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Fuzzy H_∞ control of nonlinear DC microgrids under aperiodic DoS attacks – an event-triggered approach

Fuqiang Li[a,*] , Kang Li [b], Lisai Gao[a], Chen Peng [c]

[a]College of Sciences, Henan Agricultural University, China; [b]School of Electronic and Electrical Engineering, University of Leeds, UK; [c]School of Mechatronics Engineering and Automation, Shanghai University, China

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ABSTRACT

This paper studies the fuzzy H_∞ control of nonlinear DC microgrids subject to the dynamic event-triggered mechanism (ETM), aperiodic DoS attacks, noises and mismatching premises. First, using information of DC microgrid's T-S fuzzy model and aperiodic DoS attacks, a discrete-time resilient dynamic ETM is proposed, which can save constrained system resources, as well as actively exclude attack-induced dropouts and Zeno behavior. Second, a fuzzy switched system model is built, which provides a unified platform to evaluate effects of all the affecting factors such as the dynamic ETM and DoS attacks. Third, by constructing a piecewise Lyapunov functional, criteria for exponential stability with guaranteed H_∞ performance are obtained, and an event-triggered fuzzy injection current controller is further designed. Simulation results confirm that, in presence of aperiodic DoS attacks and noises, the proposed controller can stabilize the nonlinear DC microgrids, while the dynamic ETM works well in reducing the triggering rate without dropouts. Trade-offs can be made between control and communication resources, and the proposed fuzzy controller achieves shorter settling times and smaller overshoots than robust controller.

KEYWORDS

DC microgrids; DoS attacks; fuzzy control; event-triggered control; exponential stability

1. Introduction

To reduce green-house gas emissions in addressing the climate change challenge, the microgrids provide viable solution to integrate the distributed renewable energy resources into power systems(Anitha & Suchitra, 2021). Due to the high penetration of DC power sources (e.g., solar photovoltaics and batteries) and DC loads (e.g., computers and light-emitting diodes), DC microgrids are attracting increasing attention in the last decade (**?**). Besides, DC microgrids do not have the problems of reactive power flow, synchronization and harmonics as the AC counterparts, and thus they have been widely used in electric vehicles, renewable power plants, data centers, etc.

CONTACT Fuqiang Li. Email: lifuqiang@henau.edu.cn

In DC microgrids, by tightly regulating power electronics devices, loads can be modeled as constant power loads (CPLs). However, the negative impedance feature of the CPLs often results in underdamping or unstable oscillation (**?**). To this end, passive damping strategy, such as adding the resistor or capacitor (**?**), is proposed, which is effective and simple. However, due to physical constraints, it is often difficult and costly to implement this method. By changing the control loops to imitate passive elements such as virtual impedance or virtual resistor, active damping strategy is presented (**?**). However, due to the usage of small-signal models, this method only ensures small-signal stability (**?**). On the other hand, the T-S fuzzy method can approximate nonlinear systems well (**?**), and global stability can be guaranteed, which motivates this paper to study the fuzzy control of the microgrid with CPLs.

Nowadays, as communication networks are greatly integrated with the microgrids, they bring distinctive advantages such as high flexibility and low costs. However, they also expose the microgrids to cyber attacks, which mainly include denial of service (DoS) attacks and deception attacks such as false data injection (FDI) attacks. DoS attacks attempt to block communication networks (**?**), while FDI attacks intend to inject false data into the original data packets (**?**). Since DoS attacks can be launched without knowing system information, they are more likely to appear in power systems, which have attracted the increasing attention. For instance, considering time-constrained DoS attacks, by constructing an attack-parameter-dependent time-varying Lyapunov function, the work (**?**) obtains the exponential stability criterion for DC microgrid with CPLs. For interconnected DC microgrids with CPLs under DoS attacks, the work (**?**) proposes an extended Kalman filter based intrusion detection and state estimation method. For islanded DC microgrids with distributed generators under DoS attacks, by introducing a time-varying sampling period, the work (**?**) presents a distributed optimal current sharing control method, and the work (**?**) proposes a distributed secondary controller while further considering heterogeneous communication delays. For multibus DC microgrids under DoS attacks, the work (**?**) proposes an aperiodic communication and control method. Considering DC microgrids under both DoS and FDI attacks, the work (**?**) presents a switching secondary controller, while the work (**?**) proposes a consensus based secondary control method. For wide-area power systems, based on switching control theory, the work (**?**) studies the load frequency control considering dynamically changing topologies, and the work (**?**) presents a dynamic loop damping method considering detectable attacks such as DoS attacks.

To facilitate system analysis using existing control theories, most works above adopt periodic or continuous control strategies. When system is running stably, it is often unnecessary to frequently implement control tasks. To this end, an alternative control method, called event-triggered control (ETC), is proposed (**?**). Compared with periodic or continuous control methods, the ETC only implements control tasks when system needs attention, which makes it possible to save constrained system resources. Therefore, the ETC has been introduced in the microgrid control. For instance, using the load current sharing error and regulation error of voltage observer to design the ETM, the work (**?**) presents a distributed event-triggered control strategy for DC microgrid. Removing the voltage observer in (**?**) by transforming both of voltage and current control into an optimization problem, the work (**?**) uses voltage deviation of the droop control to design the ETM, and proposes an optimal consensus algorithm for distributed energy resources. Further considering the economic operation, the work (**?**) uses information of the voltage, power and increment cost to design the ETM, and presents a hierarchical and economic distributed ETC method for hybrid microgrids.

Although the aforementioned works have presented many useful results, there still

exist the following limitations. The works about security control of microgrids seldom consider limited system resources, while the works using the ETC seldom consider effects of cyber attacks. Besides, the effects of noises have not drawn enough attention. Further, when using the T-S fuzzy control method to handle the CPL-induced nonlinear issue, the ETM will result in the premise mismatching problem, which should be also considered. Thus, it is necessary to study the event-triggered security control of DC microgrids while considering effects of the noises and premise mismatching.

To address the issues above, this paper investigates the fuzzy H_∞ control of DC microgrids with the dynamic ETM, while addressing a variety of issues, including the DoS attacks, noises and premise mismatching. The main contributions are summarized as follows. Firstly, based on the T-S fuzzy model of DC microgrids, using information of DC microgrids and DoS attacks, a resilient dynamic ETM (DETM) is proposed, which can save communication resources, ensure at least one transmission during each attack-sleeping interval, and actively exclude the attack-induced dropouts and Zeno behavior. Secondly, a fuzzy switched closed-loop system model is built, which provides a unified framework to study effects of the DETM, aperiodic DoS attacks, noises and premise mismatching. Thirdly, by constructing a piecewise Lyapunov-Krasovskii functional, criteria for exponential stability with guaranteed H_∞ performance are derived. Further, an event-triggered fuzzy injection current controller is designed, which can achieve smaller overshoots and shorter settling times than the robust controller in (**?**).

The paper is organised as follows. The closed-loop system model of the DC microgrid is built in Section 2, and Section 3 studies the stability and H_∞ performance of the DC microgrid. Co-design method of the controller and the DETM is provided in Section 4. Section 5 shows case studies, and conclusions are given in Section 6.

Notations. Col and $diag$ indicate the column matrix and diagonal matrix, respectively. I denotes the identity matrix, and $He\{A\}$ refers to $A + A^T$. $\lambda_{min}\{P\}$ indicates the minimum eigenvalue of the matrix P. $\mathbb{N}$ refer to the natural number set. $\|\cdot\|$ denotes the Euclidean norm. * refers to the symmetric item in a matrix. $max\{\}$ and $min\{\}$ denote the maximum and minimum functions, respectively.

2. System Modelling for the DC microgrid

2.1. System description

As shown in Figure 1, a DC microgrid contains a DC source, an energy storage system (ESS) and Q CPLs. The voltage and current information of the DC microgrid is sampled periodically. The DETM determines whether or not to transmit the sample data according to the triggering condition. The triggered data are sent to the event-triggered fuzzy injection current (ETFIC) controller through communication networks. The control signals are used to adjust the injection current. Communication networks are affected by aperiodic DoS attacks.

Using Kirchhoff laws (**?**), and shifting the operating point x_0 to the origin, the DC microgrid can be described as

$$\dot{\bar{x}}(t) = \bar{A}\bar{x}(t) - DH(\bar{x}(t)) + B_{es}\bar{i}_{es}(t) \tag{1}$$

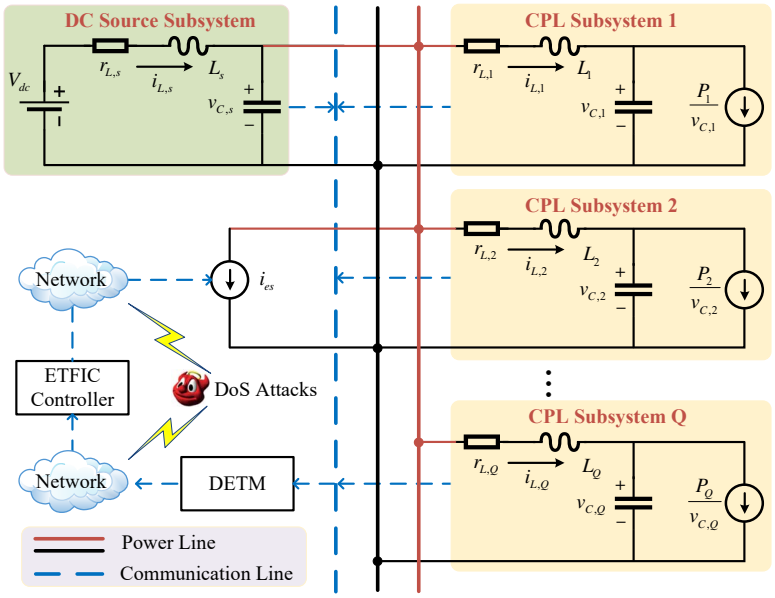

Figure 1. A DC microgrid with Q CPLs.

where $\bar{i}_{es}(t)$ is injection current, and

$$\begin{cases} \bar{x}(t) = \begin{bmatrix} \bar{x}_1(t) \\ \cdots \\ \bar{x}_Q(t) \\ \bar{x}_s(t) \end{bmatrix}, \ H(\bar{x}(t)) = \begin{bmatrix} -h_1(\bar{x}_1(t)) \\ \cdots \\ -h_Q(\bar{x}_Q(t)) \end{bmatrix}, \ \bar{x}_s(t) = \begin{bmatrix} \bar{i}_{L,s} \\ \bar{v}_{C,s} \end{bmatrix} \\ \bar{x}_j(t) = \begin{bmatrix} \bar{i}_{L,j} \\ \bar{v}_{C,j} \end{bmatrix}, \ h_j(\bar{x}_j(t)) = \frac{\bar{v}_{C,j}}{v_{C_0,j}(\bar{v}_{C,j}+v_{C_0,j})}, \ j = 1, \ldots, Q \end{cases}$$

$$\begin{cases} \bar{A} = \begin{bmatrix} \bar{A}_1 & \ldots & 0 & \bar{A}_{1s} \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \ldots & \bar{A}_Q & \bar{A}_{Qs} \\ \bar{A}_{cn} & \ldots & \bar{A}_{cn} & \bar{A}_s \end{bmatrix}, D = \begin{bmatrix} d_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & d_Q \\ 0 & \ldots & 0 \end{bmatrix}, B_{es} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ b_{es} \end{bmatrix} \\ \bar{A}_j = \begin{bmatrix} -\frac{r_{L,j}}{L_j} & -\frac{1}{L_j} \\ \frac{1}{C_j} & 0 \end{bmatrix}, \bar{A}_{js} = \begin{bmatrix} 0 & \frac{1}{L_j} \\ 0 & 0 \end{bmatrix}, d_j = \begin{bmatrix} 0 \\ \frac{P_j}{C_j} \end{bmatrix}, \ j = 1, \ldots, Q \\ \bar{A}_s = \begin{bmatrix} -\frac{r_s}{L_s} & -\frac{1}{L_s} \\ \frac{1}{C_s} & 0 \end{bmatrix}, \bar{A}_{cn} = \begin{bmatrix} 0 & 0 \\ -\frac{1}{C_s} & 0 \end{bmatrix}, b_{es} = \begin{bmatrix} 0 \\ -\frac{1}{C_s} \end{bmatrix} \end{cases}$$

where $r_{L,j}$, C_j, L_j and $r_{L,s}$, C_s, L_s denote the resistance, capacitance, inductance in the CPL subsystem and DC source subsystem, respectively. P_j is the power of the j_{th} CPL, and V_{dc} is the voltage of the DC source. $v_{C,j}$, $v_{C,s}$ and $i_{L,j}$, $i_{L,s}$ denote the corresponding capacitor voltages and inductor currents. $v_{C_0,j}$ is the operating point of the voltage $v_{C,j}$.

Considering that a DC microgrid with several CPLs can be transformed into an

equivalent microgrid with one CPL (**?**), without loss of generality, a DC microgrid with one CPL is studied here.

Using the T-S fuzzy method, and considering the effect of noises, the DC microgrid (1) can be described as

$$\begin{cases} \dot{\bar{x}}(t) = \sum_{i=1}^{2} \eta_i(\bar{x}(t))\{A_i\bar{x}(t) + B_{es}\bar{i}_{es} + B_{\omega i}\omega(t)\} \\ z(t) = \sum_{i=1}^{2} \eta_i(\bar{x}(t))\{F_i\bar{x}(t) + H_i\bar{i}_{es}\} \end{cases} \tag{2}$$

where $\omega(t)$ is noises, $z(t)$ is controlled output, B_i^{ω}, F_i and H_i are gain matrices, and

$$\begin{cases} A_i = \begin{bmatrix} \tilde{A}_i & \bar{A}_{1s} \\ \bar{A}_{cn} & \bar{A}_s \end{bmatrix},\ \tilde{A}_1 = \begin{bmatrix} -\frac{r_{L,1}}{L_1} & -\frac{1}{L_1} \\ \frac{1}{C_1} & \frac{P_1}{C_1}\check{\mathscr{K}} \end{bmatrix},\ \tilde{A}_2 = \begin{bmatrix} -\frac{r_{L,1}}{L_1} & -\frac{1}{L_1} \\ \frac{1}{C_1} & \frac{P_1}{C_1}\hat{\mathscr{K}} \end{bmatrix} \\ \eta_1(\bar{x}(t)) = \frac{\hat{\mathscr{K}}\bar{v}_{C,1} - h_1(\bar{x}(t))}{(\hat{\mathscr{K}} - \check{\mathscr{K}})\bar{v}_{C,1}},\ \eta_2(\bar{x}(t)) = \frac{h_1(\bar{x}(t)) - \check{\mathscr{K}}\bar{v}_{C,1}}{(\hat{\mathscr{K}} - \check{\mathscr{K}})\bar{v}_{C,1}} \\ \check{\mathscr{K}} = \frac{1}{v_{C_0,1}(\bar{v}_{C,1}^m + v_{C_0,1})},\ \hat{\mathscr{K}} = \frac{1}{v_{C_0,1}(-\bar{v}_{C,1}^m + v_{C_0,1})},\ \bar{v}_{C,1} \in [-\bar{v}_{C,1}^m, \bar{v}_{C,1}^m] \end{cases}$$

2.2. Aperiodic DoS attacks

Consider the aperiodic DoS attacks as

$$\mathscr{A}(t) = \begin{cases} 0,\ t \in \mathscr{T}_{1,n} = [b^{n-1}, b^{n-1} + b_{off}^{n-1}) \\ 1,\ t \in \mathscr{T}_{2,n} = [b^{n-1} + b_{off}^{n-1}, b^n), n \in \mathbb{N} \end{cases} \tag{3}$$

where 0 and 1 indicate the sleeping and active statuses of DoS attacks, respectively. During the attack-sleeping intervals $\mathscr{T}_{1,n} = [b^{n-1}, b^{n-1} + b_{off}^{n-1})$, network communication is allowed. During the attack-active intervals $\mathscr{T}_{2,n} = [b^{n-1} + b_{off}^{n-1}, b^n)$, network communication is denied.

For DC microgrid systems, to avoid undergoing instability, the amount of DoS attacks can not be arbitrary, and suitable conditions should be imposed on the frequency and duration of DoS attacks. Considering first the attacking frequency, let $\Lambda_n = b^n + b_{off}^n - (b^{n-1} + b_{off}^{n-1})$ denote the time interval between two successive attack activations, while $\underline{\Lambda}$ indicates the lower bound of sampling intervals. If $\Lambda_n < \underline{\Lambda}$, system stability will be lost regardless of the used control strategies. To ensure system stability, the attacking frequency should be small compared to the minimum sampling frequency. Thus, using concept of average dwell-time (**?**), the attacking frequency is assumed to satisfy

$$\varkappa(t) = \mathscr{D}\{n \in \mathbb{N} | b^{n-1} + b_{off}^{n-1} < t\} \leq \xi + \frac{t}{\sigma} \tag{4}$$

where scalars $\xi \geq 0$, $\sigma > \underline{\Lambda}$, $\mathscr{D}$ marks element number, $\varkappa(t)$ refers to the number of attack activations during $[0, t]$.

In addition to the attacking frequency, the attacking duration should also be constrained. The attacking duration refers to the time interval over which communication is denied. For instance, if there is only one attack activation, the assumption of attacking frequency in (4) is satisfied with $\xi \geq 1$. However, if the attack keeps being active after activation (i.e., communication is never allowed), system stability is lost regardless of the designed control strategies. Thus, to constrain the attacking

duration, assume that there exists the maximum attack-active interval b_{on}^{m} satisfying $b_{on}^{m} \geq b^{n} - b^{n-1} - b_{off}^{n-1}$ and the minimum attack-sleeping interval b_{off}^{s} satisfying $b_{off}^{s} \leq b_{off}^{n-1}$.

Remark 1. The above assumptions of the attacking frequency and duration, not only make the control problem meaningful, but also have practical consideration. In practice, some technologies can be used to mitigate effects of DoS attacks, such as the spreading techniques (**?**) and high-pass filtering (**?**). Using these methods, the successful chance of DoS attacks is decreased, and thus, the frequency and duration of the communication-denial intervals are limited in practice.

2.3. Resilient dynamic event-triggered mechanism

To save the limited communication resource, a dynamic ETM is proposed as

$$\begin{cases} d_{k+1,n}h = d_{k,n}h + min_{j\in\mathbb{N}}\{jh|\mathscr{C} > 0\},\ d_{k,n}h \in \mathscr{T}_{1,n} \\ d_{1,n}h = b^{n-1} \in \mathscr{T}_{1,n} \\ \mathscr{C} = \|\Phi^{\frac{1}{2}}(\bar{x}(d_{k,n}h + jh) - \bar{x}(d_k h))\|^2 - \bar{\delta}(t)\|\Phi^{\frac{1}{2}}\bar{x}(d_k h)\|^2 \\ \bar{\delta}(t) = \delta - \delta tanh(g_1 b_{on}^{m} + g_2\|\bar{x}(d_{k,n}h + jh) - \bar{x}(d_k h)\|) \end{cases} \tag{5}$$

where scalars $\delta > 0, g_1 > 0, g_2 > 0$, positive definite matrix $\Phi > 0$, $d_{k,n}h (k, n, d_{k,n} \in \mathbb{N})$ indicates the k_{th} triggering instant in the attack-sleeping interval $\mathscr{T}_{1,n}$, and h is sampling period.

During the attack-sleeping intervals $\mathscr{T}_{1,n}$, data are transmitted only when the triggering conditions are satisfied, which makes it possible to save communication resources. After each attack-active interval, an event is triggered (i.e., $d_{1,n}h = b^{n-1}$), which guarantees that at least one transmission exists during each attack-sleeping interval. During the attack-active intervals $\mathscr{T}_{2,n}$, no event is triggered, which excludes the attack-induced dropouts phenomenon.

Remark 2. Compared with the continuous-time ETMs (**???**) which require complex computation to exclude Zeno behavior (i.e., infinite number of events appear in finite time interval (**?**)), the DETM (5) avoids Zeno behavior naturally, since its minimum triggering interval is sampling period. Unlike the static ETMs (**???**), the DETM introduces a dynamic threshold parameter $\bar{\delta}(t) = \delta - \delta tanh(g_1 b_{on}^{m} + g_2\|\bar{x}(d_{k,n}h + jh) - \bar{x}(d_k h)\|)$. If the attacks are serious with a bigger b_{on}^{m}, or states fluctuate violently with a bigger $\|\bar{x}(d_{k,n}h+jh)-\bar{x}(d_k h)\|$, the threshold parameter $\bar{\delta}(t)$ becomes smaller, which helps to transmit more data to improve system performance.

2.4. Closed-loop system modelling

Defining $\ell_{k,n} = d_{k+1,n} - d_{k,n} - 1$, triggering intervals of the DETM (5) can be divided as

$$[d_{k,n}h, d_{k+1,n}h) = \bigcup_{\varrho_{k,n}=0}^{\ell_{k,n}} \{\psi_{\varrho_{k,n}}^{d_{k,n}} = [d_{k,n}h + \varrho_{k,n}h, d_{k,n}h + \varrho_{k,n}h + h)\} \tag{6}$$

During $\bar{\psi}_{\varrho_{k,n}}^{d_{k,n}} = \psi_{\varrho_{k,n}}^{d_{k,n}} \cap \mathscr{T}_{1,n}$, define two piecewise functions as

$$\epsilon_{k,n}(t) = \bar{x}(d_{k,n}h) - \bar{x}(d_{k,n}h + \varrho_{k,n}h), \quad \phi_{k,n}(t) = t - (d_{k,n}h + \varrho_{k,n}h) \tag{7}$$

Using (7), the released data of the DETM can be described as

$$\bar{x}(d_{k,n}h) = \epsilon_{k,n}(t) + \bar{x}(t - \phi_{k,n}(t)),\ t \in \bar{\psi}_{\varrho_{k,n}}^{d_{k,n}} \tag{8}$$

As shown in Figure 1, using $\bar{x}(d_{k,n}h)$ in (8) as controller input, the ETFIC controller is designed as

$$\bar{i}_{es} = \sum_{j=1}^{2} \bar{\eta}_j(\bar{x}(d_{k,n}h))K_j[\bar{x}(t - \phi_{k,n}(t)) + \epsilon_{k,n}(t)],\ t \in \bar{\psi}_{\varrho_{k,n}}^{d_{k,n}} \tag{9}$$

where $\bar{\eta}_1(\bar{x}(d_{k,n}h)) = \frac{\hat{\mathscr{K}}\bar{v}_{C,1} - h_1(\bar{x}(d_{k,n}h))}{(\hat{\mathscr{K}} - \check{\mathscr{K}})\bar{v}_{C,1}}$ and $\bar{\eta}_2(\bar{x}(d_{k,n}h)) = \frac{h_1(\bar{x}(d_{k,n}h)) - \check{\mathscr{K}}\bar{v}_{C,1}}{(\hat{\mathscr{K}} - \check{\mathscr{K}})\bar{v}_{C,1}}$.

Remark 3. Since there exist the DETM and communication networks between the microgrid and controller as shown in Figure 1, this paper considers the premise mismatching issue when designing the controller (9), which is more reasonable and complex than the works (**??**) which assume the same premises in both of the plant and controller.

Using the DC microgrid model (2) and the controller model (9), the T-S fuzzy time-delayed closed-loop system model is obtained as

$$\begin{cases} \dot{\bar{x}}(t) = \sum_{i=1}^{2}\sum_{j=1}^{2} \eta_i\bar{\eta}_j\{A_i\bar{x}(t) + B_{es}K_j\mathscr{U} + B_{\omega i}\omega(t)\} \\ z(t) = \sum_{i=1}^{2}\sum_{j=1}^{2} \eta_i\bar{\eta}_j\{F_i\bar{x}(t) + H_iK_j\mathscr{U}\},\ t \in \mathscr{T}_{1,n} \\ \dot{\bar{x}}(t) = \sum_{i=1}^{2} \eta_i\{A_i\bar{x}(t) + B_{\omega i}\omega(t)\} \\ z(t) = \sum_{i=1}^{2} \eta_iF_i\bar{x}(t),\ t \in \mathscr{T}_{2,n} \end{cases} \tag{10}$$

where $\mathscr{U} = \bar{x}(t - \phi_{k,n}(t)) + \epsilon_{k,n}(t)$, $\eta_i = \eta_i(\bar{x}(t))$ and $\bar{\eta}_j = \bar{\eta}_j(\bar{x}(d_{k,n}h))$.

3. System Stability and H_∞ performance

3.1. Exponential stability

Theorem 3.1. For given sampling period $h > 0$, the DETM parameter $\delta \geq 0$, DoS attacks parameters $d_{on}^m > 0$, $d_{off}^s > 0$, scalars $a_1 > 0, a_2 > 0$, and β_j satisfying $\bar{\eta}_j \geq \beta_j\eta_j (j = 1, 2)$, if there exist positive definite matrices $P_i, Q_i, R_i, S_i (i = 1, 2), \Phi > 0$, symmetric matrices Γ^1, Γ^2, matrices $G_i, W_i (i = 1, 2)$ satisfying $\begin{bmatrix} R_i & * \\ G_i & R_i \end{bmatrix} > 0$,

$\begin{bmatrix} S_i & * \\ W_i & S_i \end{bmatrix} > 0$ and

$$\Xi^{ij\theta} - \Gamma^i < 0,\ 1 \le i, j \le 2, \theta = 2,3 \tag{11}$$

$$\beta_i(\Xi^{ii\theta} - \Gamma^i) + \Gamma^i < 0,\ i = 1,2, \theta = 2,3 \tag{12}$$

$$\beta_j(\Xi^{ij\theta} - \Gamma^i) + \beta_i(\Xi^{ji\theta} - \Gamma^j) + \Gamma^i + \Gamma^j < 0, 1 \le i < j \le 2, \theta = 2,3 \tag{13}$$

$$\Pi^{i\theta} < 0,\ i = 1,2, \theta = 2,3 \tag{14}$$

$$\begin{cases} P_1 \le \mu_2 P_2, P_2 \le e^{2(a_1+a_2)h}\mu_1 P_1, Q_1 \le \mu_2 Q_2, Q_2 \le \mu_1 Q_1 \\ R_1 \le \mu_2 R_2, R_2 \le \mu_1 R_1, S_1 \le \mu_2 S_2, S_2 \le \mu_1 S_1 \end{cases} \tag{15}$$

$$\varrho = (2a_1 d^s_{off} - 2a_2 d^m_{on} - ln(\mu_1\mu_2) - 2(a_1 + a_2)h)/\sigma > 0 \tag{16}$$

where

$$\Xi^{ij\theta} = \begin{bmatrix} \Xi^{ij\theta}_{11} & * & * & * \\ \Xi^{ij}_{21} & \Xi_{22} & * & * \\ \Xi^{ij}_{31} & 0 & \Xi_{33} & * \\ \Xi_{41} & 0 & 0 & \Xi_{44} \end{bmatrix},\ \Pi^{i\theta} = \begin{bmatrix} \Pi^{i\theta}_{11} & * & * \\ \Pi^{i}_{21} & \Pi_{22} & * \\ \Pi^{i}_{31} & 0 & \Pi_{33} \end{bmatrix} \tag{17}$$

with
$\Xi^{ij\theta}_{11} = 2a_1\mathscr{I}_1^T P_1 \mathscr{I}_1 + He\{\mathscr{I}_1^T P_1(A_i\mathscr{I}_1 + B_{es}K_j(\mathscr{I}_2 + \mathscr{I}_5))\}$
$+ \mathscr{I}_1^T Q_1 \mathscr{I}_1 - e^{-2a_1h}\mathscr{I}_4^T Q_1 \mathscr{I}_4 - (3-\theta)e^{-a_1h}(\mathscr{I}_1 - \mathscr{I}_2)^T R_1(\mathscr{I}_1 - \mathscr{I}_2)$
$- (3-\theta)e^{-a_1h}(\mathscr{I}_2 - \mathscr{I}_3)^T R_1(\mathscr{I}_2 - \mathscr{I}_3) - (3-\theta)e^{-a_1h}He((\mathscr{I}_2 - \mathscr{I}_3)^T G_1(\mathscr{I}_1 - \mathscr{I}_2))$
$- (3-\theta)e^{-2a_1h}(\mathscr{I}_3 - \mathscr{I}_4)^T S_1(\mathscr{I}_3 - \mathscr{I}_4) - (\theta-2)e^{-2a_1h}(\mathscr{I}_3 - \mathscr{I}_2)^T S_1(\mathscr{I}_3 - \mathscr{I}_2)$
$- (\theta-2)e^{-2a_1h}(\mathscr{I}_2 - \mathscr{I}_4)^T S_1(\mathscr{I}_2 - \mathscr{I}_4) - (\theta-2)e^{-2a_1h}He((\mathscr{I}_2 - \mathscr{I}_4)^T W_1(\mathscr{I}_3 - \mathscr{I}_2))$
$- (\theta-2)e^{-a_1h}(\mathscr{I}_1 - \mathscr{I}_3)^T R_1(\mathscr{I}_1 - \mathscr{I}_3) - \mathscr{I}_5^T \Phi \mathscr{I}_5$,
$\Xi^{ij}_{21} = 0.5h(A_i\mathscr{I}_1 + B_{es}K_j(\mathscr{I}_2 + \mathscr{I}_5))$, $\Xi_{22} = -R_1^{-1}$,
$\Xi^{ij}_{31} = 0.5h(A_i\mathscr{I}_1 + B_{es}K_j(\mathscr{I}_2 + \mathscr{I}_5))$, $\Xi_{33} = -S_1^{-1}$,
$\Xi^{ij}_{41} = \delta^{0.5}(\mathscr{I}_2 + \mathscr{I}_5)$, $\Xi_{44} = -\Phi^{-1}$,
$\Pi^{i\theta}_{11} = -2a_2\bar{\mathscr{I}}_1^T P_2 \bar{\mathscr{I}}_1 + He\{\bar{\mathscr{I}}_1^T P_2(A_i\bar{\mathscr{I}}_1)\}$
$+ \bar{\mathscr{I}}_1^T Q_2 \bar{\mathscr{I}}_1 - e^{2a_2h}\bar{\mathscr{I}}_4^T Q_2 \bar{\mathscr{I}}_4 - (3-\theta)(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2)^T R_2(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2)$
$- (3-\theta)(\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3)^T R_2(\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3) - (3-\theta)He((\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3)^T G_2(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2))$
$- (3-\theta)e^{a_2h}(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_4)^T S_2(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_4) - (\theta-2)e^{a_2h}(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2)^T S_2(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2)$
$- (\theta-2)e^{a_2h}(\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4)^T S_2(\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4) - (\theta-2)e^{a_2h}He((\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4)^T W_2(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2))$
$- (\theta-2)(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_3)^T R_2(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_3)$,
$\Pi^{i}_{21} = 0.5h(A_i\bar{\mathscr{I}}_1)$, $\Pi_{22} = -R_2^{-1}$, $\Pi^{i}_{31} = 0.5h(A_i\bar{\mathscr{I}}_1)$, $\Pi_{33} = -S_2^{-1}$,
$\mathscr{I}_i = [\ \underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{5-i}\ ](i = 1, \dots, 5)$, $\bar{\mathscr{I}}_i = [\ \underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{4-i}\ ](i = 1, \dots, 4)$,
then, the DC microgrid system (10) under the dynamic ETM, DoS attacks and premise mismatching is exponentially stable.

Proof. Construct a piecewise Lyapunov-Krasovskii functional (LKF) as

$$V(t) = \begin{cases} V_1(t),\ t \in \mathscr{T}_{1,n} \\ V_2(t),\ t \in \mathscr{T}_{2,n} \end{cases} \tag{18}$$

where

$$\begin{aligned} V_\varsigma(t) =&\bar{x}^T(t)P_\varsigma\bar{x}(t) + \int_{t-h}^{t}\bar{x}^T(\vartheta)\varphi_\varsigma(\vartheta)Q_\varsigma\bar{x}(\vartheta)d\vartheta \\ &+ \frac{h}{2}\int_{-\frac{h}{2}}^{0}\int_{t+\iota}^{t}\dot{\bar{x}}^T(\vartheta)\varphi_\varsigma(\vartheta)R_\varsigma\dot{\bar{x}}(\vartheta)d\vartheta d\iota \\ &+ \frac{h}{2}\int_{-h}^{-\frac{h}{2}}\int_{t+\iota}^{t}\dot{\bar{x}}^T(\vartheta)\varphi_\varsigma(\vartheta)S_\varsigma\dot{\bar{x}}(\vartheta)d\vartheta d\iota, \varsigma = 1,2 \end{aligned} \tag{19}$$

with positive definite matrices $P_\varsigma > 0, Q_\varsigma > 0, R_\varsigma > 0, S_\varsigma > 0$, functions $\varphi_1 = e^{2a_1(\vartheta-t)}$ and $\varphi_2 = e^{2a_2(t-\vartheta)}$.

When $t \in \mathscr{T}_{1,n}$, the derivative of $V_1(t)$ is derived as

$$\begin{aligned} \dot{V}_1(t) \leq &\sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\bar{\mu}_j\{-2a_1V_1(t) + 2\dot{\bar{x}}^T(t)P_1\bar{x}(t) + 2a_1\bar{x}^T(t)P_1\bar{x}(t) \\ &+ \bar{x}^T(t)Q_1\bar{x}(t) - e^{-2a_1h}\bar{x}^T(t-h)Q_1\bar{x}(t-h) \\ &+ 0.25h^2\dot{\bar{x}}^T(t)(R_1+S_1)\dot{\bar{x}}(t) + \mathcal{G}_1 + \mathcal{G}_2\} \end{aligned} \tag{20}$$

where $\mathcal{G}_1 = -0.5he^{-a_1h}\int_{t-\frac{h}{2}}^{t}\dot{\bar{x}}^T(\iota)R_1\dot{\bar{x}}(\iota)d\iota, \mathcal{G}_2 = -0.5he^{-2a_1h}\int_{t-h}^{t-\frac{h}{2}}\dot{\bar{x}}^T(\iota)S_1\dot{\bar{x}}(\iota)d\iota$.

When $\phi_1(t) \in [0, 0.5h)$, applying reciprocally convex method (**?**) and Jensen inequality (**?**) to $\mathcal{G}_1$ and $\mathcal{G}_2$ yields

$$\begin{cases} \mathcal{G}_1 \leq -e^{-a_1h}(\mathscr{H}_1^TR_1\mathscr{H}_1 + \mathscr{H}_2^TR_1\mathscr{H}_2 + He(\mathscr{H}_2^TG_1\mathscr{H}_1)) \\ \mathcal{G}_2 \leq -e^{-2a_1h}(\bar{x}(t-0.5h) - \bar{x}(t-h))^TS_1(\bar{x}(t-0.5h) - \bar{x}(t-h)) \end{cases} \tag{21}$$

where $\mathscr{H}_1 = \bar{x}(t) - \bar{x}(t-\phi_1(t))$ and $\mathscr{H}_2 = \bar{x}(t-\phi_1(t)) - \bar{x}(t-0.5h)$.

Similarly, when $\phi_1(t) \in [0.5h, h)$, we have

$$\begin{cases} \mathcal{G}_1 \leq -e^{-a_1h}(\bar{x}(t) - \bar{x}(t-0.5h))^TR_1(\bar{x}(t) - \bar{x}(t-0.5h)) \\ \mathcal{G}_2 \leq -e^{-2a_1h}(\mathscr{H}_3^TS_1\mathscr{H}_3 + \mathscr{H}_4^TS_1\mathscr{H}_4 + He(\mathscr{H}_4^TW_1\mathscr{H}_3)) \end{cases} \tag{22}$$

where $\mathscr{H}_3 = \bar{x}(t-0.5h) - \bar{x}(t-\phi_1(t))$ and $\mathscr{H}_4 = \bar{x}(t-\phi_1(t)) - \bar{x}(t-h)$.

Using (21), (22), (5) and Schur complement lemma, it follows from (20) that

$$\dot{V}_1(t) \leq -2a_1V_1(t) + \sum_{i=1}^{2}\sum_{j=1}^{2}\eta_i\bar{\eta}_j\zeta_1^T(t)\Xi^{ij\theta}\zeta_1(t), \theta = 2,3 \tag{23}$$

where $\zeta_1(t) = col\{\bar{x}(t), \bar{x}(t-\phi_1(t)), \bar{x}(t-0.5h), \bar{x}(t-h), \epsilon(t)\}$.

To deal with the premise mismatching issue (**?**), introducing a zero term $\sum_{i=1}^{2}\sum_{j=1}^{2}\eta_i(\eta_j - \bar{\eta}_j)\zeta_1^T(t)\Gamma^i\zeta_1(t) = 0$, and using the conditions $\bar{\eta}_j \geq \beta_j\eta_j$ and (11)

in Theorem 3.1, the following inequality holds

$$\begin{aligned}
&\sum_{i=1}^{2}\sum_{j=1}^{2}\eta_i\bar{\eta}_j\zeta_1^T(t)\Xi^{ij\theta}\zeta_1(t)+\sum_{i=1}^{2}\sum_{j=1}^{2}\eta_i(\eta_j-\bar{\eta}_j)\zeta_1^T(t)\Gamma^i\zeta_1(t)\\
&\le\sum_{i=1}^{2}\eta_i\eta_i\zeta_1^T(t)\{\beta_i(\Xi^{ii\theta}-\Gamma^i)+\Gamma^i\}\zeta_1(t)\\
&\quad+\sum_{i=1}^{2}\sum_{j>i}^{2}\eta_i\eta_j\zeta_1^T(t)\{\beta_j(\Xi^{ij\theta}-\Gamma^i)+\beta_i(\Xi^{ji\theta}-\Gamma^j)+\Gamma^i+\Gamma^j\}\zeta_1(t)
\end{aligned}\tag{24}$$

Using (12) and (13), it follows from (24) that $\sum_{i=1}^{2}\sum_{j=1}^{2}\eta_i\bar{\eta}_j\chi^T(t)\Xi^{ij\theta}\chi(t)\le 0$. Thus, one can derive from (23) that $\dot{V}_1(t)\le -2a_1V_1(t)$ and

$$V_1(t)\le e^{-2a_1(t-\rho_n)}V_1(\rho_n),\ \rho_n=b^{n-1}\tag{25}$$

Similarly, when $t\in\mathscr{T}_{2,n}$, the derivative of $V_2(t)$ satisfies

$$\dot{V}_2(t)\le 2a_2V_2(t)+\sum_{i=1}^{2}\eta_i\zeta_2^T(t)\Pi^{i\theta}\zeta_2(t)\tag{26}$$

where $\zeta_2(t)=col\{\bar{x}(t),\bar{x}(t-\phi_2(t)),\bar{x}(t-0.5h),\bar{x}(t-h)\}$.

Using (14), it follows from (26) that $\dot{V}_2(t)\le 2a_2V_2(t)$ and

$$V_2(t)\le e^{2a_2(t-\bar{\rho}_n)}V_2(\bar{\rho}_n),\ \bar{\rho}_n=b^{n-1}+b_{off}^{n-1}\tag{27}$$

Using (25) and (27), the LKF (18) satisfies

$$\begin{cases}V(t)\le e^{-2a_1(t-\rho_n)}V_1(\rho_n),\ t\in\mathscr{T}_{1,n}\\ V(t)\le e^{2a_2(t-\bar{\rho}_n)}V_2(\bar{\rho}_n),\quad t\in\mathscr{T}_{2,n}\end{cases}\tag{28}$$

Using (15), the LKF (18) also satisfies

$$V_1(\rho_n)\le\mu_2V_2(\rho_n^-),\quad V_2(\bar{\rho}_n)\le e^{2(a_1+a_2)h}\mu_1V_1(\bar{\rho}_n^-)\tag{29}$$

When $t\in\mathscr{T}_{1,n}$, using (28) and (29), we have

$$\begin{aligned}
V(t)&\le e^{-2a_1(t-\rho_n)}V_1(\rho_n)\le e^{-2a_1(t-\rho_n)}\mu_2V_2(\rho_n^-)\\
&\le\mu_2e^{-2a_1(t-\rho_n)}e^{2a_2(\rho_n-\bar{\rho}_{n-1})}V_2(\bar{\rho}_{n-1})\le\ldots\le e^{\mathscr{C}}V_1(0)e^{-\varrho t}
\end{aligned}\tag{30}$$

where $\mathscr{C}=\xi(-2a_1b_{off}^s+2a_2b_{on}^m+ln(\mu_1\mu_2)+2(a_1+a_2)h)$ and ϱ is shown in (16).

Similarly, when $t\in\mathscr{T}_{2,n}$, we have

$$V(t)\le e^{2a_2(t-\bar{\rho}_n)}V_2(\bar{\rho}_n)\le e^{2a_2(t-\bar{\rho}_n)}e^{2(a_1+a_2)h}\mu_1V_1(\bar{\rho}_n^-)\le\ldots\le\frac{e^{\mathscr{C}}}{\mu_2}V_1(0)e^{-\varrho t}\tag{31}$$

Using (30), (31) and (18), we have

$$\|\bar{x}(t)\| \leq \mathscr{F}_1 e^{-\bar{\varrho}t},\ \forall\ t \geq 0 \tag{32}$$

where $\mathscr{F}_1 = (\frac{\mathscr{F}_2}{\mathscr{F}_3} e^{\mathscr{C}} V_1(0))^{0.5}$, $\mathscr{F}_2 = max\{1, 1/\mu_2\}$, $\mathscr{F}_3 = min\{\lambda_{min}(P_1), \lambda_{min}(P_2)\}$ and $\bar{\varrho} = 0.5\varrho$. The proof is thus completed.

□

3.2. H_∞ performance

Theorem 3.2. For given sampling period $h > 0$, the DETM parameter $\delta \geq 0$, DoS attacks parameters $d_{on}^m > 0$, $d_{off}^s > 0$, noise parameter $\gamma > 0$, scalars $a_1 > 0, a_2 > 0$, and β_j satisfying $\bar{\eta}_j \geq \beta_j \eta_j (j = 1, 2)$, if there exist positive definite matrices $P_i, Q_i, R_i, S_i (i = 1, 2), \Phi > 0$, symmetric matrices Γ^1, Γ^2, matrices $G_i, W_i (i = 1, 2)$ satisfying $\begin{bmatrix} R_i & * \\ G_i & R_i \end{bmatrix} > 0$, $\begin{bmatrix} S_i & * \\ W_i & S_i \end{bmatrix} > 0$, (15), (16) and

$$\hat{\Xi}^{ij\theta} - \Gamma^i < 0,\ 1 \leq i, j \leq 2, \theta = 2, 3 \tag{33}$$

$$\beta_i(\hat{\Xi}^{ii\theta} - \Gamma^i) + \Gamma^i < 0,\ i = 1, 2, \theta = 2, 3 \tag{34}$$

$$\beta_j(\hat{\Xi}^{ij\theta} - \Gamma^i) + \beta_i(\hat{\Xi}^{ji\theta} - \Gamma^j) + \Gamma^i + \Gamma^j < 0, 1 \leq i < j \leq 2, \theta = 2, 3 \tag{35}$$

$$\hat{\Pi}^{i\theta} < 0,\ i = 1, 2, \theta = 2, 3 \tag{36}$$

where

$$\hat{\Xi}^{ij\theta} = \begin{bmatrix} \hat{\Xi}_{11}^{ij\theta} & * & * & * & * \\ \hat{\Xi}_{21}^{ij} & \hat{\Xi}_{22} & * & * & * \\ \hat{\Xi}_{31}^{ij} & 0 & \hat{\Xi}_{33} & * & * \\ \hat{\Xi}_{41} & 0 & 0 & \hat{\Xi}_{44} & * \\ \hat{\Xi}_{51}^{ij} & 0 & 0 & 0 & \hat{\Xi}_{55} \end{bmatrix},\ \hat{\Pi}^{i\theta} = \begin{bmatrix} \hat{\Pi}_{11}^{i\theta} & * & * & * \\ \hat{\Pi}_{21}^{i} & \hat{\Pi}_{22} & * & * \\ \hat{\Pi}_{31}^{i} & 0 & \hat{\Pi}_{33} & * \\ \hat{\Pi}_{41}^{i} & 0 & 0 & \hat{\Pi}_{44} \end{bmatrix} \tag{37}$$

with
$\hat{\Xi}_{11}^{ij\theta} = 2a_1 \mathscr{I}_1^T P_1 \mathscr{I}_1 + He\{\mathscr{I}_1^T P_1 (A_i \mathscr{I}_1 + B_{es} K_j (\mathscr{I}_2 + \mathscr{I}_5) + B_{\omega i} \mathscr{I}_6)\}$
$+ \mathscr{I}_1^T Q_1 \mathscr{I}_1 - e^{-2a_1 h} \mathscr{I}_4^T Q_1 \mathscr{I}_4 - (3-\theta) e^{-a_1 h} (\mathscr{I}_1 - \mathscr{I}_2)^T R_1 (\mathscr{I}_1 - \mathscr{I}_2)$
$- (3-\theta) e^{-a_1 h} (\mathscr{I}_2 - \mathscr{I}_3)^T R_1 (\mathscr{I}_2 - \mathscr{I}_3) - (3-\theta) e^{-a_1 h} He((\mathscr{I}_2 - \mathscr{I}_3)^T G_1 (\mathscr{I}_1 - \mathscr{I}_2))$
$- (3-\theta) e^{-2a_1 h} (\mathscr{I}_3 - \mathscr{I}_4)^T S_1 (\mathscr{I}_3 - \mathscr{I}_4) - (\theta-2) e^{-2a_1 h} (\mathscr{I}_3 - \mathscr{I}_2)^T S_1 (\mathscr{I}_3 - \mathscr{I}_2)$
$- (\theta-2) e^{-2a_1 h} (\mathscr{I}_2 - \mathscr{I}_4)^T S_1 (\mathscr{I}_2 - \mathscr{I}_4) - (\theta-2) e^{-2a_1 h} He((\mathscr{I}_2 - \mathscr{I}_4)^T W_1 (\mathscr{I}_3 - \mathscr{I}_2))$
$- (\theta-2) e^{-a_1 h} (\mathscr{I}_1 - \mathscr{I}_3)^T R_1 (\mathscr{I}_1 - \mathscr{I}_3) - \mathscr{I}_5^T \Phi \mathscr{I}_5 - \gamma^2 \mathscr{I}_6^T \mathscr{I}_6$,
$\hat{\Xi}_{21}^{ij} = 0.5h(A_i \mathscr{I}_1 + B_{es} K_j (\mathscr{I}_2 + \mathscr{I}_5) + B_{\omega i} \mathscr{I}_6)$, $\hat{\Xi}_{22} = -R_1^{-1}$,
$\hat{\Xi}_{31}^{ij} = 0.5h(A_i \mathscr{I}_1 + B_{es} K_j (\mathscr{I}_2 + \mathscr{I}_5) + B_{\omega i} \mathscr{I}_6)$, $\hat{\Xi}_{33} = -S_1^{-1}$,
$\hat{\Xi}_{41} = h^{0.5}(\mathscr{I}_2 + \mathscr{I}_5)$, $\hat{\Xi}_{44} = -\Phi^{-1}$,
$\hat{\Xi}_{51}^{ij} = F_i \mathscr{I}_1 + H_i K_j (\mathscr{I}_2 + \mathscr{I}_5)$, $\hat{\Xi}_{55} = -I$,
$\hat{\Pi}_{11}^{i\theta} = -2a_2 \bar{\mathscr{I}}_1^T P_2 \bar{\mathscr{I}}_1 + He\{\bar{\mathscr{I}}_1^T P_2 (A_i \bar{\mathscr{I}}_1 + B_{\omega i} \mathscr{I}_5)\}$
$+ \bar{\mathscr{I}}_1^T Q_2 \bar{\mathscr{I}}_1 - e^{2a_2 h} \bar{\mathscr{I}}_4^T Q_2 \bar{\mathscr{I}}_4 - (3-\theta) (\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2)^T R_2 (\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2)$
$- (3-\theta) (\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3)^T R_2 (\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3) - (3-\theta) He((\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3)^T G_2 (\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2))$
$- (3-\theta) e^{a_2 h} (\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_4)^T S_2 (\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_4) - (\theta-2) e^{a_2 h} (\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2)^T S_2 (\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2)$
$- (\theta-2) e^{a_2 h} (\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4)^T S_2 (\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4) - (\theta-2) e^{a_2 h} He((\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4)^T W_2 (\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2))$
$- (\theta-2) (\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_3)^T R_2 (\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_3) - \gamma^2 \bar{\mathscr{I}}_5^T \bar{\mathscr{I}}_5$,

$\hat{\Pi}^i_{21} = 0.5h(A_i\bar{\mathscr{I}}_1 + B_{\omega i}\mathscr{I}_5)$, $\hat{\Pi}_{22} = -R_2^{-1}$,
$\hat{\Pi}^i_{31} = 0.5h(A_i\bar{\mathscr{I}}_1 + B_{\omega i}\mathscr{I}_5)$, $\hat{\Pi}_{33} = -S_2^{-1}$, $\hat{\Pi}^i_{41} = F_i\mathscr{I}_1$, $\hat{\Pi}_{44} = -I$,
$\mathscr{I}_i = [\underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{6-i}](i = 1, \dots, 6), \bar{\mathscr{I}}_i = [\underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{5-i}](i = 1, \dots, 5)$,
then, the DC microgrid system (10) under the dynamic ETM, DoS attacks, noises, and premise mismatching is exponentially stable with guaranteed H_∞ performance.

Proof. Considering effects of the noise $\omega(t)$, when $t \in \mathscr{T}_{1,n}$, it follows from (23) that

$$\dot{V}_1(t) + 2a_1V_1(t) \leq \sum_{i=1}^{2}\sum_{j=1}^{2} \eta_i\bar{\eta}_j\bar{\zeta}_1^T(t)\hat{\Xi}^{ij\theta}\bar{\zeta}_1(t) + \gamma^2\omega^T(t)\omega(t) - z^T(t)z(t) \tag{38}$$

where $\bar{\zeta}_1(t) = col\{\bar{x}(t), \bar{x}(t-\phi_1(t)), \bar{x}(t-0.5h), \bar{x}(t-h), \epsilon(t), \omega(t)\}$.

Using (33), (34) and (35), we have $\sum_{i=1}^{2}\sum_{j=1}^{2}\eta_i\bar{\eta}_j\zeta_1^T(t)\hat{\Xi}^{ij\theta}\zeta_1(t) \leq 0$. Substituting this inequality into (38) yields

$$\dot{V}_1(t) + 2a_1V_1(t) \leq \gamma^2\omega^T(t)\omega(t) - z^T(t)z(t) \tag{39}$$

Similarly, when $t \in \mathscr{T}_{2,n}$, using (26) and (36), we have

$$\begin{cases} \dot{V}_2(t) - 2a_2V_2(t) \leq \sum_{i=1}^{2}\eta_i\bar{\zeta}_2^T(t)\hat{\Pi}^{i\theta}\bar{\zeta}_2(t) + \gamma^2\omega^T(t)\omega(t) - z^T(t)z(t) \\ \Rightarrow \dot{V}_2(t) - 2a_2V_2(t) \leq \gamma^2\omega^T(t)\omega(t) - z^T(t)z(t) \end{cases} \tag{40}$$

where $\bar{\zeta}_2(t) = col\{\bar{x}(t), \bar{x}(t-\phi_2(t)), \bar{x}(t-0.5h), \bar{x}(t-h), \omega(t)\}$.

When $t \in \mathscr{T}_{1,n}$, we have

$$\begin{aligned} \mathscr{Q}_1 =& \sum_{i=0}^{n-2}\int_{d^i}^{d^i+d^i_{off}} \tau_i^1(\iota)[\dot{V}_1(\iota) + 2a_1V_1(\iota)]d\iota \\ &+ \sum_{i=0}^{n-2}\int_{d^i+d^i_{off}}^{d^{i+1}} \tau_i^2(\iota)[\dot{V}_2(\iota) - 2a_2V_2(\iota)]d\iota + \int_{d^{n-1}}^{t}\tau_{n-1}^1(\iota)[\dot{V}_1(\iota) + 2a_1V_1(\iota)]d\iota \\ =& \sum_{i=0}^{n-2}\Big[\frac{1}{\mu_2}e^{2a_1d^i_{off}}V_1(d^i + d^i_{off}) - \frac{1}{\mu_2}V_1(d^i) + V_2(d^{i+1}) \\ &- e^{2a_2(d^{i+1}-d^i-d^i_{off})}V_2(d^i + d^i_{off})\Big] + \frac{1}{\mu_2}e^{2a_1(t-d^{n-1})}V_1(t) - \frac{1}{\mu_2}V_1(d^{n-1}) \end{aligned} \tag{41}$$

where $\tau_i^1(\iota) = e^{2a_1(\iota-d^i)}/\mu_2$ and $\tau_i^2(\iota) = e^{2a_2(d^{i+1}-\iota)}$.

Using (16) and (29), it follows from (41) that

$$\mathscr{Q}_1 \geq \frac{\mathscr{G}}{\mu_2}\sum_{i=0}^{n-2}V_1(d^i + d^i_{off}) + \frac{1}{\mu_2}e^{2a_1(t-d^{n-1})}V_1(t) - \frac{1}{\mu_2}V_1(0) \geq 0 \tag{42}$$

where $\mathscr{G} = e^{2a_1d^s_{off}} - e^{2a_2d^m_{on}+2(a_1+a_2)h+ln(\mu_1\mu_2)} > 0$.

Similarly, when $t \in \mathscr{T}_{2,n}$, we have

$$\begin{aligned}\mathscr{Q}_2 =& \sum_{i=0}^{n-1}\int_{d^i}^{d^i+d^i_{off}} \tau_i^1(\iota)[\dot{V}_1(\iota)+2a_1V_1(\iota)]d\iota + \sum_{i=0}^{n-2}\int_{d^i+d^i_{off}}^{d^{i+1}} \tau_i^2(\iota)[\dot{V}_2(\iota)-2a_2V_2(\iota)]d\iota \\ &+ \int_{d^{n-1}+d^{n-1}_{off}}^{t} \tau_{n-1}^2(\iota)[\dot{V}_2(\iota)-2a_2V_2(\iota)]d\iota \\ \geq& \frac{\mathscr{G}}{\mu_2}\sum_{i=0}^{n-1} V_1(d^i+d^i_{off}) + e^{2a_2(d^n-t)}V_2(t) - \frac{1}{\mu_2}V_1(0) \geq 0\end{aligned} \tag{43}$$

Using (39)-(43), we have

$$\int_0^t \mathscr{P}(\gamma^2\omega^T(t)\omega(t) - z^T(t)z(t))d\iota \geq \mathscr{Q}_\zeta \geq 0,\ \forall\ t \in \mathscr{T}_{\varsigma,n}, \varsigma = 1,2 \tag{44}$$

where $\mathscr{P} = max\{\tau_i^1(\iota), \tau_i^2(\iota)\} = max\{e^{2a_1 d^m_{off}}/\mu_2, e^{2a_2 d^m_{on}}\}$, $d^m_{off} = max\{d^n_{off}\}$ refers to the maximum continuous sleeping interval of attacks. Using (44), we have $\|z(t)\| \leq \gamma\|\omega(t)\|$, which guarantees the H_∞ performance. The proof is thus completed.

□

In Theorem 3.2, the gain matrices $K_j (j = 1, 2)$ of the ETFIC controller (9) are coupled with the matrix P_1 of the LKF (18), which makes it difficult to directly compute K_j. Thus, Section 4 will provide the controller design method.

4. Co-design of the ETFIC controller and the dynamic ETM

Lemma 4.1. (**?**) For given matrices $\Theta > 0$ and W satisfying $W^T = W$, there exists $\epsilon > 0$ such that

$$-W\Theta^{-1}W \leq \epsilon^2\Theta - 2\epsilon W \tag{45}$$

Theorem 4.2. For given sampling period $h > 0$, the DETM parameter $\delta \geq 0$, DoS attacks parameters $d^m_{on} > 0$, $d^s_{off} > 0$, noise parameter $\gamma > 0$, scalars $a_1 > 0, a_2 > 0$, and β_j satisfying $\bar{\eta}_j \geq \beta_j\eta_j (j = 1, 2)$, if there exist positive definite matrices $X_i, \bar{Q}_i, \bar{R}_i, \bar{S}_i (i = 1, 2), \bar{\Phi} > 0$, symmetric matrices $\bar{\Gamma}^1, \bar{\Gamma}^2$, matrices $\bar{G}_i, \bar{W}_i (i = 1, 2)$ satisfying $\begin{bmatrix}\bar{R}_i & * \\ \bar{G}_i & \bar{R}_i\end{bmatrix} > 0$, $\begin{bmatrix}\bar{S}_i & * \\ \bar{W}_i & \bar{S}_i\end{bmatrix} > 0$, (16) and

$$\bar{\Xi}^{ij\theta} - \bar{\Gamma}^i < 0,\ 1 \leq i, j \leq 2, \theta = 2, 3 \tag{46}$$

$$\beta_i(\bar{\Xi}^{ii\theta} - \bar{\Gamma}^i) + \bar{\Gamma}^i < 0,\ i = 1, 2, \theta = 2, 3 \tag{47}$$

$$\beta_j(\bar{\Xi}^{ij\theta} - \bar{\Gamma}^i) + \beta_i(\bar{\Xi}^{ji\theta} - \bar{\Gamma}^j) + \bar{\Gamma}^i + \bar{\Gamma}^j < 0, 1 \leq i < j \leq 2, \theta = 2, 3 \tag{48}$$

$$\bar{\Pi}^{i\theta} < 0,\ i = 1, 2, \theta = 2, 3 \tag{49}$$

$$\begin{cases}\begin{bmatrix}-\mu_2 X_2 & * \\ X_2 & -X_1\end{bmatrix}\le 0,\begin{bmatrix}-e^{2(a_1+a_2)h}\mu_1 X_1 & * \\ X_1 & -X_2\end{bmatrix}\le 0\\ \begin{bmatrix}-\mu_2\bar{Q}_2 & * \\ X_2 & \varepsilon_1^2\bar{Q}_1-2\varepsilon_1 X_1\end{bmatrix}\le 0,\begin{bmatrix}-\mu_1\bar{Q}_1 & * \\ X_1 & \varepsilon_2^2\bar{Q}_2-2\varepsilon_2 X_2\end{bmatrix}\le 0\\ \begin{bmatrix}-\mu_2\bar{R}_2 & * \\ X_2 & \varepsilon_3^2\bar{R}_1-2\varepsilon_3 X_1\end{bmatrix}\le 0,\begin{bmatrix}-\mu_1\bar{R}_1 & * \\ X_1 & \varepsilon_4^2\bar{R}_2-2\varepsilon_4 X_2\end{bmatrix}\le 0\\ \begin{bmatrix}-\mu_2\bar{S}_2 & * \\ X_2 & \varepsilon_5^2\bar{S}_1-2\varepsilon_5 X_1\end{bmatrix}\le 0,\begin{bmatrix}-\mu_1\bar{S}_1 & * \\ X_1 & \varepsilon_6^2\bar{S}_2-2\varepsilon_6 X_2\end{bmatrix}\le 0\end{cases}\tag{50}$$

where

$$\bar{\Xi}^{ij\theta}=\begin{bmatrix}\bar{\Xi}_{11}^{ij\theta} & * & * & * & * \\ \bar{\Xi}_{21}^{ij} & \bar{\Xi}_{22} & * & * & * \\ \bar{\Xi}_{31}^{ij} & 0 & \bar{\Xi}_{33} & * & * \\ \bar{\Xi}_{41} & 0 & 0 & \bar{\Xi}_{44} & * \\ \bar{\Xi}_{51}^{ij} & 0 & 0 & 0 & \bar{\Xi}_{55}\end{bmatrix},\ \bar{\Pi}^{i\theta}=\begin{bmatrix}\bar{\Pi}_{11}^{i\theta} & * & * & * \\ \bar{\Pi}_{21}^{i} & \bar{\Pi}_{22} & * & * \\ \bar{\Pi}_{31}^{i} & 0 & \bar{\Pi}_{33} & * \\ \bar{\Pi}_{41}^{i} & 0 & 0 & \bar{\Pi}_{44}\end{bmatrix}\tag{51}$$

with
$\bar{\Xi}_{11}^{ij\theta}=2a_1\mathscr{I}_1^T X_1\mathscr{I}_1+He\{\mathscr{I}_1^T(A_iX_1\mathscr{I}_1+B_{es}Y_j(\mathscr{I}_2+\mathscr{I}_5)+B_{\omega i}\mathscr{I}_6)\}$
$+\mathscr{I}_1^T\bar{Q}_1\mathscr{I}_1-e^{-2a_1h}\mathscr{I}_4^T\bar{Q}_1\mathscr{I}_4-(3-\theta)e^{-a_1h}(\mathscr{I}_1-\mathscr{I}_2)^T\bar{R}_1(\mathscr{I}_1-\mathscr{I}_2)$
$-(3-\theta)e^{-a_1h}(\mathscr{I}_2-\mathscr{I}_3)^T\bar{R}_1(\mathscr{I}_2-\mathscr{I}_3)-(3-\theta)e^{-a_1h}He((\mathscr{I}_2-\mathscr{I}_3)^T\bar{G}_1(\mathscr{I}_1-\mathscr{I}_2))$
$-(3-\theta)e^{-2a_1h}(\mathscr{I}_3-\mathscr{I}_4)^T\bar{S}_1(\mathscr{I}_3-\mathscr{I}_4)-(\theta-2)e^{-2a_1h}(\mathscr{I}_3-\mathscr{I}_2)^T\bar{S}_1(\mathscr{I}_3-\mathscr{I}_2)$
$-(\theta-2)e^{-2a_1h}(\mathscr{I}_2-\mathscr{I}_4)^T\bar{S}_1(\mathscr{I}_2-\mathscr{I}_4)-(\theta-2)e^{-2a_1h}He((\mathscr{I}_2-\mathscr{I}_4)^T\bar{W}_1(\mathscr{I}_3-\mathscr{I}_2))$
$-(\theta-2)e^{-a_1h}(\mathscr{I}_1-\mathscr{I}_3)^T\bar{R}_1(\mathscr{I}_1-\mathscr{I}_3)-\mathscr{I}_5^T\bar{\Phi}\mathscr{I}_5-\gamma^2\mathscr{I}_6^T\mathscr{I}_6$,
$\bar{\Xi}_{21}^{ij}=0.5h(A_iX_1\mathscr{I}_1+B_{es}Y_j(\mathscr{I}_2+\mathscr{I}_5)+B_{\omega i}\mathscr{I}_6)$, $\bar{\Xi}_{22}=\varepsilon_7^2R_1-2\varepsilon_7X_1$,
$\bar{\Xi}_{31}^{ij}=0.5h(A_iX_1\mathscr{I}_1+B_{es}Y_j(\mathscr{I}_2+\mathscr{I}_5)+B_{\omega i}\mathscr{I}_6)$, $\bar{\Xi}_{33}=\varepsilon_8^2S_1-2\varepsilon_8X_1$,
$\bar{\Xi}_{41}=h^{0.5}X_1(\mathscr{I}_2+\mathscr{I}_5)$, $\bar{\Xi}_{44}=\varepsilon_9^2\Phi-2\varepsilon_9X_1$,
$\bar{\Xi}_{51}^{ij}=F_iX_1\mathscr{I}_1+H_iY_j(\mathscr{I}_2+\mathscr{I}_5)$, $\bar{\Xi}_{55}=-I$,
$\bar{\Pi}_{11}^{i\theta}=-2a_2\bar{\mathscr{I}}_1^TX_2\bar{\mathscr{I}}_1+He\{\bar{\mathscr{I}}_1^T(A_iX_2\bar{\mathscr{I}}_1+B_{\omega i}\mathscr{I}_5)\}$
$+\bar{\mathscr{I}}_1^T\bar{Q}_2\bar{\mathscr{I}}_1-e^{2a_2h}\bar{\mathscr{I}}_4^T\bar{Q}_2\bar{\mathscr{I}}_4-(3-\theta)(\bar{\mathscr{I}}_1-\bar{\mathscr{I}}_2)^T\bar{R}_2(\bar{\mathscr{I}}_1-\bar{\mathscr{I}}_2)$
$-(3-\theta)(\bar{\mathscr{I}}_2-\bar{\mathscr{I}}_3)^T\bar{R}_2(\bar{\mathscr{I}}_2-\bar{\mathscr{I}}_3)-(3-\theta)He((\bar{\mathscr{I}}_2-\bar{\mathscr{I}}_3)^T\bar{G}_2(\bar{\mathscr{I}}_1-\bar{\mathscr{I}}_2))$
$-(3-\theta)e^{a_2h}(\bar{\mathscr{I}}_3-\bar{\mathscr{I}}_4)^T\bar{S}_2(\bar{\mathscr{I}}_3-\bar{\mathscr{I}}_4)-(\theta-2)e^{a_2h}(\bar{\mathscr{I}}_3-\bar{\mathscr{I}}_2)^T\bar{S}_2(\bar{\mathscr{I}}_3-\bar{\mathscr{I}}_2)$
$-(\theta-2)e^{a_2h}(\bar{\mathscr{I}}_2-\bar{\mathscr{I}}_4)^T\bar{S}_2(\bar{\mathscr{I}}_2-\bar{\mathscr{I}}_4)-(\theta-2)e^{a_2h}He((\bar{\mathscr{I}}_2-\bar{\mathscr{I}}_4)^T\bar{W}_2(\bar{\mathscr{I}}_3-\bar{\mathscr{I}}_2))$
$-(\theta-2)(\bar{\mathscr{I}}_1-\bar{\mathscr{I}}_3)^T\bar{R}_2(\bar{\mathscr{I}}_1-\bar{\mathscr{I}}_3)-\gamma^2\bar{\mathscr{I}}_5^T\bar{\mathscr{I}}_5$,
$\bar{\Pi}_{21}^{i}=0.5h(A_iX_2\bar{\mathscr{I}}_1+B_{\omega i}\mathscr{I}_5)$, $\bar{\Pi}_{22}=\varepsilon_{10}^2R_2-2\varepsilon_{10}X_2$,
$\bar{\Pi}_{31}^{i}=0.5h(A_iX_2\bar{\mathscr{I}}_1+B_{\omega i}\mathscr{I}_5)$, $\bar{\Pi}_{33}=\varepsilon_{11}^2S_2-2\varepsilon_{11}X_2$, $\bar{\Pi}_{41}^{i}=F_iX_2\mathscr{I}_1$, $\bar{\Pi}_{44}=-I$,
$\bar{Q}_i=X_iQ_iX_i$, $\bar{R}_i=X_iR_iX_i$, $\bar{S}_i=X_iS_iX_i$, $\bar{G}_i=X_iG_iX_i$, $\bar{W}_i=X_iW_iX_i$,
$\bar{\Gamma}_i=diag\{X_1,X_1,X_1,X_1,X_1,I\}\Gamma_i diag\{X_1,X_1,X_1,X_1,X_1,I\}(i=1,2)$,
$Y_j=K_jX_1(j=1,2)$, $\bar{\Phi}=X_1\Phi X_1$,
$\mathscr{I}_i=[\underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{6-i}](i=1,\dots,6)$, $\bar{\mathscr{I}}_i=[\underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{5-i}](i=1,\dots,5)$,
then, the DC microgrid system (10) under the dynamic ETM, DoS attacks, noises and premise mismatching is exponentially stable with guaranteed H_∞ performance. Besides, parameters of the controller (9) and the ETM (5) can be obtained as $K_j=Y_jX_1^{-1}(j=1,2)$ and $\Phi=X_1^{-1}\bar{\Phi}X_1^{-1}$, respectively.

Proof. Define the following matrices

$$\begin{cases} X_1 = P_1^{-1}, \mathscr{L}_1 = diag\{X_1, X_1\}, \mathscr{R}_1 = diag\{X_1, X_1, X_1, X_1, X_1, I, I, I, I, I\} \\ X_2 = P_2^{-1}, \mathscr{L}_2 = diag\{X_2, X_2\}, \mathscr{R}_2 = diag\{X_2, X_2, X_2, X_2, I, I, I, I\} \end{cases} \tag{52}$$

Using (52), transform the conditions in Theorem 3.2 as

$$\begin{bmatrix} \bar{R}_i & * \\ \bar{G}_i & \bar{R}_i \end{bmatrix} = \mathscr{L}_i^T \begin{bmatrix} R_i & * \\ G_i & R_i \end{bmatrix} \mathscr{L}_i > 0, i = 1, 2 \tag{53}$$

$$\begin{bmatrix} \bar{S}_i & * \\ \bar{W}_i & \bar{S}_i \end{bmatrix} = \mathscr{L}_i^T \begin{bmatrix} S_i & * \\ W_i & S_i \end{bmatrix} \mathscr{L}_i > 0, i = 1, 2 \tag{54}$$

$$\check{\Xi}^{ij\theta} - \bar{\Gamma}^i = \mathscr{R}_1^T (\Xi^{ij\theta} - \Gamma^i) \mathscr{R}_1 < 0, \ 1 \le i, j \le 2, \theta = 2, 3 \tag{55}$$

$$\check{\Pi}^{i\theta} = \mathscr{R}_2^T \Pi^{i\theta} \mathscr{R}_2 < 0, \ i = 1, 2, \theta = 2, 3 \tag{56}$$

$$\begin{cases} X_2 P_1 X_2 \le \mu_2 X_2 P_2 X_2, \ X_1 P_2 X_1 \le e^{2(a_1+a_2)h} \mu_1 X_1 P_1 X_1 \\ X_2 Q_1 X_2 \le \mu_2 X_2 Q_2 X_2, \ X_1 Q_2 X_1 \le \mu_1 X_1 Q_1 X_1 \\ X_2 R_1 X_2 \le \mu_2 X_2 R_2 X_2, \ X_1 R_2 X_1 \le \mu_1 X_1 R_1 X_1 \\ X_2 S_1 X_2 \le \mu_2 X_2 S_2 X_2, \ X_1 S_2 X_1 \le \mu_1 X_1 S_1 X_1 \end{cases} \tag{57}$$

where

$$\check{\Xi}^{ij\theta} = \begin{bmatrix} \bar{\Xi}_{11}^{ij\theta} & * & * & * & * \\ \bar{\Xi}_{21}^{ij} & \check{\Xi}_{22} & * & * & * \\ \bar{\Xi}_{31}^{ij} & 0 & \check{\Xi}_{33} & * & * \\ \bar{\Xi}_{41} & 0 & 0 & \check{\Xi}_{44} & * \\ \bar{\Xi}_{51}^{ij} & 0 & 0 & 0 & \bar{\Xi}_{55} \end{bmatrix}, \ \check{\Pi}^{i\theta} = \begin{bmatrix} \bar{\Pi}_{11}^{i\theta} & * & * & * \\ \bar{\Pi}_{21}^{i} & \check{\Pi}_{22} & * & * \\ \bar{\Pi}_{31}^{i} & 0 & \check{\Pi}_{33} & * \\ \bar{\Pi}_{41}^{i} & 0 & 0 & \bar{\Pi}_{44} \end{bmatrix} \tag{58}$$

Applying lemma 4.1 and Schur complement lemma to (57) and (58), the conditions (50) and (51) can be obtained. The proof is thus completed.

□

Specially, without considering effects of DoS attacks and noises, the closed-loop system model (10) can be rewritten as

$$\dot{\bar{x}}(t) = \sum_{i=1}^{2} \sum_{j=1}^{2} \eta_i \bar{\eta}_j \{A_i \bar{x}(t) + B_{es} K_j [\bar{x}(t - \phi_{k,n}(t)) + \epsilon_{k,n}(t)]\} \tag{59}$$

In this case, the ETM (5) changes into

$$\begin{cases} d_{k+1,n} h = d_{k,n} h + min_{j \in \mathbb{N}} \{jh | \mathscr{C} > 0\} \\ \mathscr{C} = \|\Phi^{\frac{1}{2}} (\bar{x}(d_{k,n} h + jh) - \bar{x}(d_k h))\|^2 - \delta \|\Phi^{\frac{1}{2}} \bar{x}(d_k h)\|^2 \end{cases} \tag{60}$$

Corollary 4.3. For given sampling period $h > 0$, the ETM parameter $\delta \ge 0$, scalars $a_1 > 0, a_2 > 0$, and β_j satisfying $\bar{\eta}_j \ge \beta_j \eta_j (j = 1, 2)$, if there exist positive definite matrices $X_i, \bar{Q}_i, \bar{R}_i, \bar{S}_i (i = 1, 2), \bar{\Phi} > 0$, symmetric matrices $\tilde{\Gamma}^1, \tilde{\Gamma}^2$, matrices $\bar{G}_i, \bar{W}_i (i =$

$1,2)$ satisfying $\begin{bmatrix} \bar{R}_i & * \\ \bar{G}_i & \bar{R}_i \end{bmatrix} > 0$, $\begin{bmatrix} \bar{S}_i & * \\ \bar{W}_i & \bar{S}_i \end{bmatrix} > 0$, and

$$\tilde{\Xi}^{ij\theta} - \tilde{\Gamma}^i < 0,\ 1 \le i, j \le 2, \theta = 2,3 \tag{61}$$

$$\beta_i(\tilde{\Xi}^{ii\theta} - \tilde{\Gamma}^i) + \tilde{\Gamma}^i < 0,\ i = 1,2, \theta = 2,3 \tag{62}$$

$$\beta_j(\tilde{\Xi}^{ij\theta} - \tilde{\Gamma}^i) + \beta_i(\tilde{\Xi}^{ji\theta} - \tilde{\Gamma}^j) + \tilde{\Gamma}^i + \tilde{\Gamma}^j < 0, 1 \le i < j \le 2, \theta = 2,3 \tag{63}$$

where

$$\tilde{\Xi}^{ij\theta} = \begin{bmatrix} \tilde{\Xi}_{11}^{ij\theta} & * & * & * \\ \tilde{\Xi}_{21}^{ij} & \tilde{\Xi}_{22} & * & * \\ \tilde{\Xi}_{31}^{ij} & 0 & \tilde{\Xi}_{33} & * \\ \tilde{\Xi}_{41} & 0 & 0 & \tilde{\Xi}_{44} \end{bmatrix}$$

with
$\tilde{\Xi}_{11}^{ij\theta} = 2a_1\mathscr{I}_1^T X_1 \mathscr{I}_1 + He\{\mathscr{I}_1^T(A_i X_1 \mathscr{I}_1 + B_{es} Y_j(\mathscr{I}_2 + \mathscr{I}_5)\}$
$+ \mathscr{I}_1^T \bar{Q}_1 \mathscr{I}_1 - e^{-2a_1 h}\mathscr{I}_4^T \bar{Q}_1 \mathscr{I}_4 - (3-\theta)e^{-a_1 h}(\mathscr{I}_1 - \mathscr{I}_2)^T \bar{R}_1(\mathscr{I}_1 - \mathscr{I}_2)$
$- (3-\theta)e^{-a_1 h}(\mathscr{I}_2 - \mathscr{I}_3)^T \bar{R}_1(\mathscr{I}_2 - \mathscr{I}_3) - (3-\theta)e^{-a_1 h} He((\mathscr{I}_2 - \mathscr{I}_3)^T \bar{G}_1(\mathscr{I}_1 - \mathscr{I}_2))$
$- (3-\theta)e^{-2a_1 h}(\mathscr{I}_3 - \mathscr{I}_4)^T \bar{S}_1(\mathscr{I}_3 - \mathscr{I}_4) - (\theta-2)e^{-2a_1 h}(\mathscr{I}_3 - \mathscr{I}_2)^T \bar{S}_1(\mathscr{I}_3 - \mathscr{I}_2)$
$- (\theta-2)e^{-2a_1 h}(\mathscr{I}_2 - \mathscr{I}_4)^T \bar{S}_1(\mathscr{I}_2 - \mathscr{I}_4) - (\theta-2)e^{-2a_1 h} He((\mathscr{I}_2 - \mathscr{I}_4)^T \bar{W}_1(\mathscr{I}_3 - \mathscr{I}_2))$
$- (\theta-2)e^{-a_1 h}(\mathscr{I}_1 - \mathscr{I}_3)^T \bar{R}_1(\mathscr{I}_1 - \mathscr{I}_3) - \mathscr{I}_5^T \bar{\Phi} \mathscr{I}_5$,
$\tilde{\Xi}_{21}^{ij} = 0.5h(A_i X_1 \mathscr{I}_1 + B_{es} Y_j(\mathscr{I}_2 + \mathscr{I}_5)$, $\tilde{\Xi}_{22} = \varepsilon_7^2 R_1 - 2\varepsilon_7 X_1$,
$\tilde{\Xi}_{31}^{ij} = 0.5h(A_i X_1 \mathscr{I}_1 + B_{es} Y_j(\mathscr{I}_2 + \mathscr{I}_5))$, $\tilde{\Xi}_{33} = \varepsilon_8^2 S_1 - 2\varepsilon_8 X_1$,
$\tilde{\Xi}_{41} = h^{0.5} X_1(\mathscr{I}_2 + \mathscr{I}_5)$, $\tilde{\Xi}_{44} = \varepsilon_9^2 \Phi - 2\varepsilon_9 X_1$,
$\tilde{\Gamma}_i = diag\{X_1, X_1, X_1, X_1, X_1\}\Gamma_i diag\{X_1, X_1, X_1, X_1, X_1\}(i = 1,2)$,
$\mathscr{I}_i = [\ \underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{5-i}\ ](i = 1, \dots, 5)$,
then, the DC microgrid system (59) under the dynamic ETM (60) and premise mismatching is exponentially stable.

Proof. The proof is similar as that of Theorem 4.2, which is omitted here.

□

Remark 4. Theorem 4.2 and Corollary 4.3 provide the co-design framework to compute gain matrices $K_j = Y_j X^{-1}$ of the ETFIC controller (9) and parameter $\Phi = X^{-1}\bar{\Phi}X^{-1}$ of the DETM, which is more convenient than the two-step emulation method (**?**) (i.e., a controller is first designed without considering the ETM, then the ETM is designed using the given controller).

The work (**?**) describes the DC microgrid (1) as Lur'e problem, and handles the CPL-induced nonlinear term $H(\bar{x}(t))$ as disturbances satisfying

$$H^T(\bar{x}(t))H(\bar{x}(t)) \le a^2 \bar{x}^T(t) M^T M \bar{x}(t) \tag{64}$$

where $a > 0$ is robustness index and the matrix M is given as

$$M = \begin{bmatrix} M_1 & \dots & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 0 & \dots & M_Q & 0 \\ 0 & \dots & 0 & 0 \end{bmatrix}, M_i = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \tag{65}$$

Considering effects of DoS attacks (3), design a controller under periodic sampling mechanism as

$$\bar{i}_{es}(t) = \begin{cases} K\bar{x}(t - \bar{\phi}_k(t)),\ t \in \mathscr{T}_{1,n} \\ 0,\ t \in \mathscr{T}_{2,n} \end{cases} \tag{66}$$

where $\bar{\phi}_k(t) = t - kh$, $\bar{x}(t - \bar{\phi}_k(t))$ refers to $\bar{x}(kh)$, and K is gain matrix.

Using DC microgrid (1) and controller (66), the closed-loop system model is presented as

$$\begin{cases} \dot{\bar{x}}(t) = \bar{A}\bar{x}(t) - DH(\bar{x}(t)) + B_{es}K\bar{x}(t - \bar{\phi}_k(t)),\ t \in \mathscr{T}_{1,n} \\ \dot{\bar{x}}(t) = \bar{A}\bar{x}(t) - DH(\bar{x}(t)),\ t \in \mathscr{T}_{2,n} \end{cases} \tag{67}$$

Theorem 4.4. For given sampling period $h > 0$, DoS attacks parameters $d_{on}^m > 0$, $d_{off}^s > 0$, scalars $a_1 > 0, a_2 > 0$, if there exist positive definite matrices $P_i, Q_i, R_i, S_i (i = 1, 2)$, matrices $G_i, W_i (i = 1, 2)$ satisfying $\begin{bmatrix} R_i & * \\ G_i & R_i \end{bmatrix} > 0$, $\begin{bmatrix} S_i & * \\ W_i & S_i \end{bmatrix} > 0$ and

$$\begin{bmatrix} \Upsilon_{11}^{\theta} & * & * & * \\ \Upsilon_{21} & \Upsilon_{22} & * & * \\ \Upsilon_{31} & 0 & \Upsilon_{33} & * \\ \Upsilon_{41} & 0 & 0 & \Upsilon_{44} \end{bmatrix} < 0,\ \theta = 2, 3 \tag{68}$$

$$\begin{bmatrix} \Psi_{11}^{\theta} & * & * & * \\ \Psi_{21} & \Psi_{22} & * & * \\ \Psi_{31} & 0 & \Psi_{33} & * \\ \Psi_{41} & 0 & 0 & \Psi_{44} \end{bmatrix} < 0,\ \theta = 2, 3 \tag{69}$$

$$\begin{cases} P_1 \le \mu_2 P_2, P_2 \le e^{2(a_1+a_2)h}\mu_1 P_1, Q_1 \le \mu_2 Q_2, Q_2 \le \mu_1 Q_1 \\ R_1 \le \mu_2 R_2, R_2 \le \mu_1 R_1, S_1 \le \mu_2 S_2, S_2 \le \mu_1 S_1 \end{cases} \tag{70}$$

$$\varrho = (2a_1 d_{off}^s - 2a_2 d_{on}^m - ln(\mu_1\mu_2) - 2(a_1 + a_2)h)/\sigma > 0 \tag{71}$$

where

$\Upsilon_{11}^{\theta} = 2a_1 \mathscr{I}_1^T P_1 \mathscr{I}_1 + He\{\mathscr{I}_1^T P_1(\bar{A}\mathscr{I}_1 - D\mathscr{I}_5 + B_{es}K\mathscr{I}_2)\}$
$+ \mathscr{I}_1^T Q_1 \mathscr{I}_1 - e^{-2a_1 h}\mathscr{I}_4^T Q_1 \mathscr{I}_4 - (3-\theta)e^{-a_1 h}(\mathscr{I}_1 - \mathscr{I}_2)^T R_1(\mathscr{I}_1 - \mathscr{I}_2)$
$- (3-\theta)e^{-a_1 h}(\mathscr{I}_2 - \mathscr{I}_3)^T R_1(\mathscr{I}_2 - \mathscr{I}_3) - (3-\theta)e^{-a_1 h}He((\mathscr{I}_2 - \mathscr{I}_3)^T G_1(\mathscr{I}_1 - \mathscr{I}_2))$
$- (3-\theta)e^{-2a_1 h}(\mathscr{I}_3 - \mathscr{I}_4)^T S_1(\mathscr{I}_3 - \mathscr{I}_4) - (\theta-2)e^{-2a_1 h}(\mathscr{I}_3 - \mathscr{I}_2)^T S_1(\mathscr{I}_3 - \mathscr{I}_2)$
$- (\theta-2)e^{-2a_1 h}(\mathscr{I}_2 - \mathscr{I}_4)^T S_1(\mathscr{I}_2 - \mathscr{I}_4) - (\theta-2)e^{-2a_1 h}He((\mathscr{I}_2 - \mathscr{I}_4)^T W_1(\mathscr{I}_3 - \mathscr{I}_2))$
$- (\theta-2)e^{-a_1 h}(\mathscr{I}_1 - \mathscr{I}_3)^T R_1(\mathscr{I}_1 - \mathscr{I}_3) - \mathscr{I}_5^T \mathscr{I}_5,$
$\Upsilon_{21} = 0.5h(\bar{A}\mathscr{I}_1 - D\mathscr{I}_5 + B_{es}K\mathscr{I}_2)$, $\Upsilon_{22} = -R_1^{-1}$,
$\Upsilon_{31} = 0.5h(\bar{A}\mathscr{I}_1 - D\mathscr{I}_5 + B_{es}K\mathscr{I}_2)$, $\Upsilon_{33} = -S_1^{-1}$, $\Upsilon_{41} = M\mathscr{I}_1$, $\Upsilon_{44} = -a^{-2}$,

$\Psi_{11}^{\theta} = -2a_2\bar{\mathscr{I}}_1^T P_2\bar{\mathscr{I}}_1 + He\{\bar{\mathscr{I}}_1^T P_2(\bar{A}\bar{\mathscr{I}}_1 - D\bar{\mathscr{I}}_5)\}$
$+ \bar{\mathscr{I}}_1^T Q_2\bar{\mathscr{I}}_1 - e^{2a_2h}\bar{\mathscr{I}}_4^T Q_2\bar{\mathscr{I}}_4 - (3-\theta)(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2)^T R_2(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2)$
$- (3-\theta)(\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3)^T R_2(\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3) - (3-\theta)He((\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_3)^T G_2(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_2))$
$- (3-\theta)e^{a_2h}(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_4)^T S_2(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_4) - (\theta-2)e^{a_2h}(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2)^T S_2(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2)$
$- (\theta-2)e^{a_2h}(\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4)^T S_2(\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4) - (\theta-2)e^{a_2h}He((\bar{\mathscr{I}}_2 - \bar{\mathscr{I}}_4)^T W_2(\bar{\mathscr{I}}_3 - \bar{\mathscr{I}}_2))$
$- (\theta-2)(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_3)^T R_2(\bar{\mathscr{I}}_1 - \bar{\mathscr{I}}_3)$,
$\Psi_{21} = 0.5h(\bar{A}\bar{\mathscr{I}}_1 - D\bar{\mathscr{I}}_5)$, $\Psi_{22} = -R_2^{-1}$,
$\Psi_{31} = 0.5h(\bar{A}\bar{\mathscr{I}}_1 - D\bar{\mathscr{I}}_5)$, $\Psi_{33} = -S_2^{-1}$, $\Psi_{41} = M\bar{\mathscr{I}}_1$, $\Psi_{44} = -a^{-2}$,
$\mathscr{I}_i = [\ \underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{5-i}\ ](i = 1, \dots, 5)$, $\bar{\mathscr{I}}_i = [\ \underbrace{0\ \dots\ 0}_{i-1}\ I\ \underbrace{0\ \dots\ 0}_{5-i}\ ](i = 1, \dots, 5)$,
then, the DC microgrid system (67) under DoS attacks is exponentially stable.

Proof. Define the augmented vector as $\zeta(t) = col\{\bar{x}(t), \bar{x}(t - \bar{\phi}_k(t)), \bar{x}(t - 0.5h), \bar{x}(t-h), H(\bar{x}(t))\}$. The proof is similar as Theorem 3.1, which is omitted here. □

5. Case studies

5.1. DC microgrid with one CPL

Table 1. DC microgrid with one CPL.

r_1	1.1 Ω	P_1	300 W	L_s	34mH
L_1	34 mH	$v_{C_0,1}$	196.64 V	C_s	500 μF
C_1	500 μF	r_s	1.1 Ω	V_{dc}	200 V

To verify the proposed method, the DC microgrid with parameters in Table 1 is introduced. Other parameters are set as: DoS attacks parameters $d_{off}^s = 0.021s, d_{on}^m = 0.03s$, the DETM parameters $\delta_s = 0.1$, $g_1 = 0.0001, g_2 = 0.001$, noise parameters $\omega(t) = 3e^{-t}sin(2\pi 100t)$, $\gamma = 3$, premise-mismatching scalars $\beta_1 = 0.9, \beta_2 = 0.02$, sampling period $h = 0.5ms$, $B_{\omega i} = col\{0.1, 0.1, 0.1, 0.1\}$, $F_i = col\{0, 0.1, 0, 0\}$, $H_i = 0.1$, $\mu_1 = \mu_2 = 1.01$, $a_1 = 0.8, a_2 = 0.2$, and the initial states $\bar{x}_0 = col\{19, -30, 19, -30\}$.

Using Theorem 3.2 and Theorem 4.2, parameters of the ETFIC controller (9) and the dynamic ETM (5) are obtained as

$$\begin{cases} K_1 = \begin{bmatrix} 0.2230 & 0.0925 & 0.2483 & 0.2178 \end{bmatrix} \\ K_2 = \begin{bmatrix} 0.1805 & 0.1234 & 0.1579 & 0.2165 \end{bmatrix} \end{cases} \tag{72}$$

$$\Phi = \begin{bmatrix} 1625.2 & 641.9 & 1212.3 & 1300.1 \\ 641.9 & 381.3 & 675.2 & 722.5 \\ 1212.3 & 675.2 & 2071.3 & 1403.7 \\ 1300.1 & 722.5 & 1403.7 & 1471.2 \end{bmatrix} \tag{73}$$

As shown in Figure 2, considering effects of the DETM, DoS attacks and noises, the designed controller (72) with mismatched premises can stabilize the microgrid system, where the voltage $v_{C,1}$ and current $i_{L,1}$ arrive at their equilibrium points $196.64V$ and $1.526A$, respectively. As for the noise effect, the obtained $\bar{\gamma} = \|z(t)\|/\|\omega(t)\| = 1.1$ satisfies $\bar{\gamma} < \gamma = 3$, and thus the H_∞ performance is guaranteed. The grey bands denote the attack-active intervals including $[0.022s, 0.032s)$, $[0.053s, 0.075s)$, $[0.097s, 0.112s)$,

$[0.133s, 0.163s)$, $[0.186s, 0.194s)$, $[0.216s, 0.241s)$ and $[0.262s, 0.275s)$.

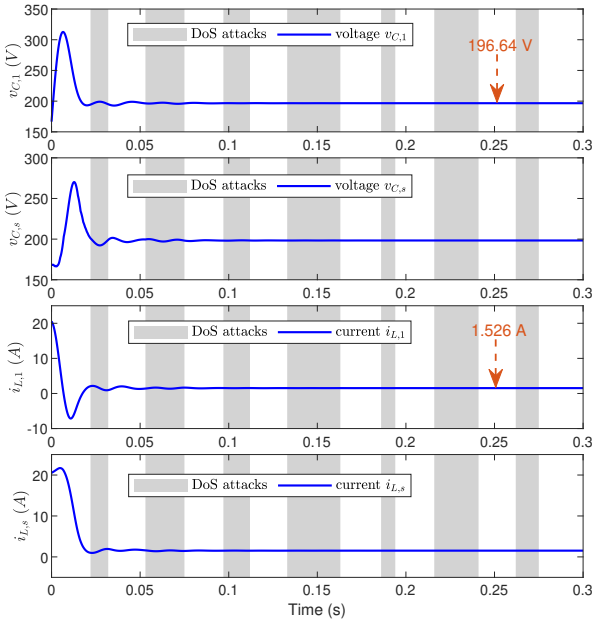

Figure 2. State response of the DC microgrid.

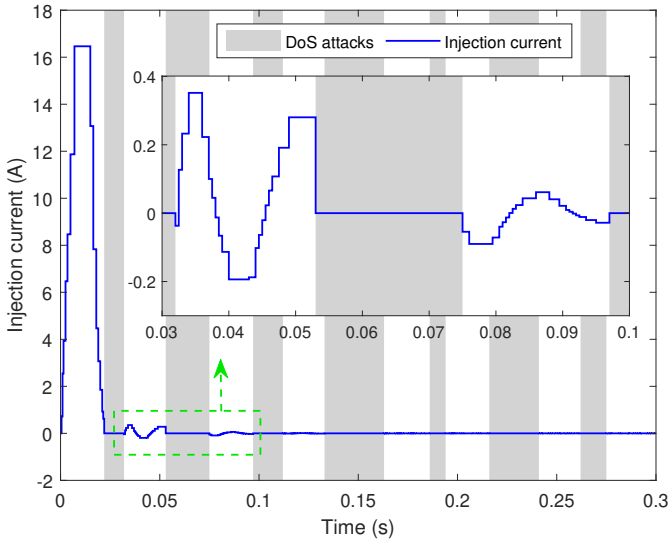

Figure 3. The injection current $\bar{i}_{es}$.

As shown in Figure 1, control signals are affected by DoS attacks. Figure 3 presents the injection current i_{es} governed by the event-driven controller. During the attack-sleeping intervals, the injection current holds in each event-triggering interval. During the attack-active intervals, control signals are blocked and the injection current becomes zero.

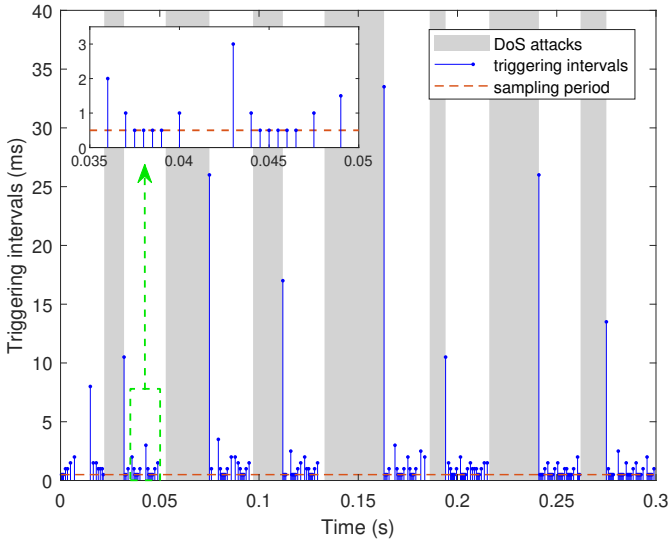

Figure 4. Triggering intervals and triggering instants of the ETM.

Figure 4 shows the triggering intervals and triggering instants of the DETM. The largest and average triggering intervals are $33.5ms$ and $1.6ms$, respectively, which are larger than the sampling period $0.5ms$. Thus, communication resources can be saved. The minimum triggering interval equals to the sampling period, which excludes the Zeno behavior. At the beginning of each attack-sleeping interval (i.e., $0.032s$, $0.075s$, $0.112s$, $0.163s$, $0.194s$, $0.241s$, $0.275s$), an event is triggered, which ensures at least one data transmission during each attack-sleeping interval. During the attack-active intervals, no event is triggered, and thus the attack-induced dropouts are avoided.

5.2. Comparison with the method in (?)

For the DC microgrid in Table 1 with $L_1 = L_s = 9mH$, without considering effects of the DETM, DoS attacks and noises, the work (**?**) presents a fuzzy controller with gain matrices $K_1 = [20.3262\ 1.7109\ -0.7600\ 0.3251]$ and $K_2 = [20.3035\ 1.6932\ -0.7363\ 0.3241]$. On the other hand, considering effects of the DETM, DoS attacks and noises, the Theorem 3.2 and Theorem 4.2 compute gain matrices of the proposed controller (9) as

$$\begin{cases} K_1 = \begin{bmatrix} 0.0051 & 0.0033 & -0.0120 & 0.2462 \end{bmatrix} \\ K_2 = \begin{bmatrix} 0.0050 & 0.0039 & -0.0119 & 0.2435 \end{bmatrix} \end{cases} \tag{74}$$

As shown in Figure 5, for the microgrid system affected by the DETM, DoS attacks and noises, the controller in (**?**) can not stabilize the system. However, if using the proposed controller with gain matrices (74), satisfactory system performance can be achieved.

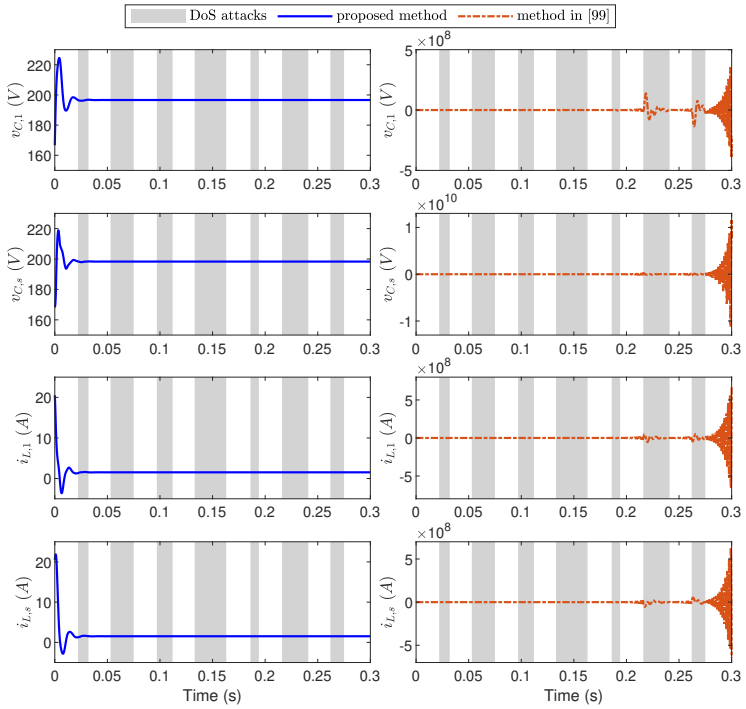

Figure 5. State responses of the proposed method and the method in (**?**).

5.3. Tradeoffs between communication and control performances

To clearly show the tradeoffs between communication and control performance, Corollary 4.3 is used to compute parameters of the controller and the ETM. Using parameters of the DC microgrid in Section 5.1 with $\delta = 0.1$ and $\delta = 0.3$, gain matrices of the controller can be respectively obtained as

$$\delta = 0.1, \begin{cases} K_1 = \begin{bmatrix} 0.5056 & 0.2140 & 0.5397 & 0.1823 \end{bmatrix} \\ K_2 = \begin{bmatrix} 0.3826 & 0.2394 & 0.3136 & 0.1849 \end{bmatrix} \end{cases} \tag{75}$$

$$\delta = 0.3, \begin{cases} K_1 = \begin{bmatrix} 0.6763 & 0.3689 & 0.6805 & 0.2459 \end{bmatrix} \\ K_2 = \begin{bmatrix} 0.6070 & 0.3771 & 0.5638 & 0.2478 \end{bmatrix} \end{cases} \tag{76}$$

As shown in Figure 6, using the triggering threshold parameter $\delta = 0.1$, the triggering rate of the DETM is 39%. If using a larger triggering parameter $\delta = 0.3$, the triggering rate of the DETM reduces to 23%, which implies more communication resources can be saved. On the other hand, as shown in Figure 7, compared with the controller (75) under $\delta = 0.1$, the controller (76) under $\delta = 0.3$ achieves larger overshoots and slower convergence speed. Namely, if using a larger triggering threshold parameter of the DETM, more communication resources can be saved, but worse control performance can be guaranteed. Thus, tradeoffs can be made between communication and control performances.

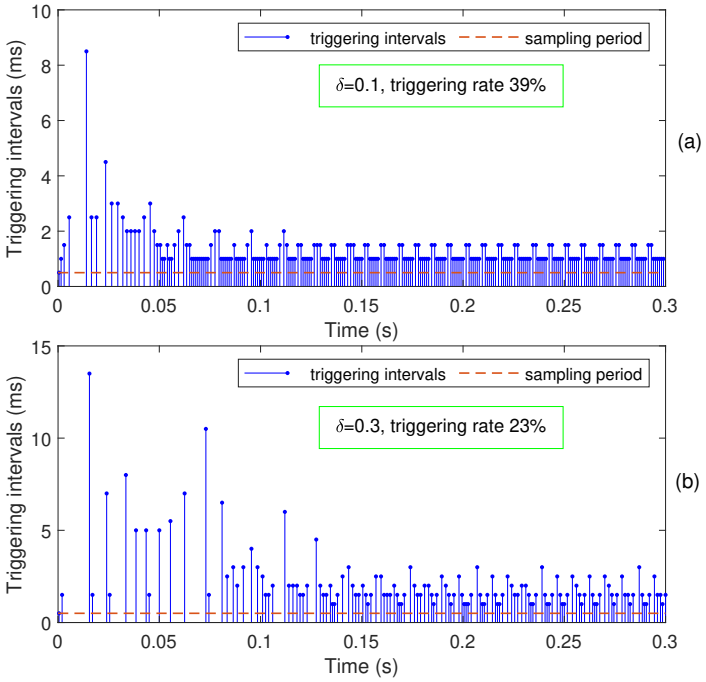

Figure 6. Triggering intervals of the DETM with $\delta = 0.1$ and $\delta = 0.3$.

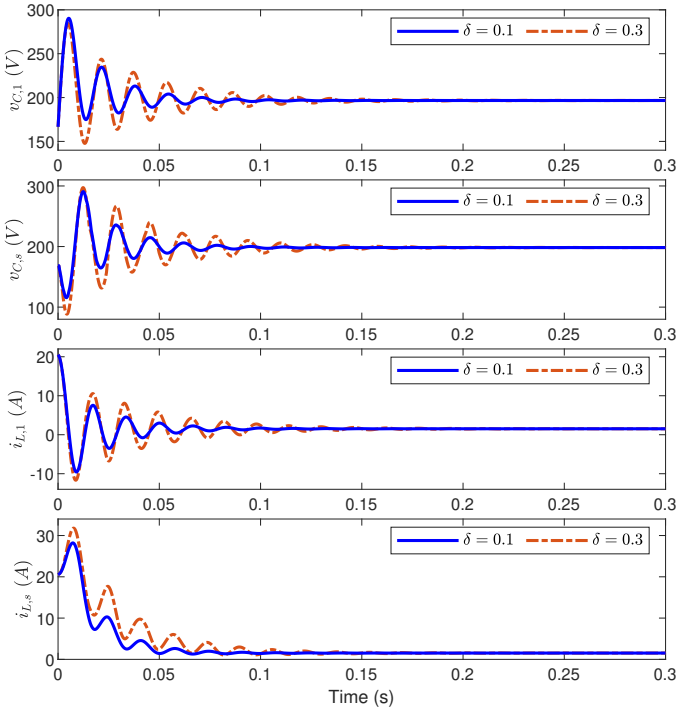

Figure 7. State responses under the triggering parameters $\delta = 0.1$ and $\delta = 0.3$.

5.4. Comparison with the method in (?)

For the DC microgrid in Table 1 subject to DoS attacks, using Theorem 4.4, gain matrix K of the robust controller (66) can be obtained as $K = 10^{-3} \times [0.0041\ 0.0201\ 0.0438\ 0.2289]$. Using Theorem 4.2 while only considering effects of DoS attacks, gain matrices of the proposed fuzzy controller (9) can be computed as $K_1 = [0.2571\ 0.0188\ 0.3344\ 0.1883], K_2 = [0.1252\ 0.1474\ 0.0241\ 0.1952]$, As shown in Figure 8 where grey bands denote the active intervals of DoS attacks, compared with the robust controller in (**?**), the proposed fuzzy controller can obtain shorter settling times and smaller overshoots.

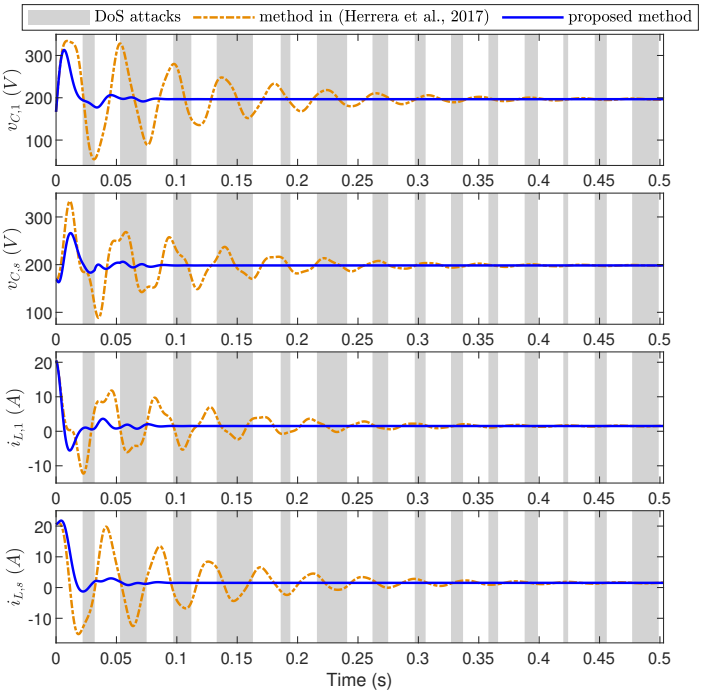

Figure 8. State responses of the proposed method and the method in (**?**).

6. Conclusion

The paper has investigated the event-triggered H_∞ control of nonlinear DC microgrids under aperiodic DoS attacks, disturbances and mismatching premises using a T-S fuzzy method. First, using T-S fuzzy model to describe DC microgrids with CPLs, and further using information of aperiodic DoS attacks and microgrid plant's fuzzy model, a resilient DETM is proposed, which can save system resources such as network bandwidth, guarantee at least one transmission during each attack-sleeping interval, as well as actively exclude attack-induced dropouts and Zeno behavior. Then, by virtually dividing the nonuniform triggering intervals of the DETM, a T-S fuzzy switched closed-loop system model is build, which integrates parameters of the microgrid's fuzzy model, the ETFIC controller subject to mismatching premises, aperiodic DoS attacks, DETM and noises all in one unified framework. Next, sufficient conditions for exponential stability with guaranteed H_∞ performance are derived. Further, co-design conditions are presented to design the ETFIC controller and the DETM, which is more

convenient than the two-step emulation method. Simulation results confirm that, in presence of aperiodic DoS attacks and noises, the proposed ETFIC controller can stabilize DC microgrids with guaranteed H_∞ performance, while the DETM effectively reduces the data transmission rate without dropouts. By choosing different triggering thresholds, corresponding controllers can be designed, and tradeoffs can be made between communication and control performances. Compared with the robust controller in (**?**), the proposed fuzzy controller achieves shorter settling times and smaller overshoots.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data Availability Statement

Data sharing not applicable - no new data generated.

Notes on contributor(s)

Fuqiang Li received Ph.D. degree in control science and engineering from Shanghai University in 2016. He is an Associate Professor in Henan Agricultural University. He has been a visiting scholar in University of Leeds in UK. His research interests include event-triggered control and security control of DC microgrids.

Kang Li received the Ph.D. degree in control theory and applications from Shanghai Jiaotong University in 1995. His research interests include nonlinear system modeling and control, energy and power systems. He chairs the IEEE UKRI Control and Communication Ireland chapter, and was the Secretary of the IEEE UK and Ireland Section. He also held Visiting Fellowship or Visiting Professorship at the National University of Singapore, University of Iowa, New Jersey Institute of Technology, Tsinghua University, Harbin Institute of Technology, Shanghai University, and Zhejiang University.

Lisai Gao received Ph.D. degree in control science and engineering from Shanghai University in 2023. She is with college of sciences at Henan Agricultural University. Her research interests include security control of microgrid systems.

Chen Peng received Ph.D. degree in control science and engineering from Chinese University of Mining Technology in 2002. He is currently a Professor in Shanghai University. His research interests include event-triggered control, networked control

systems and smart grids. He was appointed as a Shanghai Eastern Scholar in 2012, a Highly Cited Researcher by Clarivate Analytics in 2020-2022, and Associate Editor of IEEE Transactions on Industrial Informatics, Information Sciences, and Transactions of the Institute of Measurement and Control.

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