	• Precise load power distribution • Stable dc bus voltage	• Data drop is not considered	• Current controller information is attacked
	Multi-mode consensus control [21], [24], [25], [26]	• Plug and play • Without voltage deviation	• Tie-line limitation is not considered	• Small disturbance occasion
	Improved secondary control method [22], [100]	• Without voltage deviation • Enhance the current sharing accuracy	• Global information cannot be easily obtained	• Low voltage microgrids

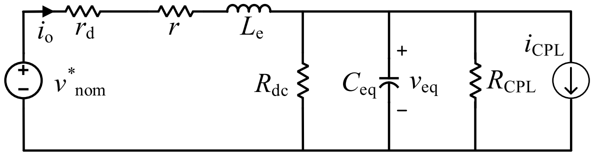

FIGURE 17. Simplified equivalent circuit for the CPLs of a dc microgrid system [101].

A. VIRTUAL IMPEDANCE CONSTRUCTION FOR CPLs

Due to the negative impedance of the CPLs, power oscillations are common problems in dc MGs when the LC filter inputs constant power loads (CPLs). Fig. 17 shows a simplified dc MG equivalent circuit to describe this phenomenon. where the dc bus voltage nominal value is v^*_{nom}, source droop coefficient is r_d, CPL line inductance is L_e, line resistor is r, equivalent load resistance is R_{dc}, CPL side equivalent capacitance is C_{eq}, capacitor voltage is v_{eq}, output current is i_o, CPL power is P_{CPL}, CPL equivalent resistance is R_{CPL}, CPL current is i_{CPL}. The global equivalent impedance can be expressed as

$$Z(s) = \frac{r_d + R_e + L_e s}{a_2 s^2 + a_1 s + a_0} \tag{16}$$

where,

$$\begin{cases} a_0 = 1 + (r_d + R_e)(1/R_{dc} + 1/R_{CPL}) \\ a_1 = C_{eq}(r_d + R_e) + L_e(1/R_{dc} + 1/R_{CPL}) \\ a_2 = C_{eq}L_e \end{cases} \tag{17}$$

$$R_{CPL} = -\frac{v_{eq}^2}{P_{CPL}} \tag{18}$$

In order to ensure the asymptotical stability of the system, the equivalent impedance $Z(s)$ has no pole in the left half plane, according to the Hurwitz stability criterion:

$$a_i > 0, \quad i = 1, 2, 3 \tag{19}$$

Solving (16), (17), (18), (19), the following equation can be derived:

$$\begin{cases} P_{CPL} < v_{eq}^2 \cdot \left(\frac{1}{r_d + R_e} + \frac{1}{R_{dc}}\right) \\ P_{CPL} < C_{eq}(r_d + R_e)v_{eq}^2/L_e + v_{eq}^2/R_{dc} \end{cases} \tag{20}$$

It can be deduced from (20), in the control diagram of the interface converter, the stability margin of the system can be increased by applying the virtual impedance to cancel out circuit inductance L_e. Therefore, in order to improve the damping of the dc MG with CPL, a virtual impedance stabilization control method can be used to introduce a virtual impedance into the output filter [102], the unstable pole caused by CPLs moves to the stable region to ensure the system stability. Furthermore, considering the voltage drop under large load variation conditions, a new active damping technique for CPL low damping input LC filter stabilization scheme is designed in [47]. In addition, a new type of active damping method is proposed in [103], which is reloaded by superconducting capacitors of the dc MG, hence the dc bus voltage oscillation can be eliminated and the system stability can be enhanced.

In the conventional active damping method, the system stability is achieved by injecting an additional current into the CPLs to adjust the input impedance, but the injected current causes fluctuations in the rotational speed of the motor loads. In order not to degrade the performance of the CPL, the output impedance is indirectly reduced by establishing a virtual resistor on the source side converter in [104], which guarantees system stability according to Middlebrook's stability criterion. However, this approach exists limitation on the closed-loop bandwidth of the source-side converter, and the requirement for the resonant frequency of the LC input filter adds additional constraints to the design of the LC filter. In addition, the smart resistor can be operated as a linear resistor CPL [105], which reduces the bulk of the capacitor and also assists decouple the power supply and load control. Thus,

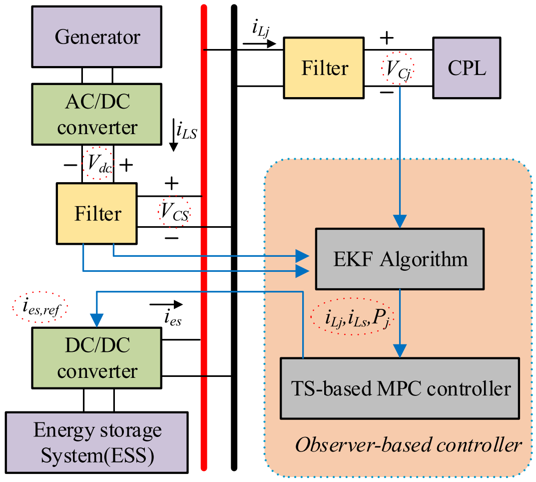

FIGURE 18. Simple block diagram of the extended Kalman filtering (EKF) method [48].

the load is dynamically stabilized locally and the overshoot current is made impossible.

Therefore, the impedance branch can be employed to reduce the voltage drop on the output side of the source converter under large load variation conditions, and the virtual impedance can be cancelled out the negative impedance. However, if it is difficult to construct a virtual impedance on the source-side converter. The active damping method can be used to apply the superconducting capacitor or smart resistor to reshape the load, hence the dc bus voltage oscillation can be eliminated and the stability of the system can be improved.

B. MODEL PREDICTION CONTROL FOR CPLs

In order to eliminate the instability effect of CPLs, the injected current of the energy storage system (ESS) can be modified by an online adaptive controller method to match the estimated power of the CPLs. The model prediction controller (MPC) is a popular control scheme, which considers the control objectives to obtain the control signal as an optimal multi-objective control problem [106].

At present, to estimate the power variation of the CPLs, adaptive control is widely adopted to drive the controller through the injection current of the energy storage system, and the current sensor is required to measure the power of the CPL. However, it is expensive and not optimal. In order to estimate the uncertain power variation in the dc MG, an extended Kalman filter (EKF) method can be applied [48], as shown in Fig. 18, the uncertain CPL power of time varying is estimated by measuring the input and output filter capacitor voltage and dc bus voltage, then the estimated power is used to control the energy storage unit based on the Takagi–Sugeno fuzzy model predictive controller (MPC), which represents a complex nonlinear system by a set of fuzzy rules, where the consequent parts are linear state-space equations. Then, the complex nonlinear system can be described as a nonlinearly weighted sum of these linear state equations. Compared with the existing methods, the transient performance is improved and the injected current is reduced. Thus, the dc MG with higher CPL power can also be stabilized, which guarantees the uncertain power flow. However, the model predictive controller poses noise susceptibility issue, hence an appropriate filter is needed.

Moreover, to derive the existence of system equilibrium, the quadratic equation solvability problem of the dc MG equilibrium state can be transformed into an existence problem of the fixed point for an increasing fractional mapping [107]. Furthermore, the system eigenvalues can be calculated to study the influence of controller gain on the stability of the microgrid when the system is subject to small disturbances [108]. However, this method requires a detailed state space model of the whole system.

To conclude, considering the structural model prediction to cancel out the negative impedance, the system eigenvalues could be calculated to analyze the stability when the detailed state space model of the whole system can be obtained. Furthermore, the extended Kalman filter (EKF) method is adopted to estimate the time-varying power. Moreover, the energy storage system can be employed to match the power of the CPLs for estimating the uncertain CPL time varying power transient performance.

C. LINEAR AND NONLINEAR FEEDBACK TECHIQUES FOR CPLs

In general, adaptive feedback technology is one of the most effective methods to deal with system stability problems [109]. In contrast to the model prediction control technique, feedback linearization can compensate any amount of CPL and stabilizes the system in large-signal model. However, the major drawbacks of this approach are its noise sensitivity due to the presence of differentiator and slower transient response compared to techniques which handle CPL nonlinearity directly.

Furthermore, a compound nonlinearity approach based on the nonlinear disturbance observer (NDO) feedforward compensation method for stabilizing the CPLs is presented in [50]. As shown in Fig. 19, the nonlinear problem introduced by CPL is first processed with precise feedback linearization technique. Furthermore, the NDO technique is adopted to estimate the load power variation with fast dynamic response for feedforward compensation. Moreover, the step-and-reverse algorithm with large signal stability is utilized to obtain the duty cycle. Thus, the global stability of CPL under large fluctuations can be guaranteed. However, the feedback controller might significantly deteriorate the load performance.

In addition, the buck converter can be cascaded with the LC input filter to increase the system stability and prevent harmonic injection. However, it adds complexity to the system. To simplify the control algorithm, a linear feedback control can be used to overcome the negative impedance characteristics and stabilize the system [49]. Furthermore, a new robust controller can be applied to minimize the oscillation caused by CPL [110]. The Chebyshev theory is adopted for a linear

TABLE 4. Advantages and disadvantages of various methods to cancel out the CPLs negative impedance characteristics.

Major technologies	Advantages	Disadvantages	Application	Determination method
Applying virtual impedance method [47], [101]-[105]	• Enhance system damping • Good robustness • Eliminate dc bus voltage oscillation	• Closed-loop bandwidth limitation	• Poorly damped system	• Nyquist stability criterion • Lyapunov stability criterion
Model prediction control[48], [107], [108]	• Good transient performance	• The algorithm is complex	• Lower order system	• Tarski fixed point theory
Employing feedback control scheme [49], [50], [110]	• Fast dynamic response • Accurate tracking	• Limited scope of stability	• The power of CPLs is unknown	• Chebyshev theory • Routh-Hurwitz stability criterion
Global stability [51]-[53], [111], [112]	• Ideal robustness	• Conservative	• When bus voltage is faulty • Predict system instability domain	• Lyapunov stability criterion • Semidefinite programming

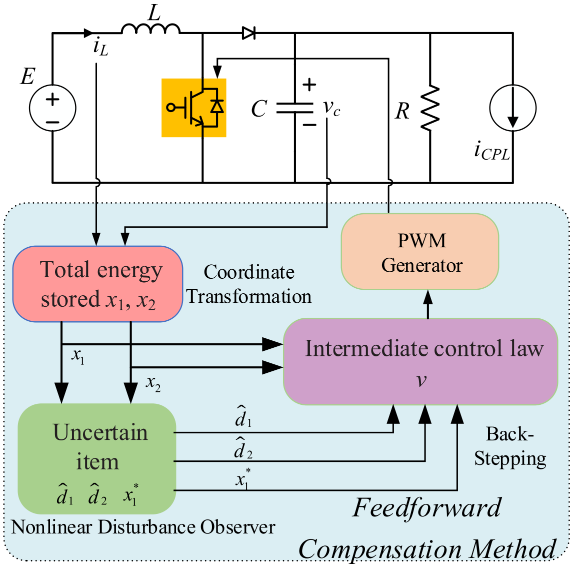

FIGURE 19. Architecture of the feedforward compensation method based on nonlinear disturbance observer [50].

programming algorithm in robust control. Thus, the stability and robustness of the MG can be ensured.

It can be concluded that the feedback control can be utilized to counteract the negative impedance in case of the large power variation of the CPL. The feedforward compensation method of the nonlinear disturbance observer (NDO) is adopted for fast dynamic response, and the power variation of the CPL is accurately tracked. Moreover, linear programming algorithm can be used to compensate the dc bus voltage oscillation and the robustness of the system can be guaranteed.

D. OTHER POSSIBLE METHODS

In the distributed power architecture dc microgrid systems, the implementation of the above feedback techniques might be more complicated. Therefore, the simplified computation of the overall stability is particularly crucial, possible methods are summarized, such as the relevant stability criteria [51], the estimation of the region of attraction algorithm and the linear system analysis of polyhedral uncertainty can be established to achieve the ideal robustness index and ensure system stability margin [52], [53].

The stability analysis of the system based on a discrete-time model of the system is established in [111]. The stability margin of the system can be determined by adjusting the parameters of the filter. Moreover, the stability margin of the system based on the hybrid potential theory is predicted in [51], which guarantees the stability of the system under large disturbances and allows the system to quickly return to steady- state. Furthermore, in order to eliminate the semi-determined problem (SDP) of robustness index, an approach to calculate an estimate the domain of attraction is presented in [52], which uses energy storage technology to mitigate transient faults. Meanwhile, an ideal robustness index and extends the region of attraction (ROA) of the operational point can be achieved.

However, most of the existing work are based on some nominal values of CPLs to study the stability around a given equilibrium point, the frequently varies in load conditions are not fully considered. In order to solve this problem, the equilibrium problem of the dc MG in the operational feasible set based on the stability robustness framework is designed in [53]. Furthermore, a fault-tolerant stable system is presented to eliminate the problem of loss of load agent [112], which guarantees the fault tolerance of multi-agent stability systems and ensures the stability of the microgrid, and the influence of the negative input impedance characteristics of the CPL can be reduced as well.

In conclusion, for overall stability improvement, hybrid potential theory can be established to mitigate the impact of disturbance. Furthermore, the algorithm for calculating the region of attraction and the linear system analysis of the polyhedral uncertainty can be used to achieve the ideal robustness index and ensure the stability margin of the system. Moreover, in order to further improve the overall system stability, it is recommended to study the impact of various CPLs on system performance and provide a mechanism to estimate the power of CPLs. Conservative problems in these cases and global stability control issues necessitates further research.

The advantages and disadvantages of various methods to cancel out the negative impedance characteristics of CPLs are shown in Table 4.

V. CONCLUSION AND PROSPECTS

This paper presents an overview of the power sharing, voltage restoration methods in hierarchical controlled dc microgrids. Owing to the negative impedance characteristics by CPLs, which may result in the output oscillation of filter. A comprehensive analysis and comparison of the stabilization techniques methods to improve system stability have been presented in the dc microgrid.

Firstly, since the line impedance has great randomness, the optimal droop parameters can be assessed by particle swarm optimization algorithm, probabilistic algorithm and equal voltage correction factor algorithm can be employed to improve the current sharing accuracy. Furthermore, in order to eliminate the tradeoff between voltage regulation and load sharing, the optimal power allocation can be achieved by adjusting the parameters of the droop polynomial, the slope of the droop curve and the piecewise quadratic polynomial descent curve (PQPDC). Moreover, to deal with the problem of the system voltage caused by the droop control deviation, the secondary control can be applied to participate in the voltage compensation, and the output voltage can be corrected on the basis of ensuring the current sharing accuracy. Thus, by adopting dynamic load current sharing method, consensus distributed secondary control approach, muti-agent system (MAS) control and virtual voltage control strategy, etc, the voltage could be regulated and power sharing can be achieved.

For the coordinated control of the microgrid clusters, in order to perceive the tertiary control of the dc MGC, an adaptive energy management system (EMS), a modular-based energy router (MBER), tie-line internal control, nose resilience observation control and other methods can be used to ensure global voltage management and power flow direction of the microgrid clusters. In addition, to determine the delay boundary and eliminate the influence of communication delay, linear matrix inequality (LMI) and Lyapunov-Krasovskii functional stability methods can be used. Moreover, Takagi–Sugeno's fuzzy model and model prediction scheme can be used to provide a basis for dc MG stability domain selection in case of applying in large-scale distributed energy systems.

Meanwhile, to eliminate the negative impedance characteristics introduced by CPLs, the feedforward compensation method of nonlinear disturbance observer (NDO) can be adopted, which can track the power variation of CPLs quickly. Moreover, the linear programming algorithm can be applied to compensate the oscillation of the dc bus voltage to enhance the robustness of the system. Furthermore, in order to analyze the influence of system parameters on system stability, the hybrid potential theory can be used to mitigate the impact of disturbance. In addition, when the system is under large disturbance, the algorithm of estimating the attraction domain and the linear system analysis method of polyhedral uncertainty can be used to achieve the ideal robustness index and ensure the stability margin of the system.

As can be concluded from the previous discussion, each summarized control technology has its own characteristics, advantages and disadvantages. In recent years, the research on hierarchical control and load stability are gradually deepened. Finally, the detailed future trends and recommendations are as follows:

1) Considering more complex scenarios, such as dynamic lines and loads. Simultaneously, the real-time implementation of the nonlinear load control strategy requires a lot of research work. In order to make distributed control more effective for secondary and superior control, a lot of research work is required. Moreover, mathematical analysis of distributed control strategies remains a complex and challenging issue. Furthermore, the distributed control strategy requires to continue to develop. From the perspective of the control protocol, the diffusion is a candidate algorithm which is superior to the consensus algorithm in the convergence speed and average stability of the distributed network.
2) Due to the limitations of existing communication rates and reliability, it is difficult to achieve real-time control at various time scales in dc MGs. With the development of communication technology, the boundaries of each control layer are weakened. Specifically, distributed optimization assesses transmission line loss and voltage, current operation limit of dc MG power management and control, economic dispatch and power generation cost. Furthermore, the power consensus algorithm generates a new set of power flow equations, and its solvability remains to be studied. The power consensus algorithm preserves the geometric weighted average of the voltage, which is a compelling application for a nonlinear consensus algorithm.
3) One of the research focuses on CPL stability is to use linear and nonlinear control techniques to mitigate the adverse dynamic effects introduced by CPLs. Moreover, more efficient nonlinear filters such as cubic Kalman filters is one of the trends in the future research. In addition, it is also suggested to study the impact of various CPLs on system performance and provide a mechanism for estimating the power of CPLs. Furthermore, conservative problems in these cases and global stability control issues needs further study.

REFERENCES

[1] K. Rahbar, C. C. Chai, and R. Zhang, "Energy cooperation optimization in microgrids with renewable energy integration," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1482–1493, Mar. 2018.

[2] A. T. Eseye, M. Lehtonen, T. Tukia, S. Uimonen, and R. J. Millar, "Optimal energy trading for renewable energy integrated building microgrids containing electric vehicles and energy storage batteries," *IEEE Access*, vol. 7, pp. 106092–106101, 2019.

[3] R. H. Lasseter, "MicroGrids," in *Proc. IEEE Power Eng. Soc. Winter Meeting Conf.*, Jan. 2002, pp. 305–308.

[4] T. Dragicevic, J. C. Vasquez, J. M. Guerrero, and D. Skrlec, "Advanced LVDC electrical power architectures and microgrids: A step toward a new generation of power distribution networks," *IEEE Electrific. Mag.*, vol. 2, no. 1, pp. 54–65, Mar. 2014.

[5] A. T. Ghareeb, A. A. Mohamed, and O. A. Mohammed, "DC microgrids and distribution systems: An overview," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2013, pp. 1–5.

[6] F. Gao, S. Bozhko, A. Costabeber, G. Asher, and P. Wheeler, "Control design and voltage stability analysis of a droop-controlled electrical power system for more electric aircraft," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9271–9281, Dec. 2017.

[7] J. G. Ciezki and R. W. Ashton, "Selection and stability issues associated with a navy shipboard DC zonal electric distribution system," *IEEE Trans. Power Del.*, vol. 15, no. 2, pp. 665–669, Apr. 2000.

[8] C.-H. Tsai, Y.-W. Bai, M.-B. Lin, R. J. R. Jhang, and C.-Y. Chung, "Reduce the standby power consumption of a microwave oven," *IEEE Trans. Consum. Electron.*, vol. 59, no. 1, pp. 54–61, Feb. 2013.

[9] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC microgrids—Part II: A review of power architectures, applications, and standardization issues," *IEEE Trans. Power Electron.*, vol. 31, no. 5, pp. 3528–3549, May 2016.

[10] R. S. Balog and P. T. Krein, "Bus selection in multibus DC microgrids," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 860–867, Mar. 2011.

[11] K. Sun, L. Zhang, Y. Xing, and J. M. Guerrero, "A distributed control strategy based on DC bus signaling for modular photovoltaic generation systems with battery energy storage," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 3032–3045, Oct. 2011.

[12] H. Kakigano, Y. Miura, and T. Ise, "Distribution voltage control for DC microgrids using fuzzy control and gain-scheduling technique," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2246–2258, May 2013.

[13] C. Liu, J. Zhao, S. Wang, W. Lu, and K. Qu, "Active identification method for line resistance in DC microgrid based on single pulse injection," *IEEE Trans. Power Electron.*, vol. 33, no. 7, pp. 5561–5564, Jul. 2018.

[14] M. Mokhtar, M. I. Marei, and A. A. El-Sattar, "An adaptive droop control scheme for DC microgrids integrating sliding mode voltage and current controlled boost converters," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 1685–1693, Mar. 2019.

[15] H. Liang, Y. Huang, and Z. Liu, "Research on nonlinear drooping control strategy of DC microgrid," in *Proc. IEEE Region 10 Conf. (TENCON)*, Oct. 2018, pp. 0865–0870.

[16] D. Salomonsson, L. Soder, and A. Sannino, "An adaptive control system for a DC microgrid for data centers," in *Proc. Ind. Appl. Conf.*, Nov. 2008, pp. 2414–2421.

[17] P. García, P. Arboleya, B. Mohamed, and A. A. M. C. Vega, "Implementation of a hybrid distributed/centralized real-time monitoring system for a DC/AC microgrid with energy storage capabilities," *IEEE Trans. Ind. Informat.*, vol. 12, no. 5, pp. 1900–1909, Oct. 2016.

[18] X. Lu, J. M. Guerrero, K. Sun, J. C. Vasquez, R. Teodorescu, and L. Huang, "Hierarchical control of parallel AC-DC converter interfaces for hybrid microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 683–692, Mar. 2014.

[19] L. Meng, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Tertiary and secondary control levels for efficiency optimization and system damping in droop controlled DC–DC converters," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2615–2626, Nov. 2015.

[20] D.-H. Dam and H.-H. Lee, "A power distributed control method for proportional load power sharing and bus voltage restoration in a DC microgrid," *IEEE Trans. Ind. Appl.*, vol. 54, no. 4, pp. 3616–3625, Aug. 2018.

[21] Z. Wang, F. Liu, Y. Chen, S. H. Low, and S. Mei, "Unified distributed control of stand-alone DC microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 1013–1024, Jan. 2019.

[22] P. Wang, X. Lu, X. Yang, W. Wang, and D. G. Xu, "An improved distributed secondary control method for DC microgrids with enhanced dynamic current sharing performance," *IEEE Trans. Power Electron.*, vol. 31, no. 9, pp. 6658–6673, Sep. 2016.

[23] S. Anand, B. G. Fernandes, and J. Guerrero, "Distributed control to ensure proportional load sharing and improve voltage regulation in low-voltage DC microgrids," *IEEE Trans. Power Electron.*, vol. 28, no. 4, pp. 1900–1913, Apr. 2013.

[24] F. Guo, Q. Xu, C. Wen, L. Wang, and P. Wang, "Distributed secondary control for power allocation and voltage restoration in islanded DC microgrids," *IEEE Trans. Sustain. Energy*, vol. 9, no. 4, pp. 1857–1869, Oct. 2018.

[25] L. Meng, T. Dragicevic, J. Roldán-Pérez, J. C. Vasquez, and J. M. Guerrero, "Modeling and sensitivity study of consensus algorithm-based distributed hierarchical control for DC microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1504–1515, May 2016.

[26] X. Lu, X. Yu, J. Lai, J. M. Guerrero, and H. Zhou, "Distributed secondary voltage and frequency control for islanded microgrids with uncertain communication links," *IEEE Trans. Ind. Informat.*, vol. 13, no. 2, pp. 448–460, Apr. 2017.

[27] C. Dou, D. Yue, Z. Zhang, and K. Ma, "MAS-based distributed cooperative control for DC microgrid through switching topology communication network with time-varying delays," *IEEE Syst. J.*, vol. 13, no. 1, pp. 615–624, Mar. 2019.

[28] W. Xie, "Multi-source coordinated control strategy of DC micro-grid based on virtual voltage," in *Proc. CSEE*, Oct. 2018, pp. 1408–1418.

[29] X. Li, L. Guo, Y. Li, C. Hong, Y. Zhang, Z. Guo, D. Huang, and C. Wang, "Flexible interlinking and coordinated power control of multiple DC microgrids clusters," *IEEE Trans. Sustain. Energy*, vol. 9, no. 2, pp. 904–915, Apr. 2018.

[30] Q. Shafiee, T. Dragičević, J. C. Vasquez, and J. M. Guerrero, "Hierarchical control for multiple DC-microgrids clusters," *IEEE Trans. Energy Convers.*, vol. 29, no. 4, pp. 922–933, Dec. 2014.

[31] I. Ciornei, M. Albu, M. Sănduleac, E. Rodriguez-Diaz, R. Teodorescu, and J. Guerrero, "Adaptive distributed EMS for small clusters of resilient LVDC microgrids," in *Proc. IEEE Int. Conf. Environ. Elect. Eng., IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Eur.)*, Jun. 2018, pp. 1–6.

[32] C. Tu, F. Xiao, Z. Lan, Q. Guo, and Z. Shuai, "Analysis and control of a novel modular-based energy router for DC microgrid cluster," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 7, no. 1, pp. 331–342, Oct. 2019.

[33] S. Adhikari, X. Qianwen, Y. Tang, and P. Wang, "Decentralized control of DC microgrid clusters," in *Proc. IEEE 3rd Int. Future Energy Electron. Conf. ECCE Asia (IFEEC-ECCE Asia)*, Jun. 2017, pp. 567–572.

[34] Z. Luo, H. Geng, and G. Zhu, "Hierarchical cooperative control for islanded DC microgrid cluster," in *Proc. IEEE Int. Power Electron. Appl. Conf. Expo. (PEAC)*, Nov. 2018, pp. 1–5.

[35] M. Shahbazi, B. Kazemtabrizi, and C. Dent, "Coordinated control of DC voltage magnitudes and state of charges in a cluster of DC microgrids," in *Proc. IEEE PES Innov. Smart Grid technol. Conf. Eur. (ISGT-Eur.)*, Oct. 2016, pp. 1–5.

[36] J. Zhou, H. Zhang, Q. Sun, D. Ma, and B. Huang, "Event-based distributed active power sharing control for interconnected AC and DC microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6815–6828, Nov. 2018.

[37] S. Abhinav, H. Modares, F. L. Lewis, and A. Davoudi, "Resilient cooperative control of DC microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 1083–1085, Jan. 2019.

[38] V. Nasirian, S. Moayedi, A. Davoudi, and F. L. Lewis, "Distributed cooperative control of DC microgrids," *IEEE Trans. Power Electron.*, vol. 30, no. 4, pp. 2288–2303, Apr. 2015.

[39] M. Dong, L. Li, Y. Nie, D. Song, and J. Yang, "Stability analysis of a novel distributed secondary control considering communication delay in DC microgrids," *IEEE Trans. Smart Grid*, to be published. doi: 10.1109/TSG.2019.2910190.

[40] Y. Nie, M. Dong, W. Yuan, J. Yang, and Z. Liu, "Delay-dependent stability analysis of DC microgrid with distributed control considering communication delay," in *Proc. Chin. Autom. Congr. (CAC)*, Oct. 2017, pp. 7646–7651.

[41] J. Lai, X. Lu, X. Yu, W. Yao, J. Wen, and S. Cheng, "Distributed voltage control for DC mircogrids with coupling delays & noisy disturbances," in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2017, pp. 2461–2466.

[42] N. Vafamand, M. H. Khooban, T. Dragičević, and F. Blaabjerg, "Networked fuzzy predictive control of power buffers for dynamic stabilization of DC microgrids," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1356–1362, Feb. 2019.

[43] Q. Shafiee, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, "Modeling, stability analysis and active stabilization of multiple DC-microgrid clusters," in *Proc. IEEE Int. Energy Conf. (ENERGYCON)*, May 2014, pp. 1284–1290.

[44] A. Emadi, A. Khaligh, C. H. Rivetta, and G. A. Williamson, "Constant power loads and negative impedance instability in automotive systems: Definition, modeling, stability, and control of power electronic converters and motor drives," *IEEE Trans. Veh. Technol.*, vol. 55, no. 4, pp. 1112–1125, Jul. 2006.

[45] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC microgrids—Part I: A review of control strategies and stabilization techniques," *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4876–4891, Jul. 2016.

[46] N. Bottrell, M. Prodanovic, and T. C. Green, "Dynamic stability of a microgrid with an active load," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 5107–5119, Nov. 2013.

[47] M. N. Hussain, R. Mishra, and V. Agarwal, "A frequency-dependent virtual impedance for voltage-regulating converters feeding constant power loads in a DC microgrid," *IEEE Trans. Ind. Appl.*, vol. 54, no. 6, pp. 5630–5639, Nov. 2018.

[48] S. Yousefizadeh, J. D. Bendtsen, N. Vafamand, M. H. Khooban, T. Dragičević, and F. Blaabjerg, "EKF-based predictive stabilization of shipboard DC microgrids with uncertain time-varying load," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 7, no. 2, pp. 901–909, Jun. 2019.

[49] H. Wang, H. Han, Z. Liu, Y. Sun, M. Su, X. Hou, and P. Yang, "A stabilization method of LC input filter in DC microgrids feeding constant power loads," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2017, pp. 4433–4438.

[50] Q. Xu, C. Zhang, C. Wen, and P. Wang, "A novel composite nonlinear controller for stabilization of constant power load in DC microgrid," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 752–761, Jan. 2019.

[51] L. Zekun, P. Wei, and K. Li, "Large-disturbance stability analysis of DC microgrid with constant power load and its transient voltage stability control strategy," in *Proc. China Int. Conf. Elect. Distrib. (CICED)*, Sep. 2018, pp. 1686–1690.

[52] L. Herrera, W. Zhang, and J. Wang, "Stability analysis and controller design of DC microgrids with constant power loads," *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 881–888, Mar. 2017.

[53] J. Liu, W. Zhang, and G. Rizzoni, "Robust stability analysis of DC microgrids with constant power loads," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 851–860, Jan. 2018.

[54] Z. Shuai, J. Fang, F. Ning, and Z. J. Shen, "Hierarchical structure and bus voltage control of DC microgrid," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3670–3682, Feb. 2018.

[55] L. Meng, Q. Shafiee, G. F. Trecate, H. Karimi, D. Fulwani, X. Lu, and J. M. Guerrero, "Review on control of DC microgrids and multiple microgrid clusters," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 5, no. 3, pp. 928–948, Sep. 2017.

[56] S. Singh, A. R. Gautam, and D. Fulwani, "Constant power loads and their effects in DC distributed power systems: A review," *Renew. Sustain. Energy Rev.*, vol. 72, pp. 407–421, May 2017.

[57] J. Yang, X. Jin, X. Wu, P. Acuna, R. P. Aguilera, T. Morstyn, and V. G. Agelidis, "Decentralised control method for DC microgrids with improved current sharing accuracy," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 3, pp. 696–706, Feb. 2017.

[58] S. Peyghami, P. Davari, H. Mokhtari, P. C. Loh, and F. Blaabjerg, "Synchronverter-enabled DC power sharing approach for LVDC microgrids," *IEEE Trans. Power Electron.*, vol. 32, no. 10, pp. 8089–8099, Oct. 2017.

[59] K. Rouzbehi, K. Miranian, J. I. Candela, A. Luna, and P. Rodriguez, "A generalized voltage droop strategy for control of multiterminal DC grids," *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 607–618, Jan. 2015.

[60] F. Cingoz, A. Elrayyah, and Y. Sozer, "Optimized settings of droop parameters using stochastic load modeling for effective DC microgrids operation," in *Proc. Energy Convers. Congr. Expo.*, Sep. 2015, pp. 512–518.

[61] P. Prajof, Y. Goyal, and V. Agarwal, "A novel communication based average voltage regulation scheme for a droop controlled DC microgrid," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 1250–1258, Mar. 2019.

[62] S. Islam, S. Agarwal, A. B. Shyam, A. Ingle, S. Thomas, and S. Anand, "Ideal current-based distributed control to compensate line impedance in DC microgrid," *IET Power Electron.*, vol. 11, no. 7, pp. 1178–1186, Jun. 2018.

[63] H. Mahmood, D. Michaelson, and J. Jiang, "Accurate reactive power sharing in an islanded microgrid using adaptive virtual impedances," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1605–1617, Mar. 2015.

[64] M. M. A. Abdelaziz, H. E. Farag, and E. F. El-Saadany, "Optimum droop parameter settings of islanded microgrids with renewable energy resources," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 434–445, Apr. 2014.

[65] Y. Mi, H. Zhang, Y. Fu, C. Wang, P. C. Loh, and P. Wang, "Intelligent power sharing of DC isolated microgrid based on fuzzy sliding mode droop control," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2396–2406, May 2019.

[66] Y. Lin and W. Xiao, "Novel piecewise linear formation of droop strategy for DC microgrid," *IEEE Trans. Smart Grid*, to be published. doi: 10.1109/TSG.2019.2911013.

[67] H. Wang, M. Han, R. Han, J. M. Guerrero, and J. C. Vasquez, "A decentralized current-sharing controller endows fast transient response to parallel DC–DC converters," *IEEE Trans. Power Electron.*, vol. 33, no. 5, pp. 4362–4372, May 2018.

[68] X. Li, L. Guo, S. Zhang, C. Wang, Y. W. Li, A. Chen, and Y. Feng, "Observer-based DC voltage droop and current feed-forward control of a DC microgrid," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 5207–5216, Sep. 2018.

[69] F. Chen, R. Burgos, D. Boroyevich, J. C. Vasquez, and J. M. Guerrero, "Investigation of nonlinear droop control in DC power distribution systems: Load sharing, voltage regulation, efficiency, and stability," *IEEE Trans. Power Electron.*, vol. 34, no. 10, pp. 9404–9421, Oct. 2019.

[70] S. Trip, M. Cucuzzella, X. Cheng, and J. Scherpen, "Distributed averaging control for voltage regulation and current sharing in DC microgrids," *IEEE Control Syst. Lett.*, vol. 3, no. 1, pp. 174–179, Jan. 2019.

[71] E. Mojica-Nava, J. M. Rey, J. Torres-Martinez, and M. Castilla, "Decentralized switched current control for DC microgrids," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1182–1191, May 2019.

[72] F. Cingoz, A. Elrayyah, and Y. Sozer, "Optimized settings of droop parameters using stochastic load modeling for effective DC microgrids operation," *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 1358–1371, Mar. 2017.

[73] D. Shu, Z. Huang, J. Li, and X. Zou, "Application of multi-agent particle swarm algorithm in distribution network reconfiguration," *Chin. J. Electron.*, vol. 25, no. 6, pp. 1179–1185, Dec. 2016.

[74] P. Prajof, F. Blaabjerg, S. Peyghami-Akhuleh, and H. Mokhtari, "Distributed secondary control in DC microgrids with low-bandwidth communication link," in *Proc. 7th Power Electron. Drive Syst. Technol. Conf. (PEDSTC)*, Feb. 2016, pp. 641–645.

[75] S. Peyghami, H. Mokhtari, P. C. Loh, P. Davari, and F. Blaabjerg, "Distributed primary and secondary power sharing in a droop-controlled LVDC microgrid with merged AC and DC characteristics," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 2284–2294, May 2016.

[76] X. Lu, J. M. Guerrero, S. Kai, and J. C. Vasquez, "An improved droop control method for DC microgrids based on low bandwidth communication with DC bus voltage restoration and enhanced current sharing accuracy," *IEEE Trans. Power Electron.*, vol. 29, no. 4, pp. 1800–1812, Apr. 2013.

[77] S. Augustine, M. K. Mishra, and N. Lakshminarasamma, "Adaptive droop control strategy for load sharing and circulating current minimization in low-voltage standalone DC microgrid," *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. 132–141, Jan. 2014.

[78] F. Chen, R. Burgos, D. Boroyevich, and W. Zhang, "A nonlinear droop method to improve voltage regulation and load sharing in DC systems," in *Proc. IEEE 1st Int. Conf. DC Microgrids (ICDCM)*, Jun. 2015, pp. 45–50.

[79] T. Hailu and J. A. Ferreira, "Piece-wise linear droop control for load sharing in low voltage DC distribution grid," in *Proc. IEEE Southern Power Electron. Conf. (SPEC)*, Dec. 2017, pp. 1–6.

[80] P.-H. Huang, P.-C. Liu, W. Xiao, and M. S. El Moursi, "A novel droop-based average voltage sharing control strategy for DC microgrids," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1096–1106, May 2015.

[81] J. Schonbergerschonberger, R. Duke, and S. D. Round, "DC-bus signaling: A distributed control strategy for a hybrid renewable nanogrid," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1453–1460, Oct. 2006.

[82] L. Zhang, T. Wu, Y. Xing, K. Sun, and J. M. Gurrero, "Power control of DC microgrid using DC bus signaling," in *Proc. 26th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2011, pp. 1926–1932.

[83] A. Tah and D. Das, "An enhanced droop control method for accurate load sharing and voltage improvement of isolated and interconnected DC microgrids," *IEEE Trans. Sustain. Energy*, vol. 7, no. 3, pp. 1194–1204, Jul. 2016.

[84] G.-Y. Lee, B.-S. Ko, J. Cho, and R.-Y. Kim, "A distributed control method based on a voltage sensitivity matrix in DC microgrids with low-speed communication," *IEEE Trans. Smart Grid*, vol. 10, no. 4, pp. 3809–3817, Jul. 2019.

[85] R. de Azevedo, M. H. Cintuglu, T. Ma, and O. A. Mohammed, "Multiagent-based optimal microgrid control using fully distributed diffusion strategy," *IEEE Trans. Smart Grid*, vol. 8, no. 4, pp. 1997–2008, Jul. 2017.

[86] M. Zhao, Y. Chen, C. Shen, and X. Huang, "Characteristic analysis of multi-microgrids and a pilot project design," *Power Syst. Technol.*, vol. 39, pp. 1469–1476, Jun. 2015.

[87] R. Han, M. Tucci, A. Martinelli, J. M. Guerrero, and G. Ferrari-Trecate, "Stability analysis of primary plug-and-play and secondary leader-based controllers for DC microgrid clusters," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 1780–1800, May 2019.

[88] Y. Li and P. Dong, "A distributed control based on finite-time consensus algorithm for the cluster of DC microgrids," in *Proc. Int. Conf. Power Syst. Technol. (POWERCON)*, Nov. 2018, pp. 1599–1606.

[89] S. Teleke, M. E. Baran, A. Q. Huang, S. Bhattacharya, and L. Anderson, "Control strategies for battery energy storage for wind farm dispatching," *IEEE Trans. Energy Convers.*, vol. 24, no. 3, pp. 725–732, Sep. 2009.

[90] L. Ren, "Coordinated control stategy for DC microgrid clusters considering intelligent power allocation," in *Proc. IEEE Conf. Energy Internet Energy Syst. Integr. (EI2)*, Nov. 2017, pp. 1–5.

[91] Q. Shafiee, T. Dragicevic, F. Andrade, J. C. Vasquez, and J. M. Guerrero, "Distributed consensus-based control of multiple DC-microgrids clusters," in *Proc. 40th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2014, pp. 2056–2062.

[92] A. Y. Kibangou, "Finite-time average consensus based protocol for distributed estimation over AWGN channels," in *Proc. 50th IEEE Conf. Decis. Control Eur. Control Conf.*, Dec. 2011, pp. 5595–5600.

[93] O. Cornea and G. Andreescu, "Bidirectional power flow control in a DC microgrid through a switched-capacitor cell hybrid DC–DC converter," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3012–3022, Apr. 2017.

[94] M. Tucci, S. Riverso, and G. Ferrari-Trecate, "Line-independent plug-and-play controllers for voltage stabilization in DC microgrids," *IEEE Trans. Control Syst. Technol.*, vol. 26, no. 3, pp. 1115–1123, May 2018.

[95] M. S. Sadabadi, Q. Shafiee, and A. Karimi, "Plug-and-play robust voltage control of DC microgrids," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6886–6896, Nov. 2018.

[96] A. Ingle, A. B. Shyam, S. R. Sahoo, and S. Anand, "Quality-index based distributed secondary controller for a low-voltage DC microgrid," *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7004–7014, Sep. 2018.

[97] S. Moayedi and A. Davoudi, "Distributed tertiary control of DC microgrid clusters," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1717–1733, Feb. 2015.

[98] T. Morstyn, A. V. Savkin, B. Hredzak, and V. G. Agelidis, "Multi-agent sliding mode control for state of charge balancing between battery energy storage systems distributed in a DC microgrid," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4735–4743, Sep. 2018.

[99] C. Dong, Q. Gao, Q. Xiao, X. Yu, L. Pekař, and H. Jia, "Time-delay stability switching boundary determination for DC microgrid clusters with the distributed control framework," *Appl. Energy*, vol. 228, pp. 189–204, Oct. 2018.

[100] F. Gao, S. Bozhko, G. Asher, P. Wheeler, and C. Patel, "An improved voltage compensation approach in a droop-controlled DC power system for the more electric aircraft," *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 7369–7383, Oct. 2016.

[101] S. Liu, P. Su, and L. Zhang, "A virtual negative inductor stabilizing strategy for DC microgrid with constant power loads," *IEEE Access*, vol. 6, pp. 59728–59741, 2018.

[102] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, L. Huang, and J. Wang, "Stability enhancement based on virtual impedance for DC microgrids with constant power loads," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2770–2783, Nov. 2015.

[103] X. Chang, Y. Li, X. Li, and X. Chen, "An active damping method based on a supercapacitor energy storage system to overcome the destabilizing effect of instantaneous constant power loads in DC microgrids," *IEEE Trans. Energy Convers.*, vol. 32, no. 1, pp. 36–47, Mar. 2017.

[104] M. Wu and D. D.-C. Lu, "A novel stabilization method of LC input filter with constant power loads without load performance compromise in DC microgrids," *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, pp. 4552–4562, Jul. 2015.

[105] J. Pakdeeto, K. Areerak, and K. Areerak, "Large-signal model of DC micro-grid systems feeding a constant power load," in *Proc. Int. Electr. Eng. Congr. (iEECON)*, Mar. 2017, pp. 1–4.

[106] M. H. Khooban, N. Vafamand, T. Niknam, T. Dragičević, and F. Blaabjerg, "Model-predictive control based on Takagi-Sugeno fuzzy model for electrical vehicles delayed model," *IET Elect. Power Appl.*, vol. 11, no. 5, pp. 918–934, May 2017.

[107] Z. Liu, M. Su, Y. Sun, W. Yuan, H. Han, and J. Feng, "Existence and stability of equilibrium of DC microgrid with constant power loads," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6999–7010, Nov. 2018.

[108] R. Kumar, S. Sneha, and R. K. Behera, "Controller gain impact on islanded DC microgrid stability with constant power load," in *Proc. IEEE Int. Conf. Power Electron., Drives Energy Syst. (PEDES)*, Dec. 2018, pp. 1–6.

[109] S. M. Ashabani and Y. A.-R. I. Mohamed, "A flexible control strategy for grid-connected and islanded microgrids with enhanced stability using nonlinear microgrid stabilizer," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1291–1301, Sep. 2012.

[110] K. E. Lucas-Marcillo, D. A. P. Guingla, W. Barra, R. L. P. De Medeiros, E. M. Rocha, D. A. Vaca-Benavides, S. J. R. Orellana, and E. V. H. Muentes, "Novel robust methodology for controller design aiming to ensure DC microgrid stability under CPL power variation," *IEEE Access*, vol. 7, pp. 64206–64222, May 2019.

[111] M. K. Zadeh, R. Gavagsaz-Ghoachani, J.-P. Martin, B. Nahid-Mobarakeh, S. Pierfederici, and M. Molinas, "Discrete-time modeling, stability analysis, and active stabilization of DC distribution systems with multiple constant power loads," *IEEE Trans. Ind. Appl.*, vol. 52, no. 6, pp. 4888–4898, Nov. 2016.

[112] P. Magne, B. Nahid-Mobarakeh, and S. Pierfederici, "Dynamic consideration of DC microgrids with constant power loads and active damping system—A design method for fault-tolerant stabilizing system," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 3, pp. 562–570, Sep. 2014.

YANG HAN (S'08–M'10–SM'17) received the Ph.D. degree in electrical engineering from Shanghai Jiaotong University (SJTU), Shanghai, China, in 2010.

From March 2014 to March 2015, he was a Visiting Scholar with the Department of Energy Technology, Aalborg University, Aalborg, Denmark. In 2010, he joined the Department of Power Electronics, School of Mechatronics Engineering, University of Electronic Science and Technology of China (UESTC), Chengdu, China, where he has been an Associate Professor, since 2013. He is currently with the Department of Electrical Engineering, School of Mechanical and Electrical Engineering, UESTC. His research interests include the ac/dc microgrids, active distribution networks, power quality, grid-connected converters for renewable energy systems, active power filters, and static synchronous compensators (STATCOMs).

Dr. Han was a recipient of the Baekhyun Award by the Korean Institute of Power Electronics, in 2016, and the Academic Talent Award by UESTC, in 2017. He was also a recipient of the best paper awards from the 4th International Conference on Power Quality, in 2008, China, the Annual Conference of HVDC and Power Electronics Committee of the Chinese Society of Electrical Engineers, in 2013, the 5th National Conference on Power Quality in 2017, the 6th Asia International Symposium on Mechatronics, in 2017, the 34th Annual Conference on Power System and Automation of Chinese Universities, in 2018, and the Joint Conference of Sichuan Power Supply Society and Chongqing Power Supply Society, in 2018. He was the Session Chair for the Emerging Technologies and End-User Systems, the Grid Operation and Management, and the Power Electronics, Control and Protection Systems for Smart Grids Sessions in the IEEE PES Innovative Smart Grid Technologies Asia (ISGT Asia 2019), Chengdu, China, in 2019, for the Microgrid and Distributed Generation Session in the Symposium on Power Electronics and Electrical Drives (SPEED), Xi'an, China, in 2019, for the Microgrid Optimization and Scheduling Session in the 2nd International Conference on Power and Renewable Energy, Chengdu, China, in 2017, for the Power Quality Mitigation and Application Session in the 5th National Conference on Power Quality, Xi'an, China, in 2017, and for the AC/DC, DC/AC Power Converter Session in the 2016 IPEMC ECCE-Asia, Hefei, China.

XING NING received the B.S. degree in electrical engineering and automation from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2018, where he is currently pursuing the M.S. degree in power electronics and electric drives. His main research interests include modeling, control, and stability analysis of inverters.

PING YANG received the B.S. degree in mechanical engineering from Shanghai Jiaotong University (SJTU), Shanghai, China, in 1984, and the M.S. degree in mechanical engineering from Sichuan University, in 1987.

He was visiting the Victory University, Australia, from July 2004 to August 2004, a Visiting Scholar with the S.M. Wu Manufacturing Research Center, University of Michigan, Ann Arbor, MI, USA, from August 2009 to February 2010, and was visiting the University of California, Irvine, CA, USA, from October 2012 to November 2012. He is currently a Full Professor and the Dean of the School of Mechatronics Engineering, University of Electronic Science and Technology of China (UESTC), Chengdu, China. He has authored more than 60 articles in various journals and international conferences, and several books on mechatronics and instrumentation. His research interests include mechatronics engineering, electrical engineering and automation, computer-aided control and instrumentation, smart mechatronics, and detection and automation of mechanical equipment. He received several provincial awards for his contribution in teaching and academic research.

LIN XU received the Ph.D. degree in electrical engineering from Shanghai JiaoTong University (SJTU), Shanghai, China, in 2011. She is currently a Senior Engineer with the Sichuan Electric Power Research Institute, State Grid Sichuan Electric Power Company, Chengdu, China. She has coauthored more than 20 journal and conference papers in the area of power electronics and power systems. Her research interests include power quality, power system analysis and real-time digital simulator (RTDS), and flexible AC transmission systems (FACTS), such as STATCOMs and power quality conditioners (DVRs, APFs). She is an Active Reviewer for the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and the IEEE TRANSACTIONS ON POWER ELECTRONICS, ELECTRIC POWER COMPONENTS AND SYSTEMS.

• • •