

Article

Event-Triggered Resilient Control with High Communication Efficiency of Networked DC Microgrid Clusters Under Nodal DoS Attacks

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Abstract

In DC microgrid (DC-MG) clusters, distributed generation units rely on electronic communication networks to exchange voltage measurements, current information, and coordination signals for voltage recovery and current sharing. As the degree of system clustering and communication coupling increases, nodal denial-of-service (DoS) attacks may interrupt the information exchange of leaders and followers, resulting in communication topology switching and degraded cooperative control performance. Accordingly, this paper proposes an event-triggered (ET) resilient control scheme with high communication efficiency for networked DC-MG clusters under nodal DoS attacks. First, a distributed secondary control model with a cross-layer communication mechanism is constructed in accordance with the requirements of the system's overall power distribution, which incorporates the two-layer node architecture of leaders and followers in DC-MG clusters. Second, a statistical multi-mode nodal DoS attack model is developed to characterize heterogeneous communication interruptions through topology-dependent attack modes and their occurrence probabilities. Finally, an exponential threshold ET mechanism based on bus-voltage recovery errors is designed within the distributed secondary control framework to reduce redundant information transmission while preserving resilience against nodal communication attacks. Simulation results demonstrate that the proposed method can maintain accurate voltage recovery and current sharing in networked DC-MG clusters under large-scale DoS attacks, while improving communication efficiency through ET updates.

Keywords: DC microgrid; denial-of-service attacks; Markov chain; distributed hierarchical control; event-triggered mechanism



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1. Introduction

DC-MGs have emerged as pivotal building blocks of distributed energy systems, by virtue of their inherent merits in highly efficient energy conversion, low harmonic interference, and native compatibility with renewable energy sources [1,2]. As a canonical localized control paradigm for distributed generation (DG) units, droop control enables proportional current sharing and voltage support by replicating the external characteristics of synchronous generators [3,4]. Nevertheless, the parameter tuning of droop controllers may cause DC bus voltage deviations and inaccurate current sharing [5]. In addition, impedance mismatch caused by heterogeneous device characteristics further aggravates unequal current distribution among DG units [6,7]. These problems become more prominent in

large-scale interconnected DC-MG clusters, where voltage recovery and proportional current sharing require not only local regulation but also coordinated information exchange through communication networks.

To meet the requirements of large-scale DC-MG interconnection and reduce the risk of single point failure, distributed hierarchical control (DHC) has been widely investigated [8–10]. At the primary control level, droop control [11], virtual impedance control [12], and virtual inertia control [13] have been applied to regulate voltage and current dynamics in DC-MG systems. At the secondary control level, cooperative control algorithms [8] and consensus-based protocols [14] are usually employed to restore the global bus voltage and improve current-sharing accuracy. The essential feature of these approaches is that DG units exchange voltage, current, and coordination information through electronic communication networks. For example, the distributed cooperative voltage and current control strategy in [15] requires current or voltage signal exchange among DG units and estimates the global average voltage of neighboring DC-DC converters to achieve voltage balancing and proportional current sharing. The partially decentralized secondary controller in [16] reduces communication and implementation costs by requiring only DC bus voltage information for current sharing and voltage recovery in single-bus DC-MGs. For multi-bus architectures where each distributed energy resource has its own local DC bus, a fully distributed dynamic edge event-triggered current sharing control strategy for power-coupled multi-bus DC-MG systems is developed [14].

Although distributed secondary control improves the scalability and reliability of DC-MGs, it also makes voltage recovery and current sharing highly dependent on communication topology. In centralized-free communication architectures, each controller possesses only localized monitoring capability, lacking global observability [17,18]. As the clustering density of DC-MGs increases, the number of inter distributed generator (inter-DG), leader–follower, and inter-cluster communication links grows accordingly, thereby escalating both communication overhead and vulnerability to cyberattacks [19,20]. In particular, DoS attacks can block the information exchange of compromised communication nodes, causing topology switching, neighbor-information loss, and degradation of cooperative control performance [21]. Different from physical disturbances acting directly on electrical circuits, nodal DoS attacks affect the closed-loop system through communication interruption, and may eventually lead to bus-voltage deviations, current-sharing mismatch, and even cascading performance deterioration in clustered DC-MGs.

To address cyber-attack issues in networked control systems, some studies focus on attack modeling [22], while others develop resilient controllers with explicit countermeasure capabilities. Existing attack models are commonly based on Bernoulli processes [23] or fixed-period switching assumptions [24]. However, due to the scarcity of real-world attack data, the state transition probabilities of Markov jump systems are often obtained from prescribed assumptions [17], which makes it difficult to describe the stochastic and persistent behaviors of practical attackers. More critically, in hierarchical DC-MG clusters, the communication coupling between primary/secondary control loops, leader–follower nodes, and inter-cluster coordination links may transmit local communication failures across different control layers [25]. Existing control methods resilient to attacks mainly focus on single-layer communication topologies [26,27], and still lack a unified cross-layer attack and defense framework for clustered networked DC-MGs. Therefore, it remains necessary to establish a nodal DoS attack model that can describe heterogeneous communication interruptions and their influence on voltage recovery and current sharing in distributed secondary control.

Meanwhile, communication efficiency is another critical requirement for networked DC-MGs under DoS attacks. Frequent information exchange increases communication load and may enlarge the exposure surface of communication nodes, whereas insufficient communication may degrade voltage recovery and current sharing accuracy. ET mechanisms provide an effective solution by activating information transmission only when necessary, rather than relying on continuous or periodic updates [28–30]. Existing ET mechanisms can generally be divided into static relative ET mechanisms with fixed error thresholds [31], dynamic ET mechanisms that extend triggering intervals through protocols that vary over time [32], and hybrid ET mechanisms that suppress redundant communication through logic with multiple conditions [33]. For secure consensus and resilient control under DoS attacks, strategies based on ET have also been developed for systems with switched topologies and incomplete measurements [34,35]. Nevertheless, many existing triggering thresholds are either statically prescribed or described by relatively complex dynamic equations, which may not be well suited for DC MG clusters with communication coupling and fast voltage recovery requirements. In contrast, an exponential-threshold ET mechanism can adapt the triggering condition to the transient response of the system: a relatively loose threshold in the initial stage suppresses frequent triggering and reduces redundant communication, while a gradually tightened threshold in the steady stage improves control accuracy and maintains voltage recovery performance [36].

In summary, existing studies have yet to fully address the problem of cooperative voltage recovery and current sharing in networked DC-MGs under sophisticated nodal DoS attacks. Three core challenges remain unresolved: First, the cross-layer communication coupling between leader nodes, follower nodes, and interconnected DC-MG clusters has not been fully characterized in existing modeling frameworks. Second, the stochastic nature of nodal DoS attacks and their induced communication topology switching are difficult to capture with conventional attack modeling paradigms. Third, the inherent trade-off between communication efficiency and control resilience in distributed secondary control is rarely addressed in a unified manner under large-scale communication disruptions.

A distributed secondary control model with communication coupling is established for networked DC-MGs. The proposed model integrates droop based primary regulation, secondary voltage recovery, current sharing compensation, and a two layer leader and follower node architecture, thereby describing the interaction between communication and control required for global power distribution.

A generalized nodal DoS attack model based on Markov processes is developed to characterize heterogeneous communication interruption modes in clustered DC-MGs. The model represents different compromised topologies through mode-dependent communication matrices and characterizes their occurrence through an empirically identifiable probability vector.

An ET resilient control strategy with improved communication efficiency is designed within the distributed secondary control framework. The proposed exponential threshold ET mechanism uses bus voltage recovery errors to determine update instants, reducing redundant information transmission while preserving voltage recovery and current sharing performance under large-scale nodal DoS attacks.

2. Networked DC-MGs System

2.1. Graph Properties and Notation

The hardware topology of the networked DC-MGs system and its DHC structure are shown in Figure 1. $\mathcal{N}^i$ denotes the set of all DGs connected to the i th bus, whose communication system is modeled as a directed graph $\mathcal{G}^i = (\mathcal{V}^i, \varepsilon^i)$. The node set $\mathcal{V}^i$ contains the leader node $\mathcal{V}_0^i$ and follower nodes $\mathcal{V}_k^i, k = 1, 2, \dots, N_i$. The set of edges

ε^i represents the weights of instruction reception from followers to followers and from followers to leader through the adjacency matrix $\mathcal{A}^i = \{a_{mk}^i\}$ and the vector $G^i = \text{row}\{g_{m0}^i\}$, respectively. If $(\mathcal{V}_k^i, \mathcal{V}_k^j) \in \varepsilon^i$ then the corresponding elements of $\mathcal{A}^i$ and G^i is 1, otherwise 0. $\mathcal{N}$ denotes the set of buses for the whole system, whose communication system is modeled as an undirected graph $\mathcal{G} = (\mathcal{V}, \varepsilon)$. The set of nodes $\mathcal{V}$ consists entirely of leaders on each bus. The set of edges ε corresponds to the adjacency matrix $\mathcal{B}^i = \{b_{ij}\}$ characterizing collaboration between leaders. If $(\mathcal{V}^i, \mathcal{V}^j) \in \varepsilon$ then $b_{ij} = 1$, otherwise being 0. The topologies are assumed to be strongly connected.

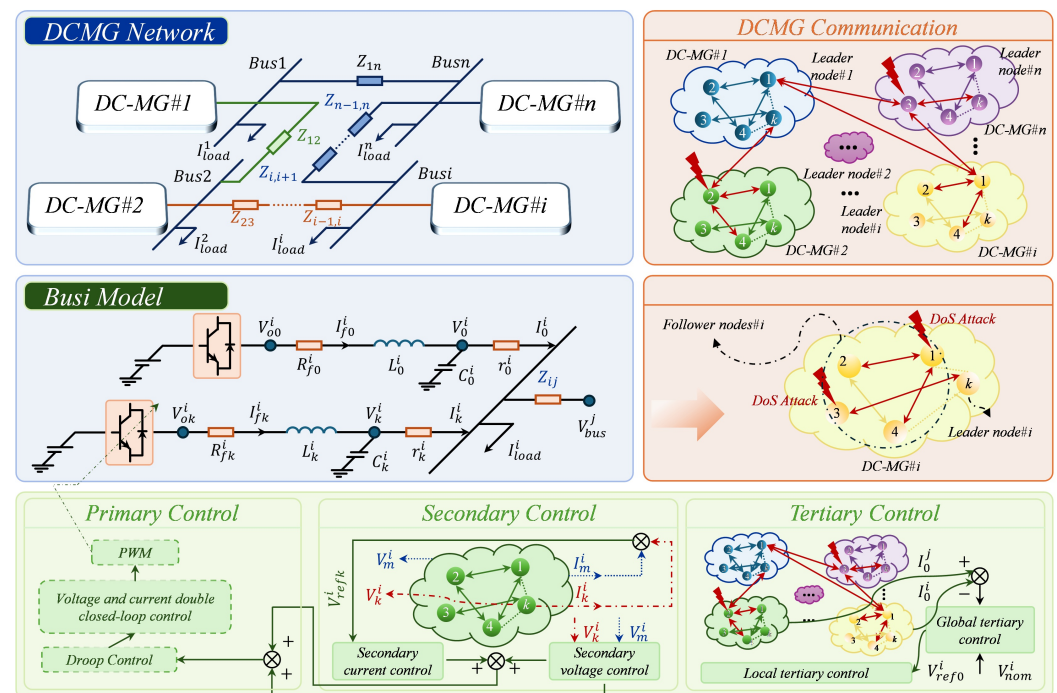


Figure 1. Communication coupled architecture of DC-MGs under DoS attacks.

Based on the communication architecture in Figure 1, the implementation procedure of the proposed controller is summarized in Figure 2. The communication layer and the sampled data control loop interact throughout the control process. At each sampling instant, the active Markov attack mode determines the availability of the leader, follower, and inter-MG communication links. The corresponding topology matrices are updated according to Equations (19)–(25). The local bus voltages and DG output currents are then measured. These measurements are used to calculate the voltage recovery and proportional current sharing errors according to Equations (3), (4), and (7). For each DG, the event condition in (26) is evaluated using the current voltage recovery error and the most recently transmitted value. If the event condition is satisfied, the current local information is transmitted to the relevant neighboring nodes, and the held data and triggering instant are updated. Otherwise, the sample and hold unit retains the previously transmitted information. Based on the available local measurements and neighboring information, the PI secondary controller calculates the compensation terms for voltage recovery, current sharing within each MG, and coordination among different MGs. The resulting compensation signals are incorporated into the primary droop control system through (1) and (2). The converter and DC-MG states are subsequently updated, and the same procedure is repeated at the next control sampling instant.

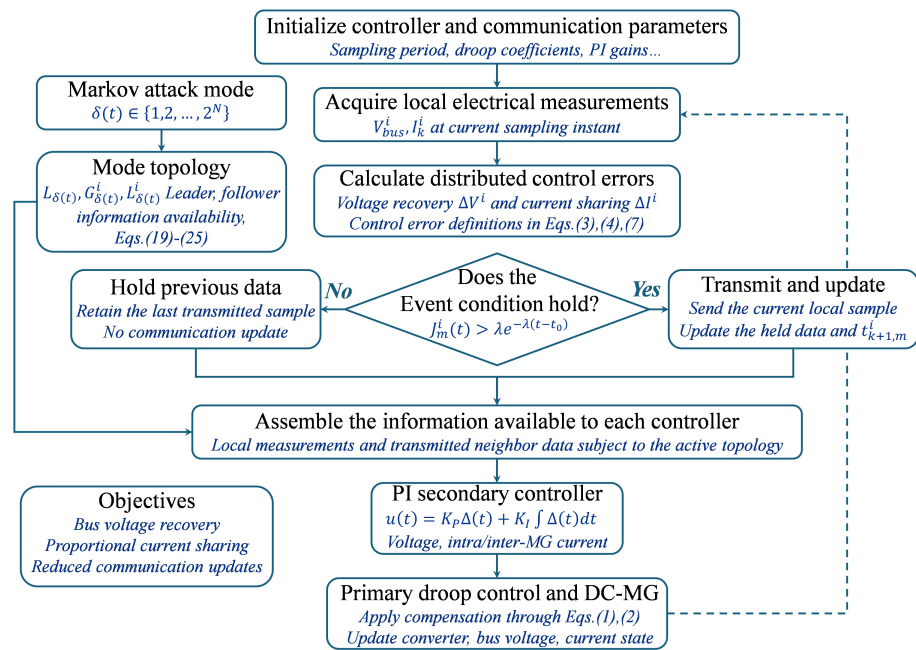


Figure 2. Implementation flowchart of the proposed method.

2.2. Hierarchical Control Structure

The k th branch in the i th DC-MG can be modeled by the filter capacitor C_k^i and filter inductor L_k^i as follows:

$$\begin{cases} C_k^i \frac{dV_k^i}{dt} = \frac{V_{bus}^i - V_k^i}{r_k^i} + I_{fk}^i \\ L_k^i \frac{dI_{fk}^i}{dt} = V_{Ok}^i - R_{fk}^i I_{fk}^i - V_k^i \end{cases} \quad (1)$$

In order to ensure the stability of the energy supply of the system, the converter has a droop characteristic. Due to the need for bus voltage recovery and load current balance, corresponding compensation terms are added. Neglecting the effect of the voltage-current double-closed loop, the converter terminal voltage can be expressed as

$$V_{Ok}^i = V_{refk}^i - k_{pk}^i I_{fk}^i + u_{k,1}^i + u_{k,2}^i \quad (2)$$

where k_{pk}^i represents the converter droop factor for the k th branch in the i th DC-MG. V_{ref}^i denotes the local rated output voltage. $u_{k,1}^i$ and $u_{k,2}^i$ denote the voltage compensation due to voltage recovery and current equalization, respectively, which is denoted under the action of the PI controller as

$$\begin{cases} u_{k,1}^i = K_{k,1}^{Pi} \Delta V_{busk}^i + K_{k,1}^{Li} \int \Delta V_{busk}^i dt \\ u_{k,2}^i = K_{k,2}^{Pi} \Delta I_{fk}^i + K_{k,2}^{Li} \int \Delta I_{fk}^i dt \end{cases} \quad (3)$$

where $K_{k,1}^{Pi}$, $K_{k,1}^{Li}$, $K_{k,2}^{Pi}$ and $K_{k,2}^{Li}$ are the PI coefficients to be designed. $\Delta V_{busk}^i = V_{refk}^i - V_{bus}^i$ and $\Delta I_{fk}^i = \sum_{m \in \mathcal{N}^i} a_{mk}^i (k_{pm}^i I_{fm}^i - k_{pk}^i I_{fk}^i)$.

However, there is still a need for current equalization between microgrids. Static rated voltage values and intra-group current compensation cannot satisfy the global power equalization of the DC-MGs system. Therefore, the leader is responsible for inter-network cooperative control and provides reference values for the followers; the followers correspond to the control commands of the leader in the network and communicate with the neighbors to update the local reference. The modeling is done separately below.

2.2.1. Modeling for Leaders

On the basis of the bus reference voltage being set, the leader designs the voltage compensation term through the global current balance demand as

$$\begin{cases} V_{ref0}^i = V_{nom}^i + u_{0,3}^i \\ u_{0,3}^i = K_{0,3}^{Pi} \Delta \hat{I}_{f0}^i + K_{0,3}^{Li} \int \Delta \hat{I}_{f0}^i dt \end{cases} \quad (4)$$

where $\Delta \hat{I}_{f0}^i = \sum_{j \in \mathcal{N}} b_{ij} (k_{p0}^j I_{f0}^j - k_{p0}^i I_{f0}^i)$. $K_{0,3}^{Pi}$ and $K_{0,3}^{Li}$ are the PI coefficients to be designed. V_{nom}^i is the local bus voltage setting. Consequently, the state space of the leader can be obtained by associating Equations (1)–(4) as

$$\begin{cases} \dot{x}_0^i = A_0^i x_0^i + B_0^i V_{O0}^i + C_0^i V_{bus}^i \\ V_{O0}^i = V_{nom}^i + \bar{k}_{p0}^i x_0^i + I_3 u_0^i \end{cases} \quad (5)$$

where $x_0^i = [V_0^i, I_{f0}^i]^T$, $A_0^i = [-\frac{1}{r_0^i C_0^i}, \frac{1}{C_0^i}; -\frac{1}{L_{f0}^i}, -\frac{R_{f0}^i}{L_{f0}^i}]$, $B_0^i = [0, \frac{1}{L_{f0}^i}]^T$, $C_0^i = [\frac{1}{r_0^i C_0^i}, 0]^T$, $\bar{k}_{p0}^i = [0, -k_{p0}^i]$ and $u_0^i = [u_{0,1}^i, u_{0,2}^i, u_{0,3}^i]^T$. To facilitate expression, I_n denotes the n -dimensional unit row vector and $\mathcal{I}_n$ denotes the n -dimensional identity matrix in this paper.

The intermediate variable $\xi_0^i = [\xi_{0,1}^i, \xi_{0,2}^i, \xi_{0,3}^i]^T$ is introduced to characterize the integral link of the controller u_0^i . The leader system is further characterized as

$$\begin{cases} \dot{x}_0^i = F_0^i x_0^i + Q_0^i u_0^i + B_0^i V_{nom}^i + C_0^i V_{bus}^i \\ u_0^i = \hat{K}_{0,1}^{Pi} V_{bus}^i - \hat{K}_{0,1}^{Pi} V_{nom}^i - \kappa_0^{Pi} (\sum_{j \in \mathcal{N}} \tilde{b}_{ij} k_{p0}^j x_0^j) \\ \quad + \gamma_0^{Pi} \tilde{x}^i + \phi_0^{Pi} \xi_0^i \\ \dot{\xi}_0^i = \hat{K}_{0,1}^{Li} V_{bus}^i - \hat{K}_{0,1}^{Li} V_{nom}^i - \kappa_0^{Li} (\sum_{j \in \mathcal{N}} \tilde{b}_{ij} k_{p0}^j x_0^j) \\ \quad + \gamma_0^{Li} \tilde{x}^i + \phi_0^{Li} \xi_0^i \end{cases} \quad (6)$$

where $F_0^i = A_0^i + B_0^i \bar{k}_{p0}^i$, $Q_0^i = B_0^i I_3$. $\hat{K}_{0,1}^{Pi} = [-K_{0,1}^{Pi}, 0, 0]^T$ and $\hat{K}_{0,1}^{Li} = [-K_{0,1}^{Li}, 0, 0]^T$. $\hat{K}_{0,n}^{Pi} = [0, K_{0,n}^{Pi}]$ and $\hat{K}_{0,n}^{Li} = [0, K_{0,n}^{Li}]$ where $n = 2, 3$. $\kappa_0^{Pi} = [-K_{0,1}^{Pi} \hat{K}_{0,3}^{Pi}; 0; \hat{K}_{0,3}^{Pi}]$ and $\kappa_0^{Li} = [-K_{0,1}^{Li} \hat{K}_{0,3}^{Li}; 0; \hat{K}_{0,3}^{Li}]$. $\tilde{b}_{ij}$ denotes the communication network connection relationship between the buses. $\tilde{b}_{ij} = b_{ij}$ and $\tilde{b}_{ii} = -\sum_{j \neq i} b_{ij}$. $\gamma_0^{Pi} = [0; \hat{K}_{0,2}^{Pi} (G_0^i k_p^i \otimes \mathcal{I}_2); 0]$ and $\gamma_0^{Li} = [0; \hat{K}_{0,2}^{Li} (G_0^i k_p^i \otimes \mathcal{I}_2); 0]$ where $G_0^i = ro\{\tilde{g}_{0m}^i\}$ and $k_p^i = diag\{k_{pm}^i\}, m = 0, 1 \dots N_i$. $\tilde{g}_{m0}^i = g_{m0}$ and $\tilde{g}_{00}^i = -\sum_{m \neq 0} g_{m0}$. $\tilde{x}^i = [x_0^i, x^i] = [x_0^i, x_1^i \dots, x_k^i, \dots, x_{N_i}^i]^T$ denotes the state ensemble of the leader with N_i followers. $\phi_0^{Pi} = \mathcal{I}_3 + [0, 0, -\hat{K}_{0,1}^{Pi}]$ and $\phi_0^{Li} = [0, 0, -\hat{K}_{0,1}^{Li}]$.

2.2.2. Modeling for Followers

After the leader adjusts the global rated output voltage according to the energy flow between buses, the follower needs to dynamically update the local rated output voltage. Its update law is designed to be

$$\begin{aligned} \dot{V}_{refk}^i &= \sum_{m \in \mathcal{N}^i} a_{mk}^i (V_{refm}^i - V_{refk}^i) + g_{m0}^i (V_{ref0}^i - V_{refk}^i) \\ &= \sum_{m \in \mathcal{N}^i} \tilde{a}_{mk}^i V_{refm}^i + g_{m0}^i (V_{nom}^i + u_{0,3}^i - V_{refk}^i). \end{aligned} \quad (7)$$

The state space of the follower single machine can be obtained by associating Equations (1)–(3) and Equation (7) as

$$\begin{cases} \dot{x}_k^i = A_k^i x_k^i + B_k^i V_{Ok}^i + C_k^i V_{bus}^i \\ V_{Ok}^i = V_{refk}^i + \bar{k}_{pk}^i x_k^i + I_2 u_k^i \end{cases} \quad (8)$$

where $u_k^i = [u_{0,1}^i, u_{0,2}^i]^T$ and the remaining terms are defined in the same way as Equation (5).

Intermediate variable $\xi_k^i = [\xi_{k,1}^i, \xi_{k,2}^i]^T$ characterizing the integral terms is introduced with reference to the method of definition of the leader system. The k th follower system of the i th bus can be denoted as

$$\begin{cases} \dot{x}_k^i = F_k^i x_k^i + Q_k^i u_k^i + B_k^i V_{refk}^i + C_k^i V_{bus}^i \\ u_k^i = \hat{K}_{k,1}^{Pi} (V_{bus}^i - V_{refk}^i) + \xi_k^i - \hat{K}_{k,2}^{Pi} (\sum_{m \in \mathcal{N}_i} \tilde{a}_{mk} k_{pm}^i x_m^i) \\ \dot{\xi}_k^i = \hat{K}_{k,1}^{Li} (V_{bus}^i - V_{refk}^i) - \hat{K}_{k,2}^{Li} (\sum_{m \in \mathcal{N}_i} \tilde{a}_{mk} k_{pm}^i x_m^i) \end{cases} \quad (9)$$

where $F_k^i = A_k^i + B_k^i \bar{k}_{pk}^i$, $Q_k^i = B_k^i I_2$, $\hat{K}_{k,1}^{Pi} = [-K_{k,1}^{Pi}, 0]^T$ and $\hat{K}_{k,1}^{Li} = [-K_{k,1}^{Li}, 0]^T$. $\hat{K}_{k,2}^{Pi} = [0, 0; 0, K_{k,2}^{Pi}]$ and $\hat{K}_{k,2}^{Li} = [0, 0; 0, K_{k,2}^{Li}]$. $\tilde{a}_{mk} = a_{mk}$ and $\tilde{a}_{kk} = \sum_{m \neq k} a_{mk}$.

The state of followers can be further characterized by associating Equations (7) and (9) as

$$\begin{cases} \dot{x}^i = F^i x^i + Q^i u^i + B^i V_{ref}^i + C^i V_{bus}^i \\ u^i = \hat{K}_1^{Pi} V_{bus}^i - \tilde{K}_1^{Pi} V_{ref}^i + \xi^i + \hat{K}_2^{Pi} (L^i \hat{k}_p^i \otimes I_2) x^i \\ \dot{\xi}^i = \hat{K}_1^{Li} V_{bus}^i - \tilde{K}_1^{Li} V_{ref}^i + \hat{K}_2^{Li} (L^i \hat{k}_p^i \otimes I_2) x^i \\ \dot{V}_{ref}^i = L^i V_{ref}^i - \hat{G}^i V_{ref}^i + \tilde{G}^i V_{nom}^i + \tilde{G}^i u_{0,3}^i \end{cases} \quad (10)$$

where $x^i = \text{col}\{x_k^i\}$, $u^i = \text{col}\{u_k^i\}$, $V_{ref}^i = \text{col}\{V_{refk}^i\}$. $F^i = \text{diag}\{F_k^i\}$, $Q^i = \text{diag}\{Q_k^i\}$, $B^i = \text{diag}\{B_k^i\}$, $C^i = \text{col}\{C_k^i\}$, $\hat{k}_p^i = \text{diag}\{k_{pm}^i\}$. $\hat{K}_1^{Pi} = \text{col}\{\hat{K}_{k,1}^{Pi}\}$ and $\hat{K}_1^{Li} = \text{col}\{\hat{K}_{k,1}^{Li}\}$. $\tilde{K}_1^{Pi} = \text{diag}\{\tilde{K}_{k,1}^{Pi}\}$ and $\tilde{K}_1^{Li} = \text{diag}\{\tilde{K}_{k,1}^{Li}\}$. $\hat{K}_2^{Pi} = \text{diag}\{\hat{K}_{k,2}^{Pi}\}$ and $\hat{K}_2^{Li} = \text{diag}\{\hat{K}_{k,2}^{Li}\}$. L^i is the Laplace matrix corresponding to $\mathcal{A}^i$. $\hat{G}^i = \text{diag}\{g_{k0}^i\}$ and $\tilde{G}^i = \text{col}\{g_{k0}^i\}$ ($k \neq 0$).

Remark 1. This system adopts a hierarchical control architecture design, combined with a two-level collaborative control mechanism. Among them, the primary control consists of droop control. Secondary control is divided into inter group control and intra group control, breaking through the limitations of traditional single-layer control. Intra group control includes local voltage recovery and current balance compensation, which are mathematically modeled by Equations (2) and (6), respectively. At the inter group control level, the system achieves coordinated control of bus current balance and rated voltage compensation through a master–slave architecture: global control tasks are executed by the master node based on Equation (4), while local control functions are executed by the slave nodes based on Equation (7).

2.2.3. Modeling for the Networked DC-MGs System

The i th bus system containing both the leader and followers can be characterized by associating Equations (6) and (10) as

$$\begin{cases} \dot{\tilde{x}}^i = \tilde{F}^i \tilde{x}^i + \tilde{Q}^i \tilde{u}^i + \tilde{B}_0^i V_{nom}^i + \tilde{B}^i V_{ref}^i + \tilde{C}^i V_{bus}^i \\ \tilde{u}^i = \tilde{K}^{Pi} V_{bus}^i - \tilde{K}_0^{Pi} V_{nom}^i - \tilde{K}^{Pi} V_{ref}^i + \phi^{Pi} \tilde{\xi}^i \\ \quad - (\sum_{j \in \mathcal{N}} \tilde{b}_{ij} k_{p0}^j \kappa_j^{Pi} \tilde{x}^j) + \mathcal{L}^{Pi} \tilde{x}^i \\ \dot{\tilde{\xi}}^i = \tilde{K}^{Li} V_{bus}^i - \tilde{K}_0^{Li} V_{nom}^i - \tilde{K}^{Li} V_{ref}^i + \phi^{Li} \tilde{\xi}^i \\ \quad - (\sum_{j \in \mathcal{N}} \tilde{b}_{ij} k_{p0}^j \kappa_j^{Li} \tilde{x}^j) + \mathcal{L}^{Li} \tilde{x}^i \\ \dot{V}_{ref}^i = L_g^i V_{ref}^i + \tilde{G}^i V_{nom}^i + \tilde{G}^i \tilde{u}^i \end{cases} \quad (11)$$

where $\tilde{x}^i = [x_0^i; x^i]$, $\tilde{u}^i = [u_0^i; u^i]$ and $\tilde{\xi}^i = [\xi_0^i; \xi^i]$. $\tilde{F}^i = [F_0^i; 0; 0; F^i]$, $\tilde{Q}^i = [Q_0^i; 0; 0; Q^i]$, $\tilde{B}_0^i = [B_0^i; 0]$, $\tilde{B}^i = [0; B^i]$ and $\tilde{C}^i = [C_0^i; C^i]$. $\tilde{K}^{Pi} = [\hat{K}_{0,1}^{Pi}; \hat{K}_1^{Pi}]$, $\tilde{K}_0^{Pi} = [\hat{K}_{0,1}^{Pi}; 0]$, $\tilde{K}^{Pi} = [0; \hat{K}^{Pi}]$, $\phi^{Pi} = [\phi_0^{Pi}; 0; 0; \mathcal{I}_{2N_i}]$, $\kappa_j^{Pi} = [\kappa_0^{Pi}; 0; 0; 0]$ is a matrix with $2N_i + 3$ rows and $2N_j + 2$ columns and $\mathcal{L}^{Pi} = [\gamma_0^{Pi}; 0; \hat{K}_2^{Pi}(L^i \hat{k}_p^i \otimes \mathcal{I}_2)]$. $\tilde{K}^{Li} = [\hat{K}_{0,1}^{Li}; \hat{K}_1^{Li}]$, $\tilde{K}_0^{Li} = [\hat{K}_{0,1}^{Li}; 0]$, $\tilde{K}^{Li} = [0; \hat{K}^{Li}]$, $\phi^{Li} = [\phi_0^{Li}; 0; 0; 0]$, $\kappa^{Li} = [\kappa_0^{Li}; 0; 0; 0]$, $\mathcal{L}^{Li} = [\gamma_0^{Li}; 0; \hat{K}_2^{Li}(L^i \hat{k}_p^i \otimes \mathcal{I}_2)]$, $L_g^i = L^i - \hat{G}^i$ is a matrix with $2N_i + 3$ rows and $2N_j + 2$ columns and $\tilde{G}^i = [0; \tilde{G}^i; 0]$.

Further, the agent system corresponding to the i th bus that contains only states and controllers can be structured as

$$\begin{cases} \dot{\eta}^i = \mathbf{A}^i \eta^i + \mathbf{B}^i \tilde{u}^i + \mathbf{C}^i V_{bus}^i + \mathbf{D}^i V_{nom}^i + \sum_{j \in \mathcal{N}} \tilde{b}_{ij} k_{p0}^j \mathbf{H}_j^i \eta^j \\ \tilde{u}^i = \mathbf{F}^i \eta^i + \tilde{K}^{Pi} V_{bus}^i - \tilde{K}_0^{Pi} V_{nom}^i + \sum_{j \in \mathcal{N}} \tilde{b}_{ij} k_{p0}^j \mathbf{G}_j^i \eta^j \end{cases} \quad (12)$$

where $\mathbf{A}^i = [\tilde{F}^i; 0; \tilde{B}^i; \mathcal{L}^{Li}; \phi^{Li}, -\tilde{K}^{Li}; 0; 0; L_g^i]$, $\mathbf{B}^i = [\tilde{Q}^i; 0; \tilde{G}^i]$, $\mathbf{C}^i = [\tilde{C}^i; \tilde{K}^{Li}; 0]$, $\mathbf{D}^i = [\tilde{B}_0^i; -\tilde{K}_0^{Li}; \tilde{G}^i]$, $\mathbf{H}_j^i = [0; 0; 0; -\kappa^{Li}; 0; 0; 0; 0]$ is a matrix with $5N_i + 5$ rows and $5N_j + 5$ columns, $\mathbf{F}^i = [\mathcal{L}^{Pi}; \phi^{Pi}, -\tilde{K}^{Pi}]$, $\mathbf{G}_j^i = [-\kappa_j^{Pi}; 0; 0]$ is a matrix with $2N_i + 3$ rows and $5N_j + 5$ columns and $\eta^i = [\tilde{x}^i; \tilde{\xi}^i; V_{ref}^i]$.

Remark 2. The dynamic characteristics of the i -th bus agent system are influenced by dual-layer topological coupling effects. Local topology reconfiguration alters leader–follower communication relationships, modifying $\mathcal{L}^{Pi}$, $\mathcal{L}^{Li}$ and L_g^i , $\tilde{G}^i$, $\tilde{C}^i$, thereby directly affecting system matrices $\mathbf{A}^i$, $\mathbf{B}^i$, $\mathbf{D}^i$, and $\mathbf{F}^i$. Follower topology variations only impact $\mathbf{A}^i$ and $\mathbf{B}^i$ through adjustments in $\mathcal{L}^{Pi}$ and $\mathcal{L}^{Li}$. Perturbations in inter-bus leader coupling weights $\tilde{b}_{ij}$ at the upper layer indirectly influence global controllers via cross-layer information channels. The phenomenon reveals that the multi-layer interconnection nature of networked DC-MGs results in asymmetric dynamic coupling between control levels. Local disturbances in any communication topology are transmitted to the overall state space of the system with different paths and intensities, which in turn leads to the need for adaptive reconfiguration of controller gains.

The synergy between all agent systems is represented by a system which can be denoted as

$$\begin{cases} \dot{\eta} = \mathbf{A} \eta + \mathbf{B} \tilde{u} + \mathbf{C} V_{bus} + \mathbf{D} V_{nom} + \mathbf{H} \eta \\ \tilde{u} = \mathbf{F} \eta + \tilde{K}^P V_{bus} - \tilde{K}_0^P V_{nom} + \mathbf{G} \eta \end{cases} \quad (13)$$

where $\eta = \text{col}\{\eta^i\}$, $\tilde{u} = \text{col}\{\tilde{u}^i\}$, $\mathbf{A} = \text{diag}\{\mathbf{A}^i\}$, $\mathbf{B} = \text{diag}\{\mathbf{B}^i\}$, $\mathbf{C} = \text{diag}\{\mathbf{C}^i\}$, $\mathbf{D} = \text{diag}\{\mathbf{D}^i\}$, $\mathbf{H} = \text{col}\{(l_i k_{p0} \otimes \mathcal{I}_{5N_i+5}) \text{diag}\{\mathbf{H}_j^i\}\}$, $\mathbf{F} = \text{diag}\{\mathbf{F}^i\}$, $\tilde{K}^P = \text{diag}\{\tilde{K}^{Pi}\}$, $\tilde{K}_0^P = \text{diag}\{\tilde{K}_0^{Pi}\}$ and $\mathbf{G} = \text{col}\{(l_i k_{p0} \otimes \mathcal{I}_{2N_i+3}) \text{diag}\{\mathbf{G}_j^i\}\}$. l_i is the matrix of elements of row i of L and $k_{p0} = \text{diag}\{k_{p0}^i\}$.

The controller $\tilde{u}$ can be expressed in terms of state quantities and external inputs. By setting the PI parameters appropriately, the original system Equation (13) can be further transformed into

$$\dot{\eta} = \mathbf{A}_\eta \eta + \mathbf{C}_{bus} V_{bus} + \mathbf{D}_{nom} V_{nom} \quad (14)$$

where $V_{bus} = \text{col}\{V_{bus}^i\}$, $V_{nom} = \text{col}\{V_{nom}^i\}$, $\mathbf{A}_\eta = \mathbf{A} + \mathbf{H} + \mathbf{B}\mathbf{G} + \mathbf{B}\mathbf{F}$, $\mathbf{C}_{bus} = \mathbf{C} + \mathbf{B}\tilde{K}^P$ and $\mathbf{D}_{nom} = \mathbf{D} - \mathbf{B}\tilde{K}_0^P$.

2.3. Power Flow Constraint

According to Kirchhoff's law, the power flow at the i th bus can be expressed as

$$\sum_{k=0}^{N_i} I_{fk}^i = I_{load}^i - \sum_{j \in \mathcal{N}} \frac{V_{bus}^j - V_{bus}^i}{Z_{ij}}. \quad (15)$$

Combined with the system modeling process of Equation (12), Equation (15) can be represented as a vector containing intermediate variables as

$$\mathbf{e}^i \eta^i = I_{load}^i - \sum_{j \in \mathcal{N}} G_{ij} (V_{bus}^j - V_{bus}^i) \quad (16)$$

where $\mathbf{e}^i = [[0, 1] \otimes I_{N_i+1}, 0]$ and G_{ij} is the value of the admittance between the buses.

In the whole system, the power flow can be represented as

$$\mathbf{e} \eta = I_{load} - \mathbf{G} V_{bus} \quad (17)$$

where $\mathbf{e} = \text{diag}\{\mathbf{e}^i\}$, $I_{load} = \text{col}\{I_{load}^i\}$ and $\mathbf{G}$ is the admittance Laplace matrix corresponding to $\{G_{ij}\}$.

Although the actual controller only needs to sample the bus voltage to complete the control, the tidal power flow factor still needs to be taken into account in the modeling process. From the power flow relationship Equation (17), it is clear that the bus voltage is related to both the system state and the load current. Therefore, V_{bus} in the system equations expressed in Equation (14) is not a disturbance input but an input that needs to be solved by load and state. In the following elastic controller design process, V_{bus} is not treated as a perturbation.

3. Generalized DoS Attacks

In this work, a typical scenario is considered as a DoS attack on a node of the system. The attacked node cannot get the information from the neighboring nodes, and at the same time it cannot pass the information to the neighboring nodes. Assuming that node $\mathcal{V}_k^i$ is under a DoS attack, and using w_{mk} to denote the set of all edges in the communication network associated with $\mathcal{V}_k^i$, the set of edges to consider the attack can be represented as

$$\bar{w}_{mk}(t) = \begin{cases} w_{mk}, & \text{without DoS attack} \\ 0, & \text{with DoS attack.} \end{cases} \quad (18)$$

The system in this study considers n DC-MGs, where a leader and N_i followers exist on the i th DC bus. There are a total of $N = (n + \sum_{i=1}^n N_i)$ nodes in the system that can be targeted by the attacker. Then, there exist 2^N attack situations that can occur. Since the occurrence of attacks is inherently random, a Markov process $\{\delta(t)\}_{t \in [0, \infty]}$ is introduced to model randomness. The exact implications are listed below.

◇ 1th Mode: Network attacks are either not executed or have failed.

◇ 2th to $(N + 1)$ th Modes: Only one node is subjected to DoS attacks.

◇ $(N + 2)$ th to $\frac{N(N+1)}{2} + 1$ th Modes: DoS attacks occur on two nodes simultaneously.

For instance, mode $(N + 2)$ represents attacks resulting in the simultaneous loss of data from the 1st and 2nd nodes.

...

◇ 2^N th Mode: All nodes experience DoS attacks.

In normal operation, the system communication topology is described by $\mathcal{G}^i = (\mathcal{V}^i, \varepsilon^i)$ and $\mathcal{G} = (\mathcal{V}, \varepsilon)$. Attacks $\{\delta_k\}$ in the system can be categorized into three scenar-

ios: attacking only the leader nodes, attacking only the follower nodes, and attacking both the leaders and the follower nodes. The attack matrix $F_{\delta_k}^i = \text{diag}\{r_1^i, r_2^i, \dots, r_{N_i}^i\}$, $F_{0\delta_k}^i = \text{diag}\{r_{0,0}^i, r_{0,1}^i, \dots, r_{0,N_i}^i\}$ and $F_{\delta_k} = \text{diag}\{r_1, r_2, \dots, r_n\}$ are defined, where r_m^i , $r_{0,m}^i$ and r_m take the values 0 or 1. Thus, the actual communication topology under attack exists in three forms as follows.

◇ Attacks against the leader nodes $\{\delta(t)_1\}$: The attack simultaneously blocks communication between the leader and the follower, and between the leader and the leader, while communication between the followers is unaffected. The Laplace matrix describing the relationship of positions can be represented as

$$\begin{cases} L_{\delta(t)_1} = F_{\delta(t)_1} L F_{\delta(t)_1} \\ G_{\delta(t)_1}^i = [0, 0, \dots, 0] \\ L_{\delta(t)_1}^i = L^i. \end{cases} \quad (19)$$

◇ Attacks against the follower nodes $\{\delta(t)_2\}$: The attack does not affect communication between leaders, but blocks communication between the corresponding follower and the leader, and the rest of the followers. The Laplace matrix describing the relationship of positions can be represented as

$$\begin{cases} L_{\delta(t)_2} = L \\ G_{\delta(t)_2}^i = F_{0\delta(t)_2}^i G^i \\ L_{\delta(t)_2}^i = F_{\delta(t)_2}^i L^i F_{\delta(t)_2}^i. \end{cases} \quad (20)$$

◇ Attacks against both the leader nodes and the follower nodes $\{\delta(t)_3\}$: In this case, the inter-cluster communication among the leader nodes, the intra-cluster communication among the follower nodes, and the leader–follower communication are simultaneously affected. Accordingly, the topology matrices under the combined attack can be expressed as

$$\begin{cases} L_{\delta(t)_3} = F_{\delta(t)_3} L F_{\delta(t)_3}, \\ G_{\delta(t)_3}^i = F_{0\delta(t)_3}^i G^i, \\ L_{\delta(t)_3}^i = F_{\delta(t)_3}^i L^i F_{\delta(t)_3}^i. \end{cases} \quad (21)$$

This paper presents a topology-specific multi-mode DoS attack model, where the topology switching behavior is characterized by a Markov process, and the switching function is constructed based on the SP switching model. The switching function is introduced to be represented as

$$\varphi_p(t) = \begin{cases} 1, & \text{if } \delta(t) = p \\ 0, & \text{otherwise} \end{cases} \quad (22)$$

where $\varphi_p(t)$ serves to mark which mode the current system is in, and is 1 when the attack is in attack mode $\delta(t) = p$ at time t and 0 otherwise. Thus, the SP is inferred as

$$\varphi_p = \text{Pr}\{\delta(t) = p\} \quad (23)$$

where $\varphi_p \in [0, 1]$. Obviously, $\sum_{p=1}^{2N} \varphi_p = \sum_{p=1}^{2N} \varphi_p(t) = 1$. Under the stationary and ergodic switching assumption adopted in this study, φ_p can be statistically characterized by the relative occurrence frequency of attack mode p , which can be represented by statistics as

$$\varphi_p = \lim_{q \rightarrow \infty} \frac{q_p}{q} \quad (24)$$

where q_p denotes the total times $\delta(t) = p$ has occurred since the start of the count and $\sum_{p=1}^{2^N} q_p = q$.

Then, the system Equation (14) after attacks can be represented as

$$\dot{\eta} = \sum_{p=1}^{2^N} \varphi_p(t) (\mathbf{A}_{\eta,p} \eta + \mathbf{C}_{bus,p} V_{bus} + \mathbf{D}_{nom,p} V_{nom}) \quad (25)$$

where $\mathbf{A}_{\eta,p}$, $\mathbf{C}_{bus,p}$ and $\mathbf{D}_{nom,p}$ can be redefined by Laplace matrices in different attack modes.

Assumption 1. Under attack-free conditions, the intra-cluster communication graph of each DC-MG, together with the corresponding leader–follower communication links, contains a directed spanning tree rooted at the local leader. Moreover, the inter-cluster communication graph composed of the leader nodes contains a directed spanning tree. Under nodal DoS attacks, the communication graph associated with an individual attack mode is allowed to be temporarily disconnected. Let $S_+ = \{p \mid \varphi_p > 0\}$ denote the set of attack modes with positive switching probabilities. It is assumed that the union of the mode-dependent communication graphs over $p \in S_+$ preserves the leader-rooted spanning-tree structure for each DC-MG, and that the union of the corresponding inter-cluster leader graphs contains a directed spanning tree. Therefore, the communication topology is required to be jointly connected, or equivalently connected in the SP-weighted sense, rather than connected at every instant.

Remark 3. The focus of this paper is on DoS attacks against the communication topology itself, which result in the loss of information at a specific node and further cut off the data flow between the affected node and its neighbors. It is crucial to overcome the limitations of traditional Bernoulli models in capturing such complex attacks. The attack model focuses on the topology consequences of nodal DoS attacks. Each attack mode corresponds to a specific combination of unavailable communication nodes and therefore determines the associated mode-dependent Laplacian and leader connection matrices. The occurrence probability of each mode can be estimated from its empirical occupation frequency.

4. Distributed Hierarchical ET Resilient Control

Frequent network communication increases the chances of malicious attacks. A novel adaptive parameter-based ET mechanism is proposed to improve the grid security performance while effectively reducing the controller update frequency. The combination of ET dynamic parameter adjustment under the action of the original system control constitutes the distributed hierarchical resilient control structure.

4.1. ET Mechanism

The current equalization index ΔI_{fm}^i varies with attack because of the change in the Laplace matrix. Therefore, the voltage recovery index ΔV_{busm}^i is used as an ET condition because it only follows the state and the sampled value of the bus voltage. During the dormant period, for the m th DG in the i th microgrid, assuming that the previous trigger instant is $t_{k,m}^i$, the following triggering condition determines the next triggering instant $t_{k+1,m}^i$:

$$t_{k+1,m}^i = \inf\{k \in \mathbb{N} : t > t_{k,m}^i, \mathbf{J}_m^i(t) > \lambda e^{-\lambda(t-t_0)}\} \quad (26)$$

where $\tau \in [0, 1)$, $\lambda > 0$, $J_m^i(t) = e_m^i(t)^T \Omega_{m1}^i e_m^i(t) - \tau \Delta V_{busm}^{iT}(t) \Omega_{m2}^i \Delta V_{busm}^i(t)$ and Ω_{m1}^i and Ω_{m2}^i are positive definite matrices. For $t \in [t_{k,m}^i, t_{k+1,m}^i)$, $e_m^i(t) = \Delta V_{busm}^i(t) - \Delta V_{busm}^i(t_{k,m}^i)$. When the system is running normally, $V_{busm}^i(t)$ can gradually converge to 0. When under attacks, the ET mechanism sets an initial threshold via λ to measure the impact of the attack and work correctly. When under attacks, the ET mechanism sets an initial threshold via λ to measure the impact of the attack and work correctly.

In order to facilitate the controller solution, the ET-related variables can be represented in vector form as

$$\begin{cases} \Delta V_{bus}(t) = \Gamma \eta - E V_{bus}(t) \\ J(t) = e(t)^T \Omega_1 e(t) - \tau \Delta V_{bus}^T(t) \Omega_2 \Delta V_{bus}(t) \\ e(t) = \Delta V_{bus}(t) - \Delta V_{bus}(t_k) \end{cases} \quad (27)$$

where $\Delta V_{bus} = [\Delta V_{bus0}^1, \Delta V_{bus1}^1, \dots, \Delta V_{busN_1}^1, \dots, \Delta V_{bus0}^i, \dots, \Delta V_{busN_i}^i, \dots, \Delta V_{bus0}^n, \dots, \Delta V_{busN_n}^n]^T$, $\Gamma = \text{diag}\{\Gamma_i\}$ and $E = \text{diag}\{E_i\}$. $\Gamma_i = [0, 0; 0, \mathcal{I}_{(N_i+1)}]$ is a matrix of $5N_i + 5$ dimensions and $E_i = [0; I_{(N_i+1)}]$ is a vector of $5N_i + 5$ dimensions. $J(t) = \text{col}\{J_m^i(t)\}$, $e(t) = \text{col}\{e_m^i(t)\}$, $\Omega_1 = \text{diag}\{\Omega_{m1}^i\}$ and $\Omega_2 = \text{diag}\{\Omega_{m2}^i\}$. It is worth noting that as long as DGs exist to trigger, either individually or as a whole, k in t_k still needs to add 1. The controller solving process does not need to know the triggering information of the whole system because the variables related to t_k are replaced as will be explained in the next section.

Remark 4. The ET mechanism adopted in this paper plays a critical role in enhancing the practicality of the distributed secondary control scheme, particularly in microgrid environments where communication resources are often constrained and vulnerable to malicious attacks. By introducing an adaptive exponential decay threshold, the mechanism dynamically adjusts the triggering conditions based on real-time system states—such as voltage tracking errors and attack-induced disturbances—thereby avoiding unnecessary information exchanges during stable operation while ensuring timely updates when deviations exceed acceptable bounds. Notably, at each triggering time $t_{k,m}^i$, $e_m^i(t_{k,m}^i) = 0$, and therefore $\Psi_m^i(t_{k,m}^i) \leq -\lambda e^{-\lambda(t_{k,m}^i - t_0)} < 0$, where $\Psi_m^i(t) = J_m^i(t) - \lambda e^{-\lambda(t - t_0)}$. For any finite $T > t_0$, in the case of a finite set of attack modes, the closed-loop state and its derivatives are uniformly bounded on the interval $[t_0, T]$. Hence, there exists $L_{m,T}^i \leq \infty$ such that $|\Psi_m^i(t)| \leq L_{m,T}^i$. Consequently, $t_{k+1,m}^i - t_{k,m}^i \geq \lambda e^{-\lambda(T - t_0)} / L_{m,T}^i > 0$. Therefore, triggering instants cannot accumulate within any finite time interval, and the proposed mechanism excludes Zeno behavior.

4.2. Distributed Hierarchical ET Resilient Control Design

Dynamic and resilient tuning of the control parameters is necessary to ensure the robustness of the system against attacks. Under Assumption 1, individual attack modes may temporarily disconnect part of the communication network, whereas the leader–follower and inter-cluster communication graphs remain connected in the joint SP-weighted sense. This connectivity condition preserves the information paths required by the Laplacian-based consensus terms.

In order to analyze the stability of the system, the Lyapunov function is designed as

$$V = \eta^T P \eta + e^{-\lambda(t-t_0)} \quad (28)$$

where P is a positive definite matrix. The attacked system can be further represented in conjunction with ET conditions as

$$\dot{\eta} = \sum_{p=1}^{2^N} \varphi_p(t) (\mathbf{A}_p \eta + \mathbf{C}_p V_{bus} + \Delta V_{bus} + \mathbf{D}_p V_{nom}) \quad (29)$$

where $\mathbf{A}_p = \mathbf{A}_{\eta,p} - \Gamma$, $\mathbf{C}_p = \mathbf{C}_{bus,p} + E$ and $\mathbf{D}_p = \mathbf{D}_{nom,p}$.

Assumption 2. Let the attack mode process be represented by $\delta_\epsilon(t) = \delta(t/\epsilon)$, where $\epsilon > 0$ denotes the ratio between the characteristic mixing time of the attack process and the dominant response time of the closed-loop system. The process $\delta(t)$ is assumed to be irreducible, stationary, and uniformly ergodic, with the invariant probability vector $\boldsymbol{\phi} = [\phi_1, \dots, \phi_{2^N}]^T$. The value of ϵ is sufficiently small such that the attack mode evolves on a faster time scale than the dominant electrical and secondary control dynamics. The closed-loop vector fields are assumed to satisfy the regularity conditions required by the stochastic averaging principle.

For $t \in [t_k, t_{k+1})$, it takes the derivation of the Lyapunov function as

$$\begin{aligned} \dot{V} &= \eta^T P \dot{\eta} + \dot{\eta}^T P \eta - \lambda e^{-\lambda(t-t_0)} \\ &= -aV + \eta^T P \dot{\eta} + \dot{\eta}^T P \eta + \eta^T P \eta - (\lambda - a)e^{-\lambda(t-t_0)} \\ &\leq \sum_{p=1}^{2^N} \varphi_p(t) (\eta^T (P \mathbf{A}_p + \mathbf{A}_p^T P) \eta + \eta^T (P \mathbf{C}_p + \mathbf{C}_p^T P) V_{bus} \\ &\quad + 2\eta^T P \Delta V_{bus}(t_k) - (\lambda - a)e^{-\lambda(t-t_0)} - aV + \eta^T P \eta \\ &\quad + \eta^T P \mathbf{D}_p (P \mathbf{D}_p)^T \eta + V_{nom}^T (P \mathbf{D}_p)^T P \mathbf{D}_p V_{nom}) \\ &= \sum_{p=1}^{2^N} \varphi_p(t) (\eta^T (P \mathbf{A}_p + \mathbf{A}_p^T P + P \mathbf{D}_p (P \mathbf{D}_p)^T + aP) \eta \\ &\quad + \eta^T (P \mathbf{C}_p + \mathbf{C}_p^T P) V_{bus} + 2\eta^T P \Delta V_{bus}(t_k) \\ &\quad - aV + b - (\lambda - a)e^{-\lambda(t-t_0)}) \end{aligned} \quad (30)$$

where $0 < a \leq \lambda$, $b = \zeta \|V_{nom}\|_2^2$ and ζ is the largest eigenvalue of the matrix $(P \mathbf{D}_p)^T P \mathbf{D}_p$. Since $\bar{V}(t) \geq \lambda_{\min} P |\bar{\eta}(t)|^2$, it follows that $\left[\limsup_{t \rightarrow \infty} |\eta(t)|^2 \leq \frac{b}{a \lambda_{\min}(P)} \right]$. From the definition of the measurement error, $\Delta V_{bus}(t_k) = \Delta V_{bus}(t) - e(t)$, $t \in [t_k, t_{k+1})$. Furthermore, because no new transmission event is generated over $t \in [t_k, t_{k+1})$, the triggering condition in Equation (26) satisfies $e^T(t) \Omega_1 e(t) - \tau \Delta V_{bus}^T(t) \Omega_2 \Delta V_{bus}(t) \leq \lambda e^{-\lambda(t-t_0)}$. Since $0 < a \leq \lambda$, the ET-related term introduced below is non-negative. Therefore, by applying Young's inequality, one obtains

$$\begin{aligned} 2\eta^T P \Delta V_{bus}(t_k) &= 2\eta^T P \Delta V_{bus}(t) - 2\eta^T P e(t) \\ &\leq \eta^T P \eta + \Delta V_{bus}^T P \Delta V_{bus} - 2\eta^T P e \\ &\quad + \frac{\lambda - a}{\lambda} (-e^T \Omega_1 e + \lambda e^{-\lambda(t-t_0)} + \\ &\quad \tau \Delta V_{bus}^T \Omega_2 \Delta V_{bus}). \end{aligned} \quad (31)$$

Thus,

$$\begin{aligned} \dot{V} &\leq \sum_{p=1}^{2^N} \varphi_p(t) (\eta^T (P \mathbf{A}_p + \mathbf{A}_p^T P + P \mathbf{D}_p (P \mathbf{D}_p)^T + aP + P) \eta \\ &\quad + \eta^T (P \mathbf{C}_p + \mathbf{C}_p^T P) V_{bus} + \Delta V_{bus}^T P \Delta V_{bus} - 2\eta^T P e \\ &\quad + \frac{\lambda - a}{\lambda} \times (\tau \Delta V_{bus}^T \Omega_2 \Delta V_{bus} + (-e^T \Omega_1 e + \lambda e^{-\lambda(t-t_0)})) \\ &\quad - aV + b - (\lambda - a)e^{-\lambda(t-t_0)}) \\ &= \eta^T \left(\sum_{p=1}^{2^N} \varphi_p(t) (P \mathbf{A}_p + \mathbf{A}_p^T P + P \mathbf{D}_p (P \mathbf{D}_p)^T) + aP + P \right) \eta \end{aligned}$$

$$\begin{aligned}
 & + \Delta V_{bus}^T (P + \frac{\lambda - a}{\lambda} \tau \Omega_2) \Delta V_{bus} - e^T \frac{\lambda - a}{\lambda} \Omega_1 e \\
 & + \eta^T \left(\sum_{p=1}^{2^N} \varphi_p(t) (P C_p + C_p^T P) \right) V_{bus} + (E V_{bus} + \iota \Delta V_{bus}) \\
 & \times Q (\mathbb{E} \eta - E V_{bus} - \Delta V_{bus}) p - \eta^T 2 P e - a V + b \\
 & = \mathbf{L}^T \mathcal{M} \mathbf{L} - a V + b
 \end{aligned}$$

where $\mathbf{L} = [\eta; e; \Delta V_{bus}; V_{bus}]$, $\iota > 0$ and Q is positive definite matrix. According to Equation (23), we have

$$E(\dot{V}) \leq \mathbf{L}^T \mathcal{M} \mathbf{L} - a V + b \quad (32)$$

where $\mathcal{M}$ is defined by Equation (33). Equation (14) models the parameters of the PI controller into the system matrix. Under the action of DoS attacks, combining the SPs to dynamically solve for the PI parameter values and gain parameters that satisfy $\mathcal{M} \leq 0$, one can ensure $E(\dot{V}) \leq -a V + b$, i.e., achieve the mean-square consistent bounded stabilization of the system state. As the SPs become more and more accurate under the statistical action, the system's determinism towards random attacks increases, and the control resilience of the system is enhanced under the dynamic parameter tuning:

$$\mathcal{M} = \begin{bmatrix} M_{11} & -P & \frac{1}{2} \iota Q E & M_{14} \\ -P & -\frac{\lambda - a}{\lambda} \Omega_1 & 0 & 0 \\ \frac{1}{2} \iota Q E & 0 & M_{33} & M_{34} \\ M_{41} & 0 & M_{43} & -E^T Q E \end{bmatrix}. \quad (33)$$

Each of these sub-items can be expressed as

$$\begin{aligned}
 M_{11} &= \sum_{p=1}^{2^N} \varphi_p \left(P A_p + A_p^T P + P D_p (P D_p)^T \right) + a P + P, \\
 M_{14} &= \sum_{p=1}^{2^N} \varphi_p P C_p + (E^T Q E)^T, \\
 M_{33} &= -\iota Q + P + \frac{\lambda - a}{\lambda} \tau \Omega_2, \\
 M_{34} &= \frac{1}{2} \left((E^T Q)^T + \iota Q E \right), \\
 M_{41} &= \left(\sum_{p=1}^{2^N} \varphi_p P C_p \right)^T + E^T Q E, \\
 M_{43} &= \frac{1}{2} \left(E^T Q + (\iota Q E)^T \right).
 \end{aligned} \quad (34)$$

5. Experimental Results

5.1. Simulation Configuration

To evaluate the proposed method from both numerical and real-time implementation perspectives, the validation is organized into two parts. First, the overall test topology illustrated in Figure 3 is constructed and verified via the Matlab/Simulink R2024a environment. This system consists of three buses and six distributed generators in total. Second, real-time HIL experiments are conducted to evaluate the online executability and control

performance of the proposed method under discrete computation, real-time sampling, communication updating, and nonideal waveform conditions. In order to increase the generalizability of the validation, each microgrid has a different number of units. The filter parameters are all set to $R_{fk}^i = 0.001 \Omega$, $L_k^i = 300 \mu\text{H}$ and $C_k^i = 1.2 \text{ mF}$. The line impedances between DG and the bus are respectively $r_0^1 = 0 \Omega$, $r_1^1 = 0.03 \Omega$, $r_0^2 = 0.01 \Omega$, $r_0^3 = 0 \Omega$, $r_0^3 = 0.02 \Omega$, $r_1^3 = 0.02 \Omega$ and $r_2^3 = 0.01$. The line impedances between the buses are $Z_{12} = Z_{13} = Z_{23} = 0.15 \Omega$. The resistive loads are $R_{load1} = R_{load2} = R_{load3} = 500/48 \Omega$. The droop coefficients were chosen to be $k_{p0}^1 = k_{p1}^1 = k_{p0}^2 = k_{p0}^3 = k_{p1}^3 = k_{p2}^3 = 1$. The rated bus voltages are set to $V_{nom1} = V_{nom2} = V_{nom3} = 48 \text{ V}$.

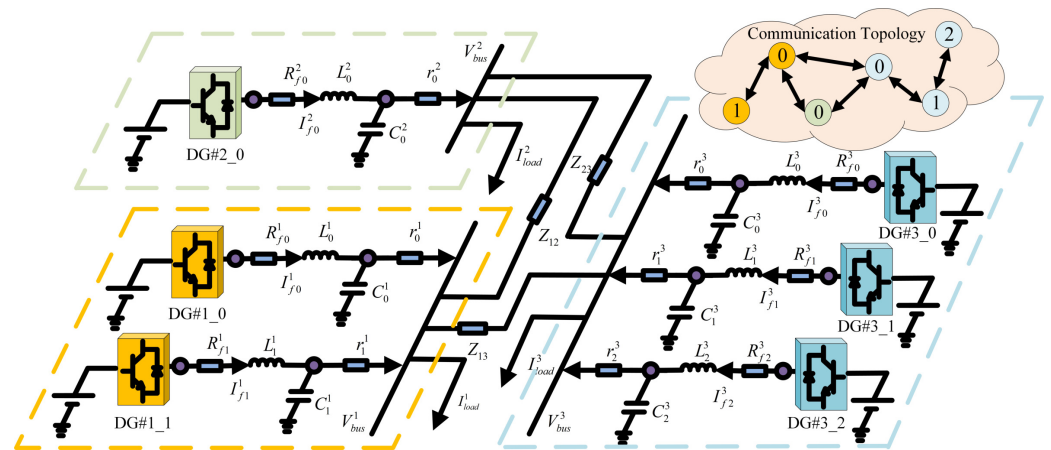


Figure 3. Simulation topology of the networked DC-MG cluster.

5.2. MATLAB/Simulink Simulation Results

5.2.1. Case I Sequential Validation of the Distributed Hierarchical Control

In order to verify the effectiveness of the proposed DHC of clusters of networked DC-MGs, the test time is chosen to be 0–15 s in Figure 4.

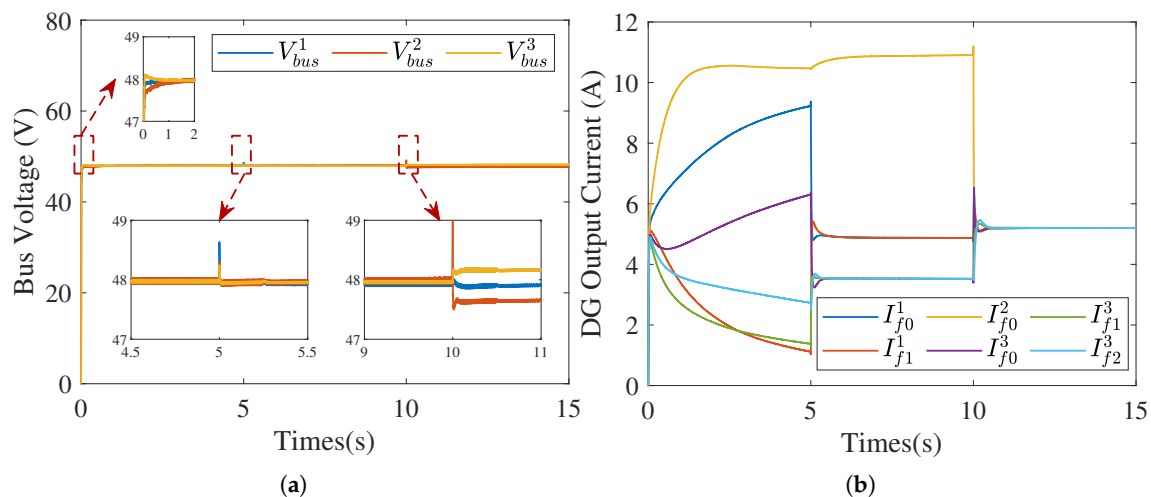


Figure 4. Dynamic response of the DC-MG under distributed hierarchical control: (a) Bus voltage responses during the sequential activation of voltage recovery, current sharing, and global coordination. (b) DG output current responses showing the transition from local current regulation to intra-group and inter-group current balancing.

During 0–5 s, secondary voltage control is introduced in order to realize the return of the bus voltage to the rated voltage. As a result, the surface bus voltage can be restored to the rated value, however, the mismatch problem due to the line impedance prevents

the current from being equally divided according to the rated current. During the 5–10 s process, secondary current control is introduced in order to balance the current in the group. The results show that the DGs within each microgrid can realize the intra-group current output in the same proportion as the rated ratio. However, due to the absence of voltage difference between buses, there is no energy interaction between networks, making the inter-grid currents still deviate. The 10–15 s process introduces global and local control. The results show that energy interactions are allowed to exist in interconnected DC-MGs while achieving global rated current consistency.

5.2.2. Case II Effects of Control Parameters and Attack Locations

In the context of hierarchical distributed control based architectures, this section discusses the impact of control parameters as well as attack locations. Two sets of experimental parameters are used for validation based on the voltage recovery control coefficients $K_{k,1}^{Pi} = 1.2$ and $K_{k,1}^{Li} = 120$, respectively. In the first experiment as shown in Figure 5, the group A test parameters were chosen as $K_{k,2}^{Pi} = 0.5$, $K_{k,2}^{Li} = 100$, $K_{0,3}^{Pi} = 5$, and $K_{0,3}^{Li} = 120$. In the second experiment as in Figure 6, the group B test parameters were chosen as $K_{k,2}^{Pi} = 2$, $K_{k,2}^{Li} = 120$, $K_{0,3}^{Pi} = 2$ and $K_{0,3}^{Li} = 120$. Two sets of experiments were performed at 1 s, 2 s, 3 s, and 4 s on DG_0^1 , DG_1^1 , DG_0^3 , and DG_2^3 of duration 0.2 s.

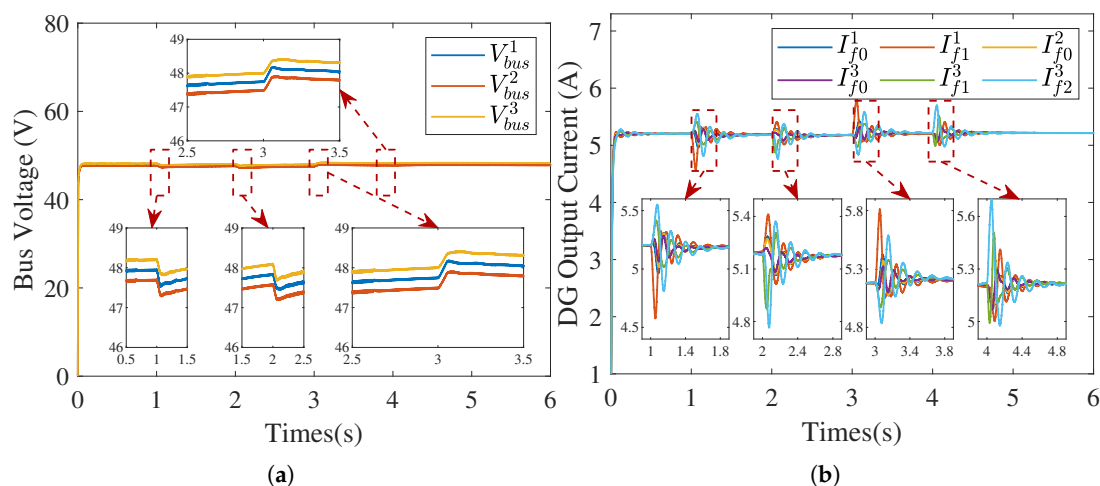


Figure 5. System response under DoS attacks for fixed control parameters of group A: (a) Voltage response of the selected leader and follower nodes are attacked. (b) Current response.

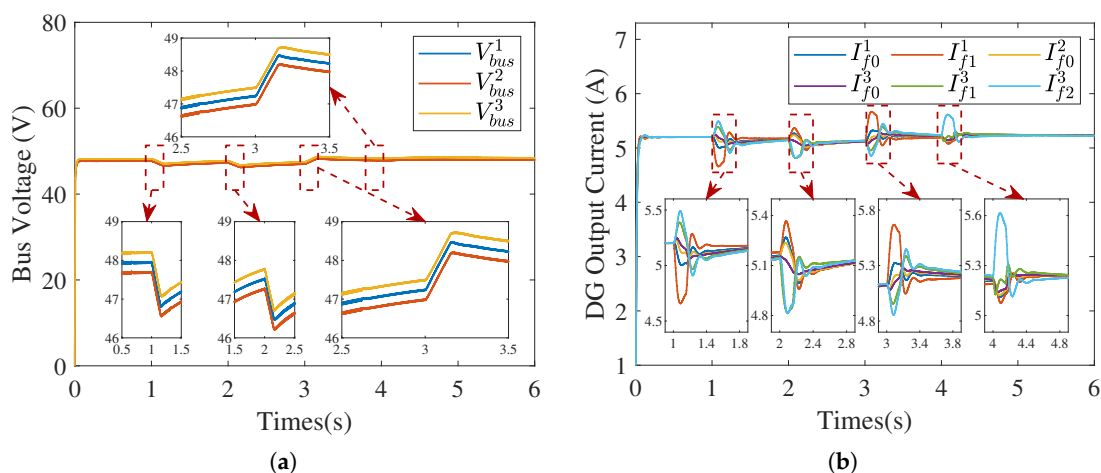


Figure 6. System response under DoS attacks for fixed control parameters of group B: (a) Voltage responses under the same attack locations but with different control parameters. (b) Current responses.

In attacking the leader, both the upper and lower topologies are affected. When attacking the follower, only the lower topology is affected. Experiments show that the system is affected differently by the attack when attacking the same location under different control parameters, or when attacking different locations under the same control parameters. Therefore, when the system is not attacked, the dynamic response characteristics of the system should be the main factor for selecting the control parameters; while when the system is attacked, the robust characteristics of the system should be the main factor for selecting the control parameters.

5.2.3. Case III Distributed Hierarchical ET Resilient Control Validation

Two sets of control experiments were designed in this part. At the beginning of the experiments, the control parameters for both experimental groups were chosen to ensure the dynamic response characteristics as $K_{k,1}^{Pi} = 1.2$, $K_{k,1}^{Li} = 120$, $K_{k,2}^{Pi} = 6$, $K_{k,2}^{Li} = 80$, $K_{0,3}^{Pi} = 5$ and $K_{0,3}^{Li} = 120$. During each experimental trial, the system maintains a 99.9% probability of remaining attack-free within the time intervals of 0–1 s and 5–6 s, whereas it experiences large-scale attacks with certainty during the 1–5 s interval. During each simulation trial, the nodal DoS mode is updated at intervals of $T_a = 0.2$ s and is held constant between two consecutive update instants. The considered system contains six potentially compromised communication nodes and therefore admits $2^6 = 64$ topology modes. Mode ($p = 1$) represents normal communication, while modes $p = 2, \dots, 64$ represent the 63 nonzero compromised node configurations. At each update instant, one complete topology mode is sampled from a categorical distribution. The samples are independent across update instants within each time interval, whereas the attack states of different nodes within one sample are not assumed to be independent because the complete topology configuration is selected as a single mode. The resulting attack status of each node is illustrated in Figure 7.

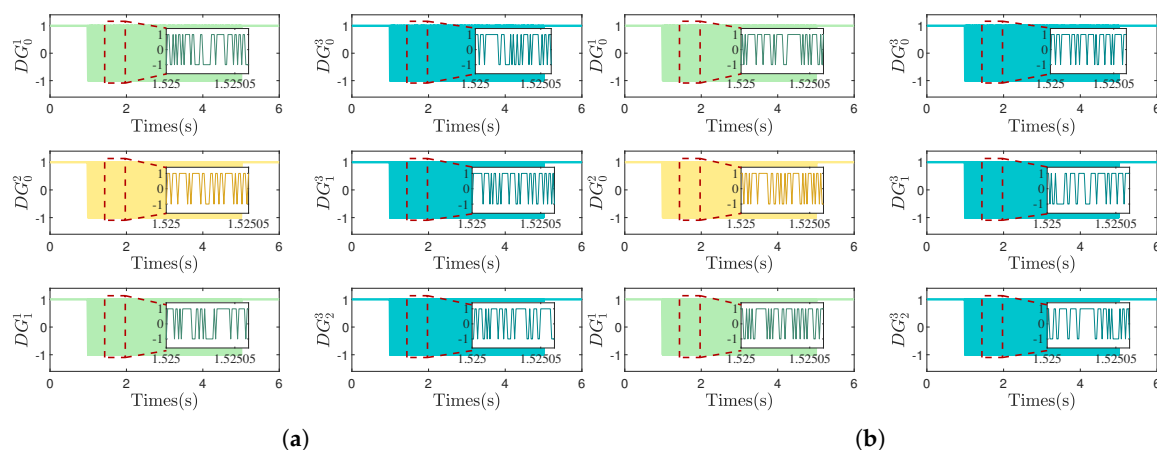


Figure 7. Generalized nodal DoS attack sequence for each DG: (a) Generalized nodal DoS attack sequence for each DG in the fixed parameter experiment. (b) Generalized nodal DoS attack sequence for each DG in the proposed ET resilient control experiment.

In the first experiment, the control parameters are kept constant. As shown in Figure 8, the system produces large deviations in both voltage and current under attack.

In the second experiment, the control parameters are updated with the ET of each DG shown by Figure 9. As shown in Figure 10, the system can achieve the final consistent bounded stabilization of the voltage and current in a short period of time during the attack onset, and still maintains the fast response characteristics before the attack when the attack disappears. Based on this, the hierarchical distributed resilient control strategy proposed in this paper can still achieve the control effect of maintaining normal and stable operation of the system in the face of more random DoS attacks in the operation of networked DC-MGs clusters.

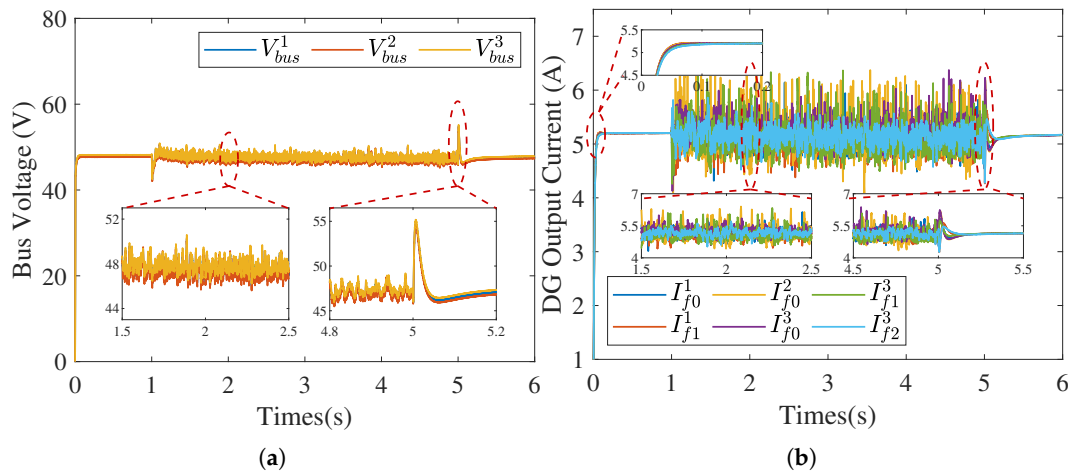


Figure 8. System response under generalized DoS attacks for fixed control parameters: (a) Voltage responses showing large deviations caused by stochastic communication interruptions. (b) Current responses showing mismatch and oscillations when the controller parameters are not adaptively updated.

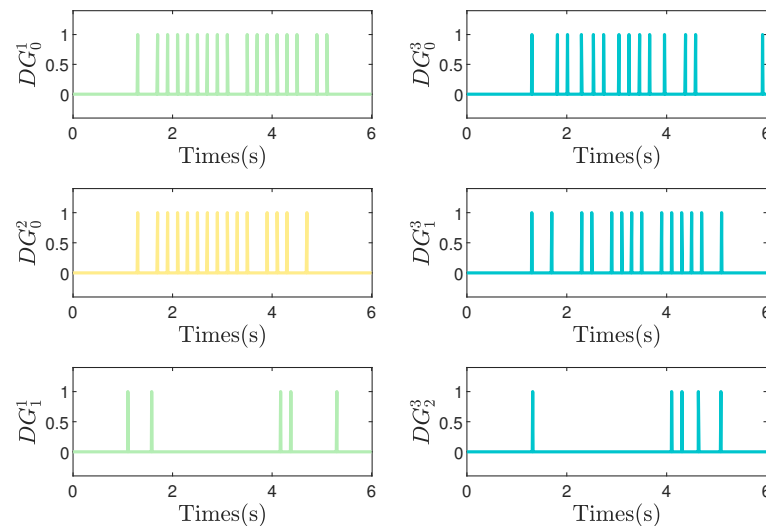


Figure 9. ET communication instants of each DG under nodal DoS attacks.

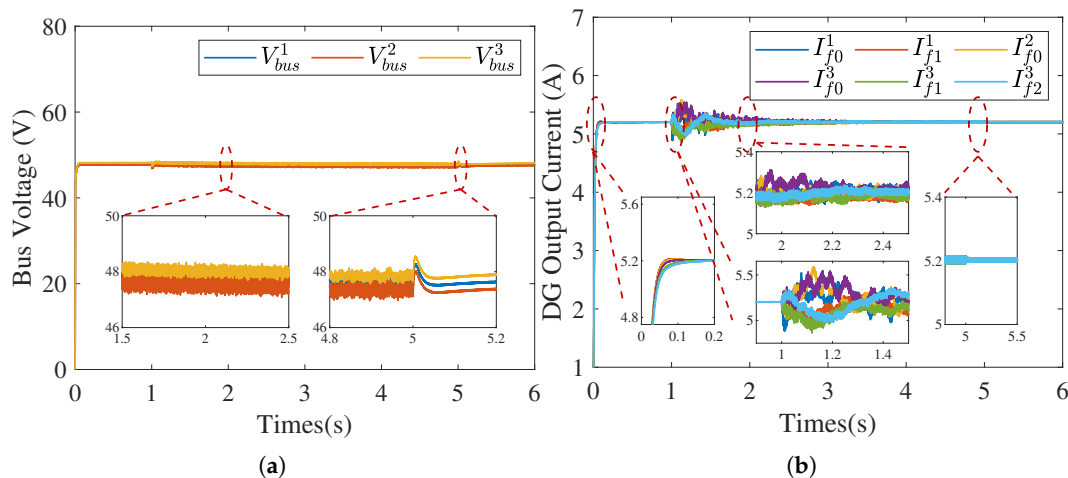


Figure 10. System response under generalized DoS attacks with the proposed methodology: (a) Voltage response showing bounded recovery and reduced voltage deviations under stochastic attacks. (b) Current response showing improved current sharing and faster stabilization compared with the fixed parameter case.

5.2.4. Case IV Comparative Study with Existing Methods

To further evaluate the performance improvement achieved by the proposed method, the resilient secondary controller in [20] and the fully distributed dynamic edge event triggered current sharing method in [14] are selected as benchmark methods. The former introduces an adaptive compensation term to attenuate the effects of mixed DoS and continuous FDI attacks, whereas the latter employs a dynamic edge event triggered mechanism to reduce the communication and controller updating frequencies in multibus DC microgrids.

For a fair comparison, all methods are implemented using the same DC microgrid cluster model, controller objectives, initial operating conditions, load parameters, numerical step size, and nodal DoS attack sequence. The system operates normally during 0–1 s, experiences stochastic nodal DoS attacks during 1–5 s, and returns to the attack free condition after $t = 5$ s. The nominal bus voltage is 48 V, and the desired DG current sharing relationship is identical for all tested methods.

To further evaluate the performance improvement achieved by the proposed method, the resilient secondary controller developed by [20] and the fully distributed dynamic edge event triggered current sharing controller proposed by [14] are selected as benchmark methods. All methods are implemented using the same DC-MG cluster model, initial operating conditions, load parameters, and nodal DoS attack sequence. Figures 11a and 12a correspond to the method of [20], whereas Figures 11b and 12b correspond to the method of [14]. The system operates normally during 0–1 s, is subjected to stochastic nodal DoS attacks during 1–5 s, and returns to normal communication after $t = 5$ s.

As shown by the DG output current responses in Figure 11, both benchmark methods regulate the currents close to their desired operating values under attack free conditions. After the nodal DoS attacks are activated, the currents remain bounded for both methods but exhibit persistent fluctuations and instantaneous current sharing errors during the attack interval. The corresponding bus voltage responses show that both benchmark methods preserve closed-loop boundedness and maintain the three bus voltages in the neighborhood of the 48 V reference. Nevertheless, observable voltage deviations and ripple remain during the attack interval. Both benchmark methods eventually return to stable operation after normal communication is restored.

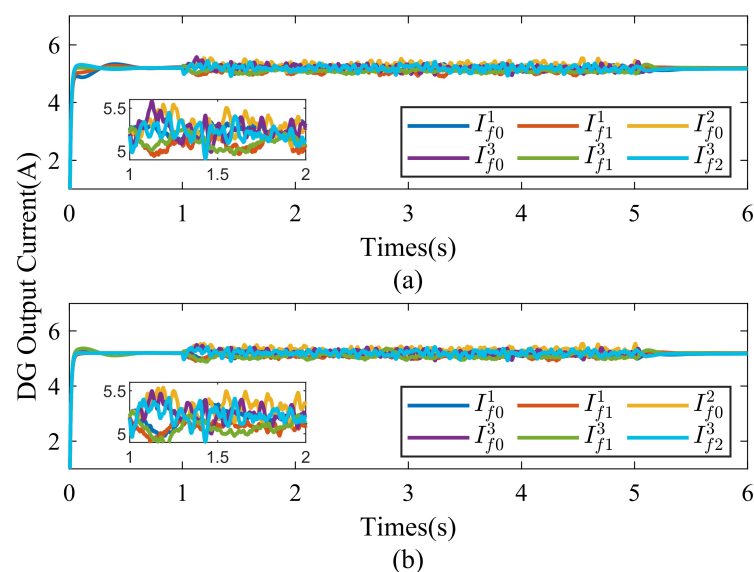


Figure 11. Comparative DG output current responses under generalized nodal DoS attacks: (a) [20]; (b) [14].

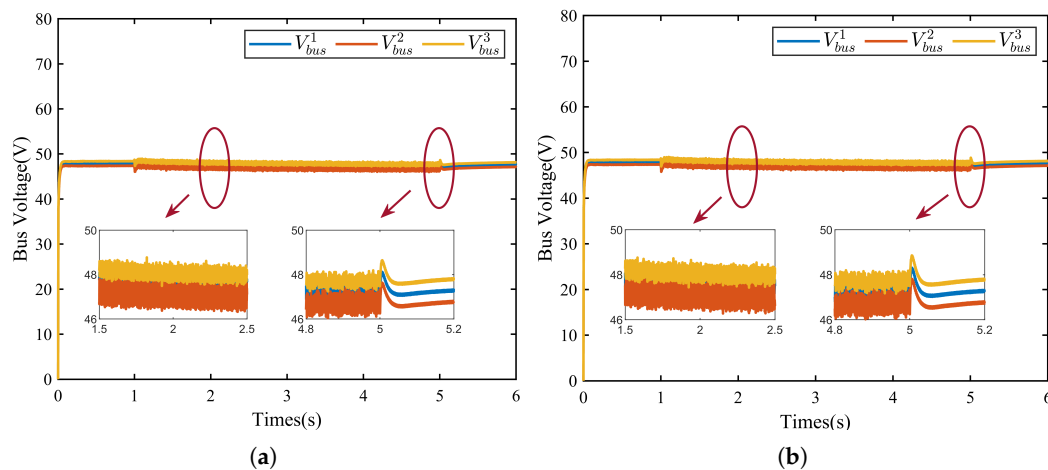


Figure 12. Comparative bus voltage responses under generalized nodal DoS attacks: (a) [20]; (b) [14].

As shown in Table 1, compared with the method of [14], the proposed method reduces the voltage RMSE by 0.45%, the maximum voltage deviation by 5.40%, and the current sharing RMSE by 85.93%. Compared with the method of [14], the corresponding reductions are 1.48%, 3.42%, and 92.87%, respectively. Although the improvement in voltage RMSE is moderate, the proposed method provides a consistently smaller voltage error and a substantially lower current sharing error under the same stochastic nodal DoS attack sequence.

Table 1. Quantitative performance comparison of different control schemes under generalized DoS attacks.

Index	Proposed Method	Method of [14]	Method of [20]
Voltage RMSE (V)	0.2199	0.2232	0.2209
Maximum voltage deviation (V)	0.3330	0.3448	0.3520
Current sharing RMSE (A)	0.001084	0.015201	0.007705
Recovery time (s)	0	0.3266	1.4130

As shown in Table 2, relative to periodic sampling, the proposed method reduces the attempted transmissions from 5760 ± 0 to 672.70 ± 19.19 , corresponding to a communication reduction of $88.321\% \pm 0.333\%$. Compared with the dynamic edge-ET method of [14], the proposed method reduces the mean attempted transmissions from 709.14 to 672.70, representing a further reduction of approximately 5.14%. During the attack interval, the proposed method provides an average inter-event time of 1.1327 ± 0.0762 s, compared with 0.7890 ± 0.0468 s for [14]. The attack-free average inter-event times remain comparable, namely 0.4305 ± 0.0125 s and 0.4428 ± 0.0069 s, respectively.

Table 2. Communication efficiency comparison over 50 paired Monte Carlo runs (mean $\pm$ 95% CI).

Index	Periodic-Fixed	Wang et al. [14]	Proposed Method
Attempted transmissions	5760 ± 0	709.14 ± 20.83	672.70 ± 19.19
Successful transmissions	5030.28 ± 61.23	560.22 ± 7.98	530.16 ± 7.81
Reduction (%)	0 ± 0	87.689 ± 0.362	88.321 ± 0.333
Attack AETI (s)	0.0723 ± 0.0023	0.7890 ± 0.0468	1.1327 ± 0.0762
Attack-free AETI (s)	0.0527 ± 0.0003	0.4428 ± 0.0069	0.4305 ± 0.0125

5.3. Real-Time HIL Experimental Validation

5.3.1. HIL Platform and Implementation

To verify the feasibility and effectiveness of the proposed event-triggered resilient control method under generalized DoS attacks, a hardware-in-the-loop platform is built as depicted in Figure 13.

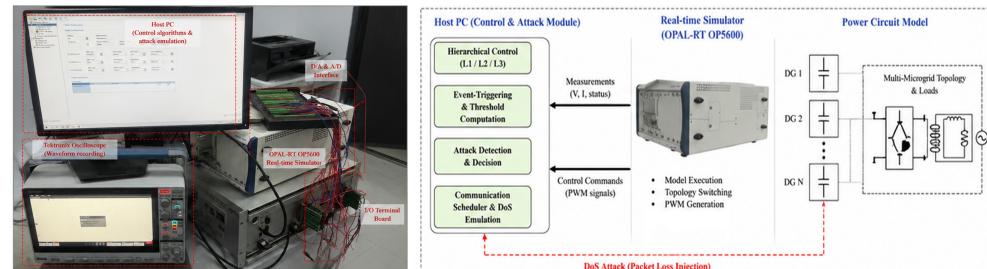


Figure 13. HIL experimental platform for the proposed resilient control scheme.

5.3.2. HIL Test Scenario and Results

Figure 14 presents the HIL responses during the sequential activation of the distributed hierarchical control functions. Initially, the DG units operate under local primary control. Voltage recovery, intra MG current sharing, and inter MG current coordination are then activated sequentially. As shown in Figure 14a, the three bus voltages remain close to the nominal value of 48 V throughout the control switching process. Only small transient deviations occur when the different control functions are activated, and these deviations are rapidly attenuated without sustained oscillations.

Figure 14b shows the staged adjustment of the DG output currents. Under local primary control, the DG currents are determined mainly by their local operating conditions and droop characteristics. After the intra MG current sharing controller is activated, the output currents of the DG units within each DC-MG gradually converge to the prescribed proportional sharing relationship. Following the activation of the inter MG coordination controller, the current references are further adjusted through information exchange among the leader nodes, thereby improving current coordination among the interconnected DC-MGs. After each control transition, the DG currents stabilize at their corresponding reference levels. These results demonstrate that the distributed hierarchical controller can maintain bus voltage recovery while achieving coordinated current sharing both within individual DC-MGs and among interconnected microgrids under real-time implementation conditions.

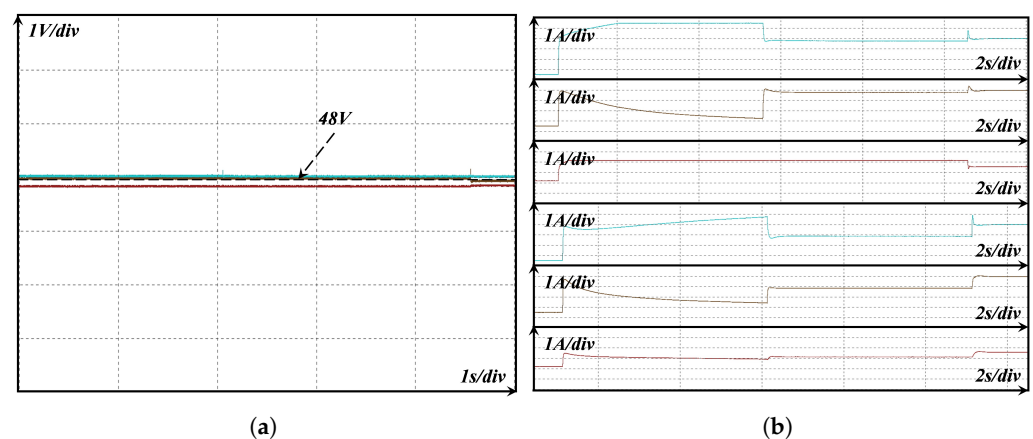


Figure 14. HIL responses during the sequential activation of the distributed hierarchical control functions: (a) bus voltage responses during the activation of voltage recovery, intra microgrid current sharing, and inter microgrid coordination; (b) DG output current responses.

Figure 15 further evaluates the HIL performance under the generalized nodal DoS attack scenario. For direct comparison, the upper waveforms in each subfigure correspond to the fixed parameter controller, whereas the lower waveforms correspond to the proposed event triggered resilient controller. Under fixed parameter control, the attack induced communication interruptions produce visible voltage fluctuations and transient deviations around the 48 V reference, as shown in the upper part of Figure 15a. The associated current responses in the upper part of Figure 15b exhibit pronounced ripple, current sharing mismatch, and local transient variations because the controller parameters cannot adapt to the changing attack modes and communication topology.

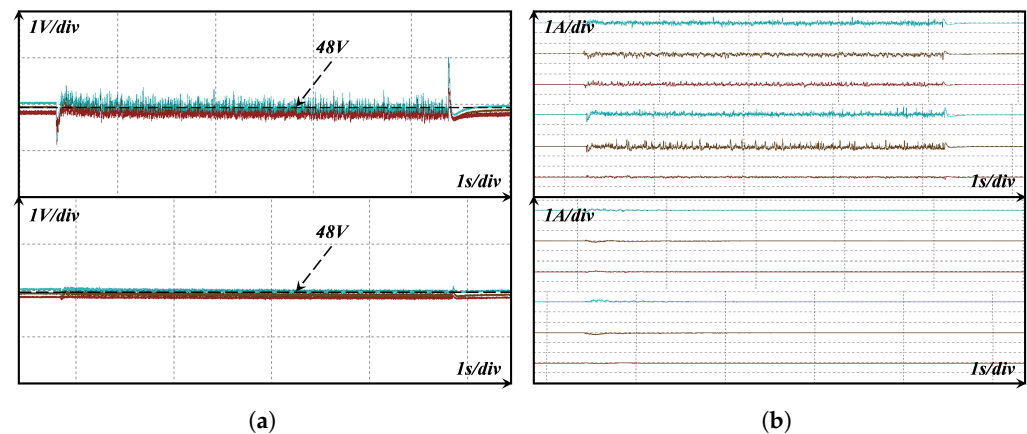


Figure 15. HIL responses under generalized nodal DoS attacks. The upper waveforms correspond to the fixed parameter controller, and the lower waveforms correspond to the proposed event triggered resilient controller: (a) bus voltage responses, showing reduced voltage deviations and improved recovery with the proposed method; (b) DG output current responses, showing reduced oscillations, improved current sharing, and faster stabilization with the proposed method.

By contrast, the lower waveforms in Figure 15 show that the proposed method maintains the bus voltages within a substantially narrower neighborhood of the nominal value and suppresses the attack induced voltage deviations. The DG output currents also preserve the required sharing relationship with considerably smaller oscillations and recover rapidly following topology changes. Although residual ripple remains because of switching operations, discrete sampling, and hardware measurement noise, no sustained oscillation or instability is observed.

6. Conclusions

With the advancement of DC-MG technologies, the coordinated voltage recovery and current sharing in clustered networked DC-MGs under hierarchical network coupling interactions remain critical yet under-addressed challenges. This paper proposes a distributed resilient control scheme featuring dual innovative mechanisms: First, a hierarchical control architecture incorporating cross-layer topological coupling effects enables inter-group energy exchange while accomplishing primary regulation objectives. Second, a generalized DoS attack model characterized by SPs is established, from which enhanced ET parameter adaptation rules for resilient controllers are analytically derived under randomized attack patterns. Extensive experimental studies validate the efficacy of the proposed methodology in maintaining operational integrity under adversarial conditions.

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Z.L. and D.M.; supervision, D.M.; project administration, D.M.; funding acquisition, D.M. All authors have read and agreed to the published version of the manuscript.

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