

Output-constrained Distributed Cooperative Control Based on Dynamic Event-triggered Average Consensus for DC Microgrid Clusters

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Abstract—To achieve global voltage regulation and current sharing with reduced communication demands while enhancing the transient voltage performance of DC microgrid (MG) clusters, this paper proposes a distributed cooperative control method featuring output constraints and a dynamic event-triggered average consensus algorithm. The proposed control strategy employs an integrated primary-secondary control structure, where a dynamic event-triggered robust average consensus algorithm (DET-RACA)-based average voltage observer is designed to estimate the average voltage of each distributed generator (DG) within the MG. This estimated average voltage is subsequently utilized to simultaneously achieve voltage regulation and precise current sharing within individual MGs. Furthermore, an output-constrained voltage controller incorporating a barrier Lyapunov function is developed to ensure high-performance transient voltage regulation for each DG. At the tertiary control level, a DET-RACA-based current observer is implemented to acquire global current information across the MG cluster, enabling the adjustment of bus reference voltages for each MG and guaranteeing global current sharing. The distinctive feature of DET-RACA lies in its event-triggering mechanism, which significantly reduces communication frequency across the network topology and effectively alleviates the communication burden of the MG cluster system. Comprehensive simulations under five different operating conditions demonstrate the effectiveness and feasibility of the proposed method for DC MG cluster control.

Index Terms—Barrier Lyapunov function, current sharing, DC microgrid clusters, distributed control, event-triggered consensus.

I. INTRODUCTION

MICROGRID (MG) is a small-scale power system that is an effective way to integrate distributed generators (DGs), energy storage systems (ESSs), and loads, enhancing security and flexibility of the power system [1]–[3]. Currently, DC MGs have become one of the future trends of MG due to DC output characteristics of power units such as photovoltaic systems and ESSs [4]–[7]. Compared with AC MG, DC MG has received wide attention because of its better power quality, no DC/AC conversion losses, and no reactive power regulation

[8], [9]. In DC MG, DGs and ESSs are directly connected to a DC bus, which is then connected to the external grid system through power electronics. To achieve normal operation of loads, maintaining the stability of DC bus voltage is the primary goal of the DC MG. Moreover, on the basis of voltage stability, it could achieve accurate proportional current sharing and optimal power dispatch by evaluating the capacity and price of each DG [10], [11].

With the high penetration of renewable energy sources in DC MGs, according to practical requirements, multiple DC MGs need to be interconnected to form MG clusters (MGCs) for better balancing among DGs/ESSs and loads [12], [13]. For DC MG clusters, a hierarchical control structure, combining primary control, secondary control, and tertiary control, is usually adopted to achieve global voltage regulation and accurate current sharing [14]. Primary control is mainly implemented by droop control to coordinate the local output voltage of each DG and realize the current sharing function [15], [16]. However, droop control tends to pull down the bus voltage level to some extent. Meanwhile, the accuracy of current sharing is not sufficient due to the presence of line impedance [17], which requires further regulation by secondary control [18]. Secondary control usually compensates voltage in the form of centralized or distributed control to achieve more accurate current sharing and higher power quality [19], [20]. Specifically, centralized control obtains voltage and current information of all DGs using a global communication network, while distributed control employs a sparse communication topology and consensus algorithms to obtain global information indirectly. Compared to centralized control, distributed control has a lower communication requirement, which is robust for failures or communication interruption [21]. Nasirian *et al.* [22] proposed a secondary control strategy for DC MG. The control strategy uses a dynamic consensus algorithm to estimate the average voltage of the MG, and voltage and current regulators are adopted to generate voltage and current regulation terms for achieving voltage regulation and current sharing. Li *et al.* [23] proposed a control strategy that integrates primary control with secondary control. The method employs an improved average consensus algorithm to observe global average voltage and embeds the two control objectives of voltage regulation and current sharing into a single controller, which can simplify the control structure and adjustment process, reducing communication requirements by half.

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Since secondary control can only realize voltage regulation and current sharing within the MG, it cannot enable current balance among multiple MGs and may cause unnecessary line losses. Thus, it is necessary to introduce tertiary control further [24]. Lu *et al.* [25] proposed a clustered distributed hierarchical consensus control strategy to achieve voltage regulation and current sharing among MGs, while the strategy uses periodic communication, which is vulnerable to the limitation of communication bandwidth and inefficient. The event-triggering mechanism is a method to avoid continuous data exchange and effectively reduce communication frequency [26]. Chen *et al.* [27] proposed a hierarchical event-triggered consensus algorithm for distributed cooperative control of DC MG clusters. The method achieves global voltage regulation and current sharing by a three-level control structure, in which an event-triggered consensus algorithm is adopted to reduce communication frequency while ensuring stability of the system. However, the strategy requires the consensus algorithm for both current and voltage to achieve coordinated control within each MG, although the strategy uses an event-triggering mechanism to reduce communication frequency, which has high requirements for communication bandwidth. Thus, further research is needed for DC MG cluster control.

Moreover, since DC MG control is usually based on converters, which have much less inertia, disturbances caused by load changes or access or removal of DGs in the system may lead to sudden voltage overshoot or dips [28]. These oscillations, even if they eventually stabilize, are harmful to sensitive loads and may lead to misoperation of the protection system. Hence, the stability of transient voltage in DC MG is also an urgent issue that needs to be solved. Peng *et al.* [29] considered the impact of transient voltage on system performance and adopted error transformation [30] to limit output voltage to a certain range, which ensures boundedness of voltage. However, the error transformation approach may increase the complexity of the controller. Meanwhile, the model built in [29] ignores line impedance in MG systems. Thus, the control strategy is not general.

From the above analysis, it can be concluded the existing control strategies for DC MG clusters have the following shortcomings: First, it is a complex control process to realize voltage regulation and current sharing for MG clusters and each MG, and the control strategy still needs to be improved for achieving more stable voltage control and accurate current sharing. Secondly, to achieve stable operation of MG clusters, normal communication needs to be maintained among MGs

and among DGs within each MG, which has high communication bandwidth requirements. Thus, it is necessary to reduce communication requirements by designing a reasonable control strategy. Besides, in DC MG, sudden voltage overshoot or dips may cause adverse effects on the system. Most existing strategies do not limit dynamic voltage and ignore the impact of transient voltage on system performance. Table I gives a comparison of some control strategies proposed in recent references, comparing control objectives, messages communicated, and the level of communication burden [31]–[35].

To address the above issues, this paper proposes an output-constrained distributed cooperative control method for DC MG clusters based on a hierarchical dynamic event-triggered average consensus algorithm (DET-RACA). The main contributions are highlighted as follows:

1) A two-layer communication network is adopted, in which the upper layer is used for information exchange among MGs and the lower layer for information exchange among DGs within each MG. In both layers, a DET-RACA algorithm is employed, which is suitable for MG system control. In particular, the event trigger mechanism can effectively reduce the communication frequency and the communication burden of the MG cluster system.

2) This paper proposes a secondary control and tertiary control strategy based on DET-RACA. This control structure achieves the objectives of voltage regulation and current sharing simultaneously, which simplifies the structure of the controller and the adjustment process.

3) Different from [29], a local voltage controller considering output constraint is designed based on barrier Lyapunov function (BLF) [36]. In the controller, the BLF can limit the output voltage of each DG to a predetermined range, ensuring high-performance transient voltage control. Moreover, a disturbance observer (DO) is implemented to estimate the disturbance term, enhancing the robustness of the control system.

The remainder of this paper is structured as follows: Section II outlines the graph theory and DET-RACA. Section III provides a detailed description of the proposed control strategy. Section IV verifies the effectiveness of the proposed control strategy in DC MG cluster control through five simulation cases. Finally, the conclusions of this study are presented in Section V.

II. CONSISTENCY THEORY

A. Graph Theory

A communication network consisting of n agents is usually

TABLE I
COMPARISON OF SOME TECHNIQUES IN RECENT LITERATURE

Literature	Types	Objectives	Communication		Event trigger	Communication burden
			Secondary control	Tertiary control		
[31], [32]	centralized	voltage regulation and power management	voltage, power		no	very high
[22]	distributed	voltage regulation and current sharing for MGs	voltage, current		no	high
[23]	distributed	voltage regulation and current sharing for MGs	voltage		no	low
[26]	distributed	voltage regulation and current sharing for MGs	voltage, current		yes	low
[33]	distributed	global voltage regulation and power flow control for MGCs	voltage, SOC		no	high
[24]	distributed	voltage regulation, current sharing among MGs	voltage	current	no	high
[34]	distributed	voltage regulation, minimum cost of power generation	voltage	marginal cost	no	high
[27]	distributed	global voltage regulation and current sharing for MGCs	voltage, current	current	yes	high
[35]	distributed	global voltage regulation and power flow control for MGCs	voltage, SOC	incremental cost	no	very high

represented by a directed graph $G = \{V, E\}$. $V = \{1, \dots, n\}$ denotes the set of network nodes; $E \subset V \times V$ denotes the edges of nodes. Define $A = [a_{ij}]$ as the weighted adjacency matrix, and a_{ij} is the connection weight of i th node and j th node. Define $a_{ii} = 0$, if j th node transmits information to i th node, then $a_{ij} \neq 0$; otherwise, $a_{ij} = 0$. The set consisting of all neighbors of i th node is $N_i = \{j \in V \mid (j, i) \in E\}$. The weighted degree of i th node defined as $d_i = \sum_{j=1}^n a_{ij}$, then the degree matrix is $D = \text{diag}\{d_1, d_2, \dots, d_n\}$. The Laplacian matrix of the directed graph G can be described as $L = D - A$.

B. Dynamic Event-triggered Robust Average Consensus Algorithm (DET-RACA)

The DET-RACA is described as follow [37].

$$\begin{cases} x_i(t) = r_i(t) + z_i(t) \\ \dot{z}_i(t) = \alpha z_i(t) - \sum_{j \in N_i} a_{ij} \text{sgn}\{\hat{x}_i(t) - \hat{x}_j(t)\} u_{ij}(t) \\ \dot{u}_{ij}(t) = |\hat{x}_i(t) - \hat{x}_j(t)| \end{cases} \quad (1)$$

where $x_i(t)$ is the state variable of i th node and $r_i(t)$ is the input signal of i th node at time t . $z_i(t)$ is an intermediate variable of this consensus algorithm, $\alpha > 0$ is a constant, and $\text{sgn}\{\cdot\}$ represents a symbolic function. $\hat{x}_i(t) = x_i(t_{k_i}^i)$ denotes the state of i th node at the k_i th trigger event, $t \in [t_{k_i}^i, t_{k_i+1}^i)$, $t_{k_i}^i = \max\{t_{k_i}^i \mid t_{k_i}^i < t\}$.

Define the state error as:

$$\varepsilon_i(t) = \hat{x}_i(t) - x_i(t) \quad (2)$$

Then the dynamic event triggering condition of i th node is:

$$\begin{cases} \phi_i(t) = \chi_i |\varepsilon_i(t)| - \varepsilon_i(t) \sum_{j \in N_i} a_{ij} \text{sgn}\{\hat{x}_i(t) - \hat{x}_j(t)\} u_{ij}(t) \\ \dot{\eta}_i(t) = -\varphi_i \eta_i(t) - \sigma_i \cdot \phi_i(t) \\ \theta_i \cdot \phi_i(t) \geq \eta_i(t), t > t_{k_i}^i \end{cases} \quad (3)$$

where $\eta_i(t)$ denotes the internal state of the trigger condition, $\eta_i(t_0) > 0$, $\varphi_i > 0$, $\theta_i \in (0, 1)$, $\sigma_i \geq 1$ and χ_i are parameters to be set.

Remark 1: Compared to the classical consensus algorithm [38], DET-RACA reduces computational cost by introducing an internal variable $z_i(t) = x_i(t) - r_i(t)$ that can eliminate derivatives of $r_i(t)$. In continuous time, each local state can converge asymptotically to the average value $r_{\text{avg}}(t) = 1/n \sum_{i=1}^n r_i(t)$ of the global input signal by appropriate initialization ($\sum_{i=1}^n z_i(t_0) = 0$).

In practical MG systems, since the environment for system deployment is not suitable for wired communication, a wireless sensor network is often applied. However, wireless networks use ISM spectrum, which has limited bandwidth resources and cannot support a large data transmission rate. In particular, each node is sharing a limited bandwidth communication channel to transmit data, and periodic data exchange may cause frequent updating of information in the system [39], [40]. If the sampling period is relatively small, a large number of sampled signals will be released into the shared communication network with limited bandwidth, which may

cause network congestion and lead to long delays or increased packet loss, inevitably degrading the stability and reliability of the system. As for the event-triggered consensus algorithm, i th node sends new state information to other nodes only when the condition is triggered ($t = t_{k_i}^i$). When $t \in (t_{k_i}^i, t_{k_i+1}^i)$, each node updates its state using node information at $t = t_{k_i}^i$. Obviously, the event-triggering mechanism can avoid continuous data exchange and effectively reduce signal transmission of the communication link without causing degradation of system performance. Under the triggering condition of (3), the state variable of each node can be converged to $r_{\text{avg}}(t)$ eventually, and the algorithm can avoid Zeno behavior, i.e., $t_{k_i}^i > t_{k_i+1}^i$, and maintain stability of the system. The specific proving process is presented in [37].

III. HIERARCHICAL CONTROL STRATEGY FOR DC MG CLUSTERS

This section provides a detailed description of the DC MG cluster model and the proposed control strategy.

A. DC MG Cluster and Global Control Structure

Figure 1 describes the DC MG cluster and the structure of global control strategy.

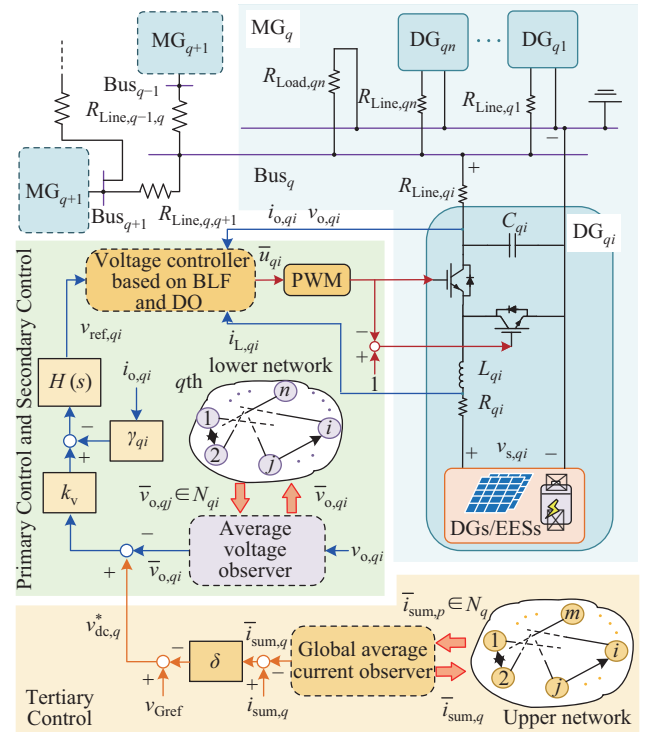


Fig. 1. DC-MG cluster and the structure of global control strategy.

As seen in Fig. 1, the structure diagram consists of the system (MG cluster) and the controller. Subscript qi denotes the parameter of i th DG in q th MG, and the meaning of each parameter will be explained specifically in the following.

The MG cluster system consists of m DC MGs, which are connected to each other by a line, with line impedance R_{Line} . In each MG system, taking MG_q as an example, MG_q consists of n DGs, $R_{\text{Load},q}$ denotes the load resistance of MG_q , Bus_q

is the DC bus of MG_q , and $R_{Line,qi}$ is the line impedance between DG_{qi} and Bus_q . Each DG or ESS is connected to a DC bus of MG_q through a bidirectional boost converter, and the local output voltage of each DG system can be regulated by adjusting the duty cycle of the boost converter, whose differential equation is shown in (4).

$$\begin{cases} \dot{v}_{o,qi} = \bar{u}_{qi} \frac{i_{L,qi}}{C_{qi}} - \frac{1}{C_{qi}} i_{o,qi} \\ \dot{i}_{L,qi} = \frac{v_{s,qi}}{L_{qi}} - \frac{R_{qi}}{L_{qi}} i_{L,qi} - \bar{u}_{qi} \frac{v_{o,qi}}{L_{qi}} \end{cases} \quad (4)$$

where L_{qi} represents equivalent inductance, R_{qi} denotes equivalent resistance, C_{qi} denotes capacitance, $v_{o,qi}$ represents output current, $v_{s,qi}$ represents input voltage, $\bar{u}$ is the input of the boost converter, $v_{o,qi}$ and $v_{L,qi}$ indicate output voltage and inductor current, respectively.

The control structure can be divided into a physical layer and a cyber layer. The physical layer consists of primary control, secondary control, and tertiary control structures. Primary control and secondary control mainly complete voltage regulation and current sharing among DGs within the MG. Implementation of the secondary controller not only removes voltage deviation caused by the droop controller but also shares current accurately. However, current cannot be shared accurately among different MGs by secondary control, which would lead to unnecessary power loss on the transmission line. Thus, tertiary control is further performed for current sharing among different MGs. Cyber layer is divided into an upper layer network and a lower layer network. Upper layer network employs a consensus algorithm to get the average current of the global system, which is used for regulating the bus voltage reference value of each MG to realize global current sharing. At the same time, the consensus protocol of the lower layer network gets an average output voltage within each MG to realize local voltage regulation and current sharing. The proposed control strategy will be described in detail in the following subsections.

B. Primary Control and Secondary Control

1) Voltage Regulation

In this paper, we adopt a control method that embeds primary and secondary control into one controller, which can realize voltage regulation and current sharing simultaneously, and reduce communication bandwidth requirement by half, as described in (5).

$$\dot{v}_{ref,qi} = -\beta v_{ref,qi} + k_v(v_{dc,qi}^* - v_{avg,q}) - \gamma_{qi} \dot{i}_{o,qi} \quad (5)$$

where $v_{ref,qi}$ denotes the local reference voltage of DG_{qi} , $v_{dc,qi}^*$ denotes the reference voltage of the DC bus for MG_q , $v_{avg,q} = 1/n \sum_{i=1}^n v_{o,qi}$ represents the average output voltage of each DG within MG_q , $v_{o,qi}$ denotes the local output voltage of DG_{qi} . $0 < \beta \leq 1$ is a global parameter, γ_{qi} is the coefficient of current feedback, k_v is a gain of the controller.

Remark 2: As described in Fig. 1, (5) can be presented as:

$$v_{ref,qi}(s) = (k_v(v_{dc,qi}^* - v_{avg,q}) - \gamma_{qi} \dot{i}_{o,qi})H(s) \quad (6)$$

where $H(s) = \frac{1}{s+\beta}$ is a compensator. Since β is a number much smaller than 1, the pole of $H(s)$ is close to 0. Thus, the

frequency characteristic of $H(s)$ is similar to an integrator, which guarantees all poles of the system are in the left half-plane and can eliminate steady-state errors [23].

Remark 3: For a DC MG, it is desired that the local output voltage of each DG is regulated to its reference bus voltage. However, due to the presence of line impedance, when current sharing is achieved within MG, the voltage drop across the line will be inconsistent in different DG systems. Therefore, in order to trade off each control objective, the average voltage of all DGs within an MG, instead of the output voltage, is regulated to its reference value.

Due to the sparse communication characteristics of MGs, information available to each DG is limited, and the local output voltage of all DGs cannot be obtained. Notably, the dynamic average consensus algorithm can enable all nodes to converge to their average value by exchanging information among nodes and their neighbors. In addition, since continuous information exchange will cause a large communication burden to the communication system, the event trigger mechanism is usually used to reduce the communication frequency of the system. Hence, DET-RACA in (1) is employed to design the average voltage observer to ensure the observed average output voltage $\bar{v}_{o,qi}$ converges to $v_{avg,q}$, which are shown in (7).

$$\begin{cases} \bar{v}_{o,qi}(t) = v_{o,qi}(t) + z_{qi}(t) \\ \dot{z}_{qi}(t) = \alpha z_{qi}(t) - \sum_{qj \in N_{qi}} a_{qi,qj} \text{sgn}\{\hat{v}_{o,qi}(t) \\ - \hat{v}_{o,qj}(t)\} u_{qi}(t) \\ \dot{u}_{qi}(t) = |\hat{v}_{o,qi}(t) - \hat{v}_{o,qj}(t)| \end{cases} \quad (7)$$

where $a_{qi,qj}$ denotes the connection weight of DG_{qi} and DG_{qj} , and $\hat{v}_{o,qi}(t) = \bar{v}_{o,qi}(t_{k_{qi}}^{qi})$ denotes the observed average voltage of DG_{qi} at the k_{qi} th event, $t \in [t_{k_{qi}}^{qi}, t_{k_{qi}+1}^{qi})$.

Remark 4: Since the access and removal of DGs usually occur in MGs, the designed average voltage observer can improve the robustness of the system and avoid special initialization requirements ($\sum_{i=1}^n \bar{v}_{o,qi}(t_0) = \sum_{i=1}^n v_{o,qi}(t_0)$).

Then, equation (5) can be adjusted as:

$$\dot{v}_{ref,qi} = -\beta v_{ref,qi} + k_v(v_{dc,qi}^* - \bar{v}_{o,qi}) - \gamma_{qi} \dot{i}_{o,qi} \quad (8)$$

2) Output-constrained Local Voltage Controller

This subsection gives a detailed design procedure of the local voltage controller, which is used to regulate the output voltage of each DG to its reference voltage. BLF and DO are used to design a local voltage controller for each DG so that the output voltage can be limited to a predefined range to ensure a high-performance control effect.

Let $x_{1,qi} = v_{o,qi}$, $x_{2,qi} = \dot{v}_{o,qi}$, then, equation (4) can be transformed into

$$\begin{cases} \dot{x}_{1,qi} = x_{2,qi} \\ \dot{x}_{2,qi} = \bar{u}_{qi} \left(\frac{v_{s,qi}}{L_{qi}C_{qi}} - \frac{R_{qi}}{L_{qi}C_{qi}} i_{L,qi} \right) - \frac{v_{o,qi} \bar{u}_{qi}^2}{L_{qi}C_{qi}} - \frac{\dot{i}_{o,qi}}{C_{qi}} \end{cases} \quad (9)$$

Tracking error is defined as:

$$e_{1,qi} = x_{1,qi} - v_{ref,qi} \quad (10)$$

The time derivative of (10) is:

$$\dot{e}_{1,qi} = x_{2,qi} - \dot{v}_{\text{ref},qi} \quad (11)$$

Let the preset boundary range be the time-varying function $p_{qi}(t)$, it is expected to satisfy $|e_{1,qi}| < p_{qi}(t)$, then take $a_{qi} = \frac{e_{1,qi}}{p_{qi}(t)}$.

Consider the following BLF:

$$V_1 = \frac{1}{2} \log \frac{1}{1 - a_{qi}^2} \quad (12)$$

Then, if the system can maintain stability, $|a_{qi}| < 1$ will be satisfied definitely, i.e., intended performance can be achieved.

Time derivative of (12) is:

$$\dot{V}_1 = \frac{a_{qi}}{(1 - a_{qi}^2)p_{qi}(t)} (x_{2,qi} - a_{qi} \cdot \dot{p}_{qi}(t) - \dot{v}_{\text{ref},qi}) \quad (13)$$

Based on (13), let virtual control input $\hat{x}_{2,qi}$ be

$$\hat{x}_{2,qi} = -k_{1,qi} a_{qi} p_{qi}(t) + a_{qi} \dot{p}_{qi}(t) + \dot{v}_{\text{ref},qi} \quad (14)$$

where $k_{1,qi} > 0$.

Define the error signal of $x_{2,qi}$ as:

$$e_{2,qi} = x_{2,qi} - \hat{x}_{2,qi} \quad (15)$$

Its derivative is:

$$\dot{e}_{2,qi} = \bar{u}_{qi} \left(\frac{v_{s,qi}}{L_{qi}C_{qi}} - \frac{R_{qi}}{L_{qi}C_{qi}} i_{L,qi} \right) - \frac{v_{o,qi} \bar{u}_{qi}^2}{L_{qi}C_{qi}} - \frac{\dot{i}_{o,qi}}{C_{qi}} - \dot{\hat{x}}_{2,qi} \quad (16)$$

Let $D_{qi} = -\frac{v_{o,qi} \bar{u}_{qi}^2}{L_{qi}C_{qi}} - \frac{\dot{i}_{o,qi}}{C_{qi}} - \dot{\hat{x}}_{2,qi}$, (16) can be expressed as:

$$\dot{e}_{2,qi} = \bar{u}_{qi} \left(\frac{v_{s,qi}}{L_{qi}C_{qi}} - \frac{R_{qi}}{L_{qi}C_{qi}} i_{L,qi} \right) + D_{qi} \quad (17)$$

In (17), D_{qi} is the integrated uncertainty term, which is estimated by a DO in this paper. Let $\hat{D}_{qi}$ be the observed value of D_{qi} and $\tilde{D}_{qi} = D_{qi} - \hat{D}_{qi}$ be the error between D_{qi} and $\hat{D}_{qi}$, then DO can be designed as the following form.

$$\begin{cases} \dot{\hat{D}}_{qi} = w_{qi} + l \cdot e_{2,qi} \\ \dot{w}_{qi} = -l \left[\bar{u}_{qi} \left(\frac{v_{s,qi}}{L_{qi}C_{qi}} - \frac{R_{qi}}{L_{qi}C_{qi}} i_{L,qi} \right) + \hat{D}_{qi} \right] \end{cases} \quad (18)$$

where $l > 0.5$ is a parameter of the DO.

Based on (17) and (18), control input can be designed as:

$$\bar{u}_{qi} = \frac{1}{\frac{v_{s,qi}}{L_{qi}C_{qi}} - \frac{R_{qi}}{L_{qi}C_{qi}} i_{L,qi}} \cdot \left[-k_{2,qi} e_{2,qi} - \frac{a_{qi}}{(1 - a_{qi}^2)p_{qi}(t)} - \hat{D}_{qi} \right] \quad (19)$$

Before the stability proof, the following reasonable assumptions and lemma are given.

Assumption 1: The reference voltage $v_{\text{ref},qi}$ and its first-time derivative $\dot{v}_{\text{ref},qi}$ are bounded.

Assumption 2: The disturbance term and its first-time derivative unknown but bounded, $|D_{qi}| \leq D_0$, $|\dot{D}_{qi}| \leq D_1$. D_0 and D_1 are known positive constants.

Lemma 1 [41]: If $y_1(a) = \log \frac{1}{1-a^2}$, $y_2(a) = \frac{a^2}{1-a^2}$, where $a = \frac{e_1}{p(t)}$ and $|a| < 1$, then $y_1(a) \leq y_2(a)$.

The stability proof of the controller:

Consider the following Lyapunov function

$$V = \frac{1}{2} \log \frac{1}{1 - a_{qi}^2} + \frac{1}{2} e_{2,qi}^2 + \frac{1}{2} \tilde{D}_{qi}^2 \quad (20)$$

The time derivative of V is:

$$\dot{V} = \dot{V}_1 + e_{2,qi} \cdot \dot{e}_{2,qi} + \tilde{D}_{qi} \cdot \dot{\tilde{D}}_{qi} \quad (21)$$

Substituting (14) and (15) into (21) yields

$$\begin{aligned} \dot{V} &= \frac{a_{qi}}{(1 - a_{qi}^2)p_{qi}(t)} (-k_{1,qi} a_{qi} p_{qi}(t) + e_{2,qi}) \\ &\quad + e_{2,qi} \dot{e}_{2,qi} + \tilde{D}_{qi} \dot{\tilde{D}}_{qi} \end{aligned} \quad (22)$$

Then, substituting (16) into (22) yields

$$\begin{aligned} \dot{V} &= e_{2,qi} \left[\frac{a_{qi}}{(1 - a_{qi}^2)p_{qi}(t)} + \bar{u}_{qi} \left(\frac{v_{s,qi}}{L_{qi}C_{qi}} - \frac{R_{qi}}{L_{qi}C_{qi}} i_{L,qi} \right) \right. \\ &\quad \left. + D_{qi} \right] - \frac{k_{1,qi} a_{qi}^2}{1 - a_{qi}^2} + \tilde{D}_{qi} \dot{\tilde{D}}_{qi} \end{aligned} \quad (23)$$

Next, substituting $D_{qi} = \tilde{D}_{qi} + \hat{D}_{qi}$ and (19) into (23) yields

$$\dot{V} = -\frac{k_{1,qi} a_{qi}^2}{1 - a_{qi}^2} - k_{2,qi} e_{2,qi}^2 + e_{2,qi} \tilde{D}_{qi} + \tilde{D}_{qi} \dot{\tilde{D}}_{qi} \quad (24)$$

Since

$$e_{2,qi} \tilde{D}_{qi} \leq \frac{e_{2,qi}^2}{2} + \frac{\tilde{D}_{qi}^2}{2} \quad (25)$$

equation (24) can be rewritten as:

$$\dot{V} \leq -\frac{k_{1,qi} a_{qi}^2}{1 - a_{qi}^2} - \left(k_{2,qi} - \frac{1}{2} \right) e_{2,qi}^2 + \frac{\tilde{D}_{qi}^2}{2} + \tilde{D}_{qi} \dot{\tilde{D}}_{qi} \quad (26)$$

Time derivative of $\hat{D}_{qi}$ can be derived from (18) as following.

$$\dot{\hat{D}}_{qi} = l(D_{qi} - \hat{D}_{qi}) = l \cdot \tilde{D}_{qi} \quad (27)$$

Since $\dot{\tilde{D}}_{qi} = \dot{D}_{qi} - \dot{\hat{D}}_{qi}$, then,

$$\dot{\tilde{D}}_{qi} = \dot{D}_{qi} - l \cdot \tilde{D}_{qi} \quad (28)$$

Further, substituting (28) into (26) yields

$$\dot{V} \leq -\frac{k_{1,qi} a_{qi}^2}{1 - a_{qi}^2} - \left(k_{2i} - \frac{1}{2} \right) e_{2,qi}^2 - \left(l - \frac{1}{2} \right) \tilde{D}_{qi}^2 + \tilde{D}_{qi} \dot{D}_{qi} \quad (29)$$

According to Assumption 2, (29) can be rewritten as:

$$\dot{V} \leq -\frac{k_{1,qi} a_{qi}^2}{1 - a_{qi}^2} - \left(k_{2i} - \frac{1}{2} \right) e_{2,qi}^2 - \left(l - \frac{1}{2} \right) \tilde{D}_{qi}^2 + 2D_0 D_1 \quad (30)$$

Further, according to Lemma 1, inequality (30) can be rewritten as:

$$\begin{aligned} \dot{V} &\leq -k_{1,qi} \log \frac{1}{1 - a_{qi}^2} - \left(k_{2,qi} - \frac{1}{2} \right) e_{2,qi}^2 - \left(l - \frac{1}{2} \right) \tilde{D}_{qi}^2 \\ &\quad + 2D_0 D_1 \end{aligned} \quad (31)$$

Let

$$\begin{cases} r_1 = \min \left\{ k_{1,qi}, k_{2,qi} - \frac{1}{2}, l - \frac{1}{2} \right\} \\ r_2 = 2D_0D_1 \end{cases} \quad (32)$$

then, inequality (31) can be reduced to

$$\dot{V} \leq -r_1 \cdot V + r_2 \quad (33)$$

According to Lyapunov synthesis [42], it can be concluded that all signals in the closed-loop system are bounded. Meanwhile, control input (19) guarantees that:

$$\lim_{t \rightarrow \infty} V \leq \frac{r_2}{r_1} \quad (34)$$

Therefore, tracking error can be made arbitrarily small by adjusting the control gain.

3) Current Sharing

Since $H(s)$ is a pole close to 0, it can eliminate the steady-state error. Therefore, the input of $H(s)$ in steady state is close to 0. Then, equation (8) can be written as:

$$k_v(v_{dc,qi}^* - \bar{v}_{o,qi}) - \gamma_{qi}i_{o,qi} \approx 0 \quad (35)$$

Removing residuals yields:

$$i_{o,qi} = \frac{k_v(v_{dc,qi}^* - \bar{v}_{o,qi})}{\gamma_{qi}} \quad (36)$$

In order to achieve accurate current sharing according to the ratio of the capacity of DGs, the output currents of each DG need to be proportional. The ratio of the output current of DG_{qi} to the DG_{qj} is:

$$\frac{i_{o,qi}}{i_{o,qj}} = \frac{\gamma_{qj}(v_{dc,qi}^* - \bar{v}_{o,qi})}{\gamma_{qi}(v_{dc,qj}^* - \bar{v}_{o,qj})} \quad (37)$$

If the consensus algorithm described in the previous section can reach a consistent state, then it can satisfy $\bar{v}_{o,qi} = \bar{v}_{o,qj}$ in finite time. Thus, equation (37) can be reduced to

$$\frac{i_{o,qi}}{i_{o,qj}} = \frac{\gamma_{qj}}{\gamma_{qi}} \quad (38)$$

Therefore, accurate current sharing can be achieved by simply satisfying (38).

C. Tertiary Control

Since secondary control can only achieve voltage regulation and current sharing within MGs, it cannot achieve current sharing among MGs. Thus, the tertiary control structure needs to be introduced. Hence, a tertiary control strategy based on DET-RACA is designed, as shown in (39).

$$v_{dc,q}^* = v_{Gref} - \delta(i_{s,q}(t) - \bar{i}_{s,q}(t)) \quad (39)$$

where v_{Gref} denotes the global reference voltage value, $v_{dc,q}^*$ denotes the bus voltage reference value of MG_q obtained by tertiary control, δ is a parameter of tertiary control, $i_{s,q}$ represents the output current of the sampling node in MG_q . $\bar{i}_{s,q}$ denotes the global average current value observed by the current observer.

$$\begin{cases} \bar{i}_{s,q}(t) = i_{s,q}(t) + z_q(t) \\ \dot{z}_q(t) = \alpha z_q - \sum_{p \in N_q} a_{qp} \text{sgn}\{\hat{i}_{s,q}(t) - \hat{i}_{s,p}(t)\} u_q(t) \\ \dot{u}_q(t) = |\hat{i}_{s,q}(t) - \hat{i}_{s,p}(t)| \end{cases} \quad (40)$$

where N_q is the neighborhood of MG_q in the upper layer topology, and $\hat{i}_{s,q}(t) = \bar{i}_{s,q}(t_{k_q}^q)$ is the observed average current of MG_q at the k_q th trigger event, $t \in [t_{k_q}^q, t_{k_q+1}^q)$.

The global average current observer in (40) is based on the upper layer communication topology and can ensure that observed current values converge to the global average current value. Moreover, the reference bus voltage of each MG is adjusted by comparing the local current in each MG with the global average current, which can further enable current sharing among MGs.

IV. SIMULATION AND RESULT ANALYSIS

In this section, the effectiveness of the proposed control strategy for DC MG cluster is verified by simulations. The DC MG cluster shown in Fig. 2 is modeled and simulated in Matlab/Simulink.

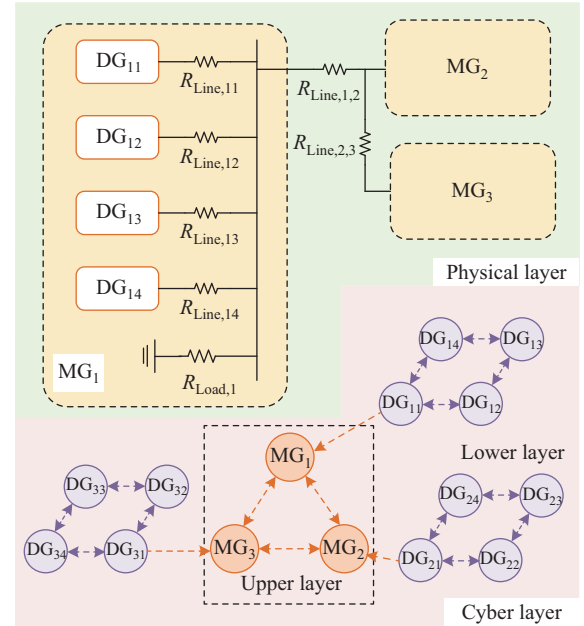


Fig. 2. A DC MG cluster consisting of three MGs.

As displayed in Fig. 2, the system consists of 3 MGs, each of which is composed of 4 DGs. For the cyber layer, all communication networks are connected in a ring, where the network among MGs is the upper layer network and the network within each MG is the lower layer network. The upper layer controller samples pinned sampling nodes in each local communication topology of the lower layer, and generates a bus voltage reference value for each MG. In the lower layer network, DGs within each MG exchange information through their respective local communication topologies and observe the average output voltage of each subsystem. Besides, communication among the nodes is bidirectional, and there is no information exchange among subsystems in the lower-layer

network. In the simulation model, the message send/receive blocks from the SimEvents library, which can convert the signal to a message, are used to simulate wireless communication of the cyber layer. Let DG_{q1} , $q = 1, 2, 3$, be sampling nodes for tertiary control.

In Fig. 2, $R_{Line,1,2}$ and $R_{Line,2,3}$ are line impedances between MG_1 and MG_2 , MG_2 and MG_3 , respectively. Parameter values of each MG and its layered controller are the same, and parameter settings of the system, controller, and event trigger conditions are detailed in Table II.

TABLE II
PARAMETER SETTING

Parameters	Value	Parameters	Value
System ($q = 1, \dots, 3; i = 1, \dots, 4$)			
L_{qi} (mH)	1	R_{qi} (Ω)	0.04
C_{qi} (μ F)	1000	$R_{Line,q1} \sim R_{Line,q4}$ (Ω)	0.2, 0.3, 0.4, 0.5
v_{Gref} (V)	80	$R_{Load,1} \sim R_{Load,3}$ (Ω)	20, 15, 10
$v_{s,qi}$ (V)	60	$R_{Line,1,2}, R_{Line,2,3}$ (Ω)	0.2, 0.3
Controller ($q = 1, \dots, 3; i = 1, \dots, 4$)			
$k_{1,qi}, k_{2,qi}$	2000, 1000	l	500
k_v	300	γ_{qi}	5
β	0.01	δ	2
α	0.01		
Triggering condition ($q = 1, \dots, 3; i = 1, \dots, 4$)			
θ_{qi}	0.9	σ_{qi}	1.5
χ_{qi}	12	ϕ_{qi}	10

Define the boundary function of output voltage as:

$$p_{qi}(t) = av_{ref,qi} + bv_{Gref}e^{\kappa t} \quad (41)$$

where a, b, κ denote parameters set by users. The larger a is, the larger the steady-state bound; the larger b is, the larger the

instantaneous bound; and the larger κ is, the faster the bound converges. Let $a = 0.05$, $b = 0.05$, $\kappa = 100$.

In order to test the performance of the proposed control strategy, simulations are performed and analyzed as follows.

A. Case 1: Performance Analysis for Voltage Controller

In this section, the performance of the designed BLF-based voltage controller is simulated and analyzed by operating MG_1 , which is disconnected from other MGs in the simulation. The simulation process experiences 1.6 s. Figs. 3 and 4 show system response curves for BLF-based controller and PID controller, respectively. Since other control structures and system parameters of the system are the same when the two controllers are employed separately, the difference in system response is only generated by the controllers.

As shown in Fig. 3, under the action of BLF-based controller, the system output has reached steady state before 0.2 s, and current sharing among DGs has been achieved precisely. When the load changes at $t = 0.8$ s, the system responds quickly, and there is no sudden change in voltage. Compared with BLF-based controller (see Fig. 4), PID controller responds slowly. It takes 0.4 s to reach stability; in addition, load change at 0.8 s causes large voltage fluctuations.

Figure 5 shows the voltage tracking error and error bounds curves of the two controllers. As observed from the figure, BLF-based controller responds quickly, and its tracking error can converge to 0. In the process of system operation, tracking error remains within the bounded range even when disturbances occur, which satisfies intended performance requirements. PID controller, on the other hand, has a large

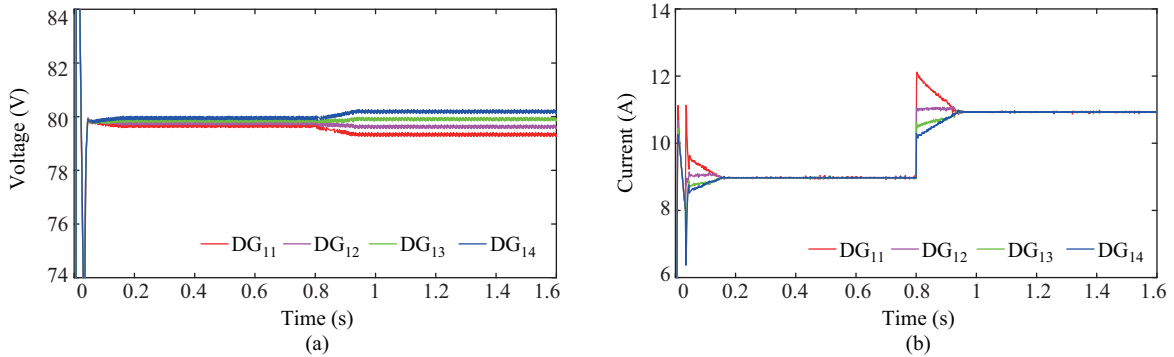


Fig. 3. The performances of BLF-based controller. (a) Output voltage. (b) Output current.

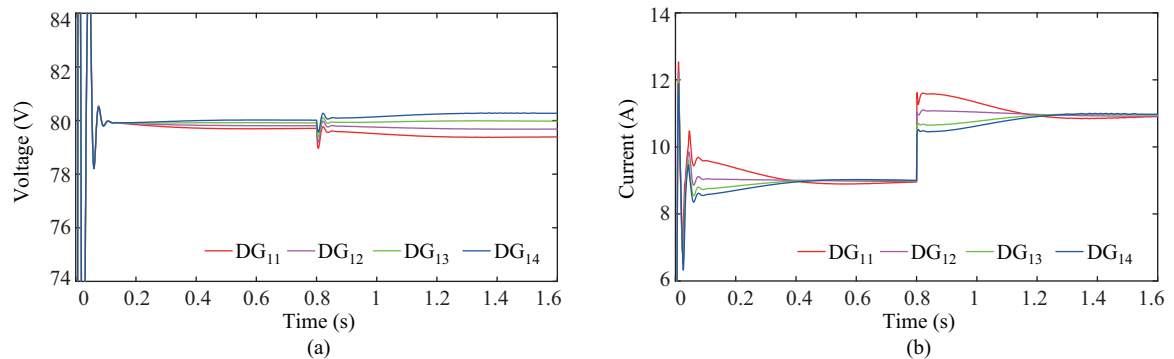


Fig. 4. The performances of PID controller. (a) Output voltage. (b) Output current.

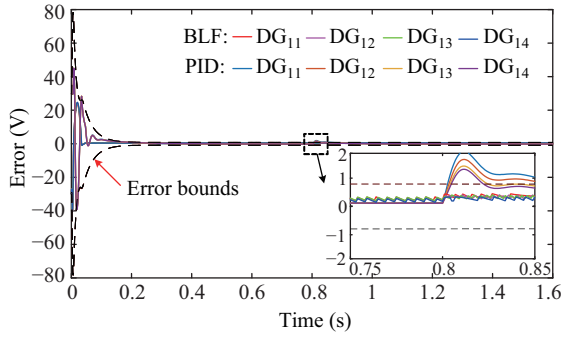


Fig. 5. Tracking error of the two controllers.

tracking error when load changes, with a maximum tracking error of 2.4 V. Therefore, this BLF-based voltage controller can act as a boundary constraint on the error and can improve the transient voltage performance of the system.

B. Case 2: Performance Analysis for the Proposed Strategy

This section simulates and analyzes the control performance of the proposed control strategy in DC MG cluster. Simulation process experiences 2 s. During $t = 0 \sim 0.5$ s, primary control and secondary control are implemented. Then the tertiary controller is activated at $t = 0.5$ s. The load of MG₃ increases from 10Ω to 30Ω at 1.2 s. In order to better illustrate the improvement of control performance by adopting DET-RACA, a comparison simulation with the classical average consensus algorithm (CACA) [38] is performed, keeping other parameters of the system and local controller unchanged. Simulation results are shown in Figs. 6–8.

Figures 6(a) and (b) depict the response curves of output voltage and output current of each DGs with the proposed strategy, respectively. As shown in the figures, during $t = 0 \sim 0.5$ s, local output voltages and output currents of DGs can be maintained stable under primary and secondary controls, and currents can be accurately shared within MGs. At $t = 0.5$, tertiary control is activated, output currents of all DGs can converge quickly, enabling accurate current sharing among different MGs. At $t = 1.2$ s, there are no sudden drops or rises in voltage with the load change, and the system regains stability within 0.05 s, as well as the current sharing function. Fig. 7 presents output voltage and output current curves of the system employing CACA. As seen in the figure, the compared algorithm converges significantly slower than the proposed control strategy, taking 0.4 s to converge to steady state.

Figures 6(c) and (d) display the moment of event triggering for the upper layer and the lower layer network, respectively. Fig. 8 provides a comparison graph of communication instants for the two methods. As shown in these figures, with the event-triggering mechanism, DET-RACA algorithm can effectively reduce the communication frequency of each layer of the network and thereby alleviate the communication burden of the DC MG cluster system.

C. Case 3: Communication Interruption

In this subsection, MG cluster with communication interruptions is simulated and analyzed.

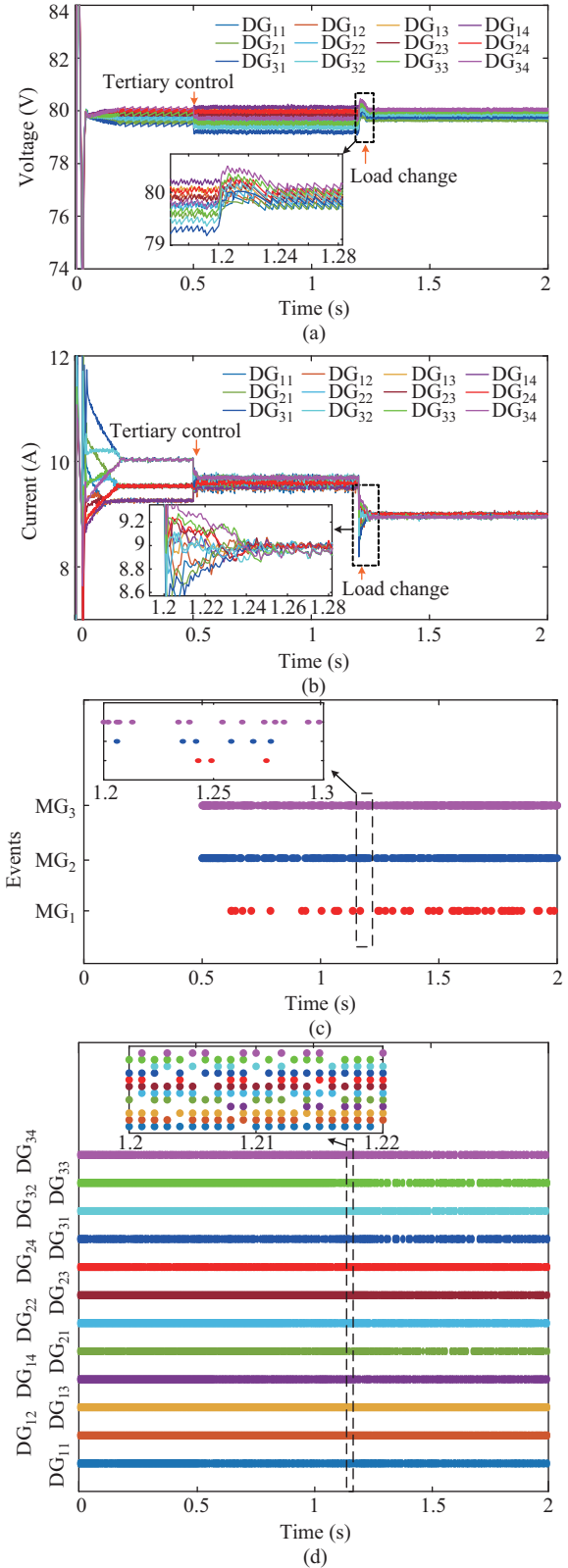


Fig. 6. Performances of the proposed strategy. (a) Output voltage of 12 DGs. (b) Output current of 12 DGs. (c) Events of the upper topology. (d) Events of the lower topology.

First, the condition of communication interruptions in the lower-layer network is studied. Simulation process experiences 2.5 s. Upper layer topology remains unchanged, and only

communication for MG₃ in the lower layer topology experiences communication interruptions, which is shown in Fig. 9. Communication interruption occurs between DG₃₂ and DG₃₃ at $t = 0.5$ s and between DG₃₁ and DG₃₂ at 1.2 s, and at 2 s, communication is restored. In the simulation, some disturbances are applied to the system to better analyze the impact of communication interruption on the system. During $t = 0 \sim 0.7$ s, the load of MG₃ is 10Ω , then the load of MG₃ increases to 30Ω at 0.7 s and returns to 10Ω at 1.5 s. Under these conditions, the operation results of the system are shown in Fig. 10.

From Figs. 10(a)–(c), it can be revealed that the output

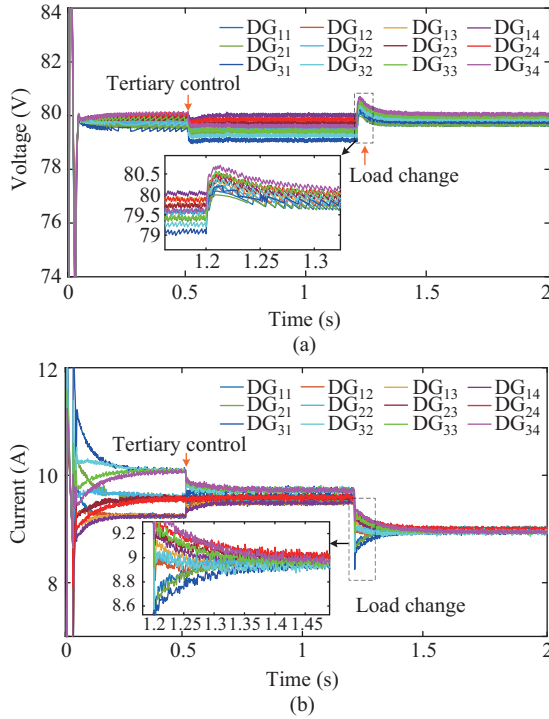


Fig. 7. Performances of the compared algorithm. (a) Output voltage of 12 DGs. (b) Output current of 12 DGs.

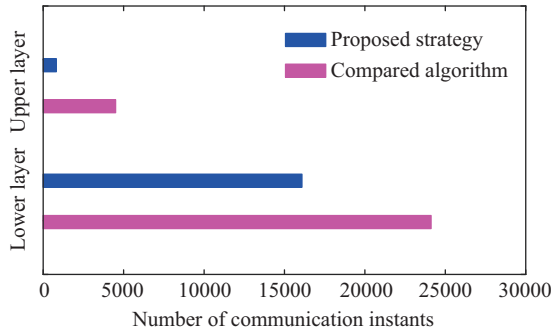


Fig. 8. Comparison of the communication instants.

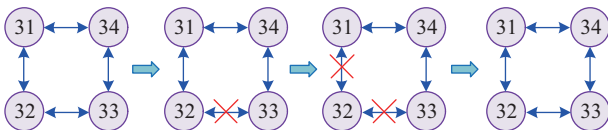


Fig. 9. Communication topology of MG₃.

current of the system can still be consistent after communication interruption at $t = 0.5$ s because the system has reached stability before 0.5 s. At $t = 0.7$ s, the load of MG₃ is increased, which generates a disturbance to the system. Since DG₃₂ and DG₃₃ can still maintain communication with other DGs, the output of each DG can still converge. At $t = 1.2$ s, communication between DG₃₁ and DG₃₂ is interrupted, i.e., communication of DG₃₂ is completely disconnected from other DGs. When the load change occurs, the reference voltage of each MG is re-regulated, and the output currents of each DG in MG₃, except DG₃₂, still converge quickly with other MGs. At $t = 2$ s, communication is restored, then all DGs return to their initial stable values.

Figures 10(d) and (e) show the moment of event trigger for the upper layer and the lower layer networks, respectively. When communication of DG₃₂ is completely interrupted with other DGs, its communication is not triggered.

Then, communication interruptions in the upper-layer network are simulated. Simulation process experiences 2.5 s. Lower layer topology remains unchanged, and upper layer topology is shown in Fig. 11. Communication interruption occurs between MG₂ and MG₃ at 0.5 s and between MG₁ and MG₃ at 1.2 s, and communication is restored at 2 s. Simulation results of the system under this operating condition are shown in Fig. 12.

As shown in Figs. 12(a) and (b), the output current of DGs within each MG can achieve accurate current sharing because the lower network keeps normal communication all the time. At $t = 0.5$ s, the communication interruption between MG₂ and MG₃ has less impact on global voltage regulation and current sharing. When communication of MG₃ is completely disconnected from other MGs, MGs except MG₃ can achieve accurate current sharing, while each DG in MG₃ can only achieve current sharing within MG₃. After $t = 2$ s, the three MGs return to their stable values before $t = 0.5$ s, resulting from restored communication topology. Fig. 12(c) shows the moment of the event trigger of the upper-layer network.

D. Case 4: Plug-and-play Capability (pnp)

Simulation process experiences 2 s. Before $t = 0.5$ s, MGs are not connected to each other and have no communication. At $t = 0.5$ s, MG₁ and MG₂ are connected to each other while they exchange information. At $t = 1.2$ s, MG₃ is connected to MG₂, and a ring communication topology is formed among the MGs. The communication topology is shown in Fig. 13. Simulation results of the system are shown in Fig. 14.

As seen in Figs. 14 (a) and (b), MG₁ is connected to MG₂ at 0.5 s while the tertiary controller is activated. Since MG₃ has no communication connection with other MGs, current sharing is achieved only between MG₁ and MG₂. After $t = 1.2$ s, MG₃ is connected to the system and generates communication with other MGs, and then the reference voltage of each MG is readjusted to realize accurate global current sharing. It is worth noting that there is no large fluctuation in the system during access of each MG, which proves the proposed control method has good PnP capability. Fig. 14(c) shows the moment of the event trigger of the upper-layer network.

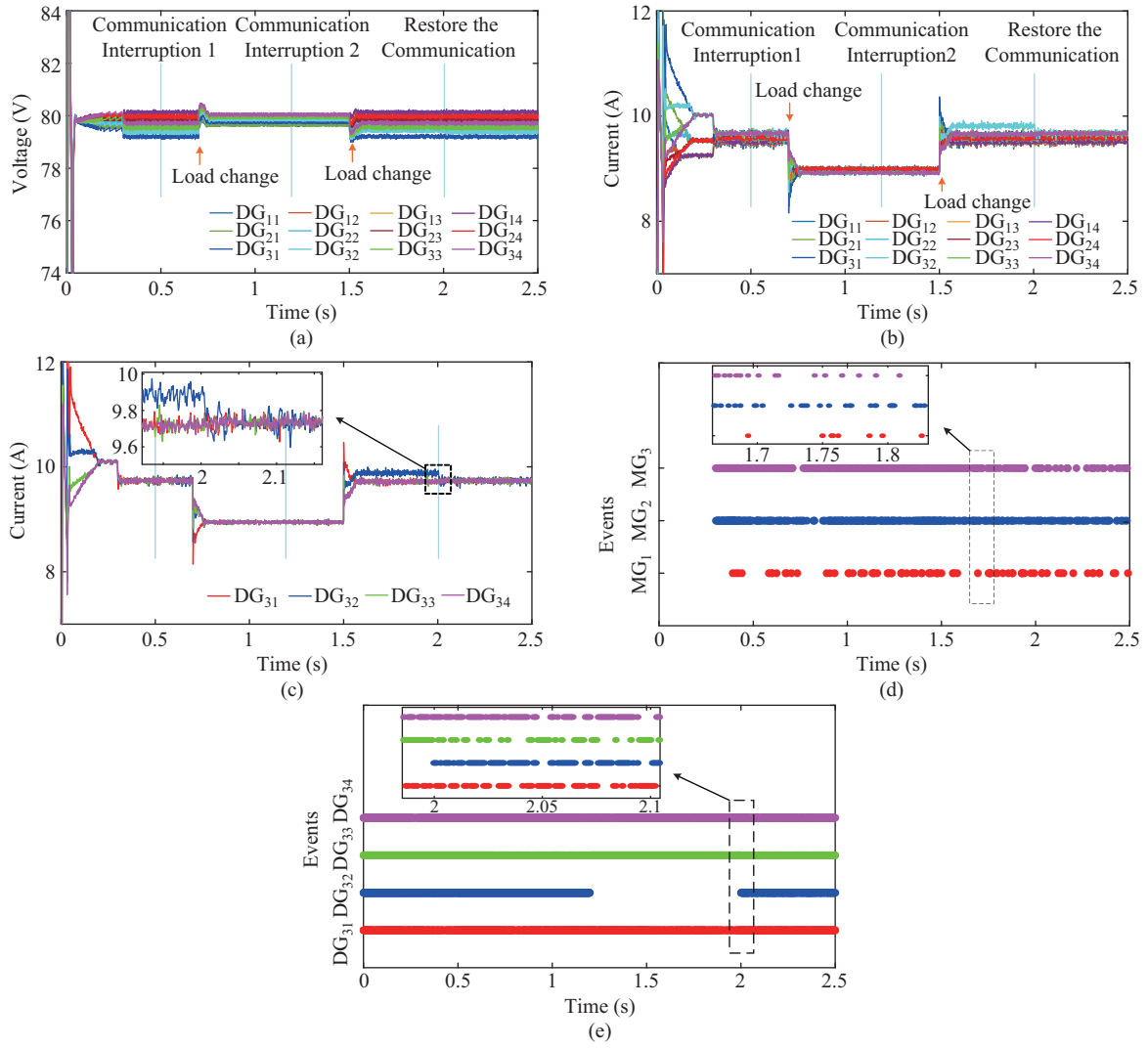


Fig. 10. Performances of three MGs in case of lower communication interruption. (a) Output voltage of 12 DGs. (b) Output current of 12 DGs. (c) Output current of DG₃₁–DG₃₄. (d) Events of the upper topology. (e) Events of the lower topology.

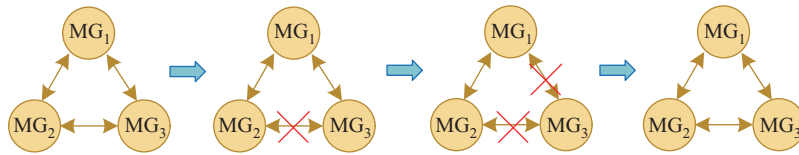
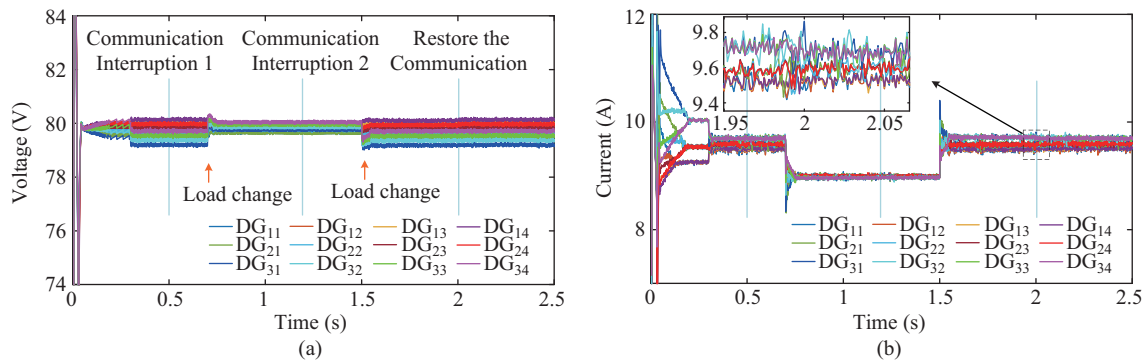


Fig. 11. Communication topology of 3 MGs.



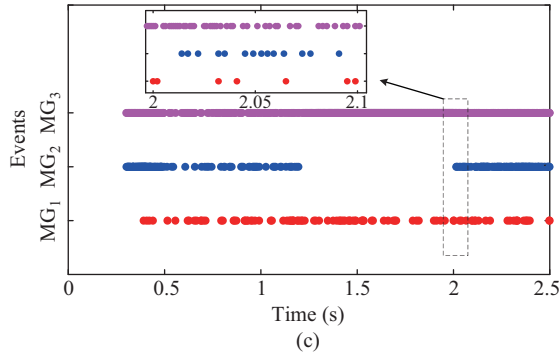


Fig. 12. Performances of three MGs in case of upper communication interruption. (a) Output voltage of 12 DGs. (b) Output current of 12 DGs. (c) Events of upper topology.

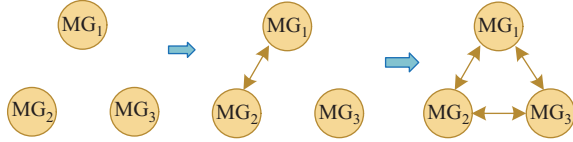


Fig. 13. Communication topology of 3 MGs with PnP.

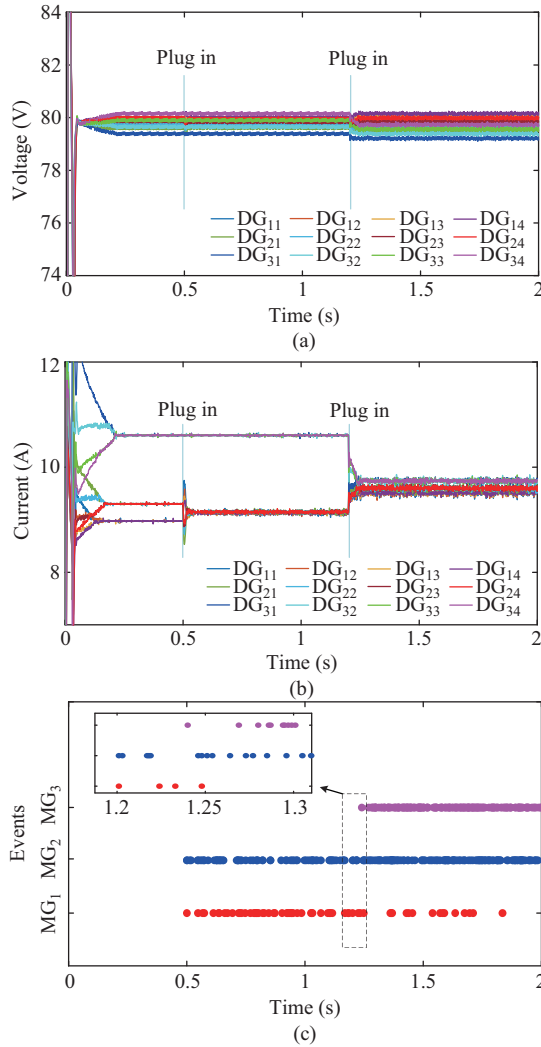


Fig. 14. Performances of three MGs in case of PnP. (a) Output voltage of 12 DGs. (b) Output current of 12 DGs. (c) Events of upper topology.

E. Case 5: Communication Delay

In this subsection, the system is simulated with communication delays. Simulation process experiences 1.6 s. Figs. 15 and 16 provide system responses for 10 ms and 20 ms communication delays, respectively.

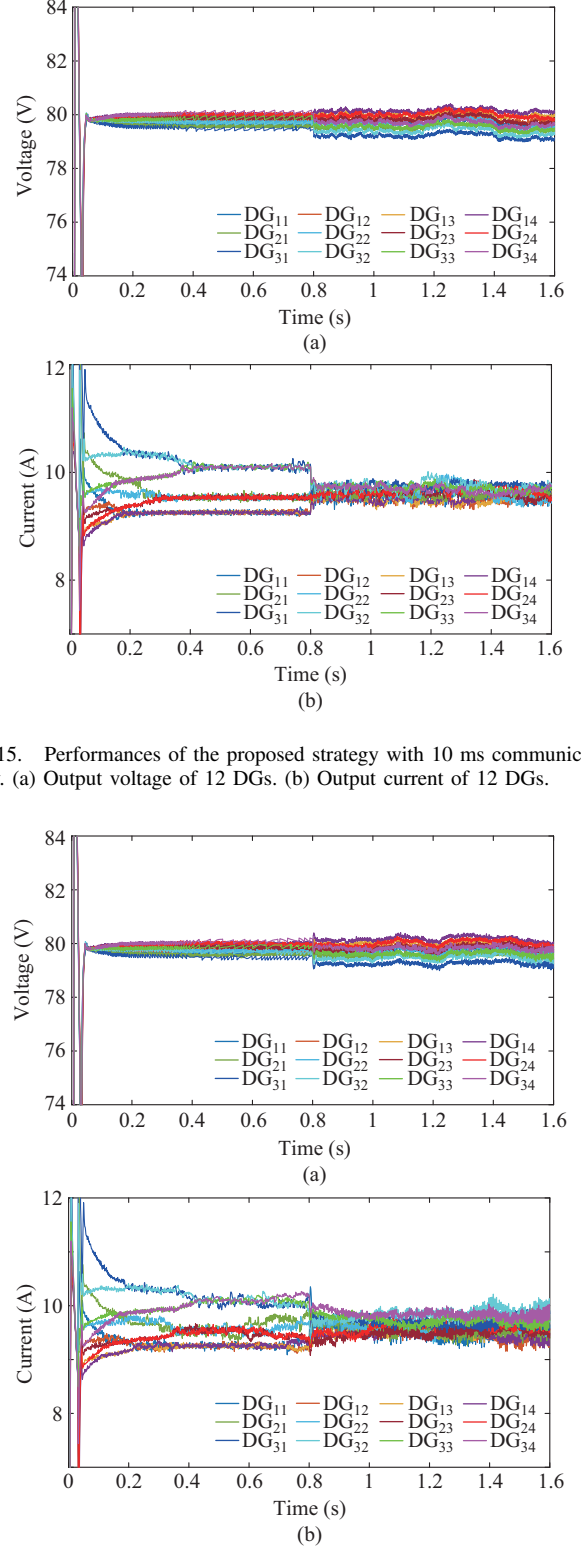


Fig. 15. Performances of the proposed strategy with 10 ms communication delay. (a) Output voltage of 12 DGs. (b) Output current of 12 DGs.

Fig. 16. Performances of the proposed strategy with 20 ms communication delay. (a) Output voltage of 12 DGs. (b) Output current of 12 DGs.

According to Fig. 15, when the communication delay is 10 ms, the system output is comparable to that without delay (see Fig. 6), although there are slight voltage and current fluctuations. When communication delay increases to 20 ms, system output oscillates more significantly; however, current sharing is basically achieved. Therefore, the control strategy can provide moderate robustness to communication delays.

V. CONCLUSION

In this paper, an output-constrained distributed cooperative control strategy for DC MG cluster based on DET-RACA is proposed to achieve voltage regulation and accurate current sharing. First, a control structure that integrates primary control and secondary control is adopted, in which the average voltage value of each DG is observed using a DET-RACA-based average voltage observer, thus realizing functions of voltage regulation and current sharing simultaneously within each MG. An output-constrained local voltage controller based on BLF is designed to limit local output voltage within a predefined range to ensure high-performance transient voltage control. Besides, tertiary control employed a DET-RACA-based average current observer to observe the global average current, and then the average current is used for adjusting the bus reference voltage of each MG to realize global current sharing of the DC MG cluster. Finally, five simulation cases verify that the proposed control strategy can achieve global voltage regulation and current sharing objectives, while effectively improving the transient voltage performance of the system. Moreover, the strategy is robust to PnP and communication delays, which proves the effectiveness and feasibility of the method for DC MG cluster control.

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