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Research Article

Quantized Dissipative Observer-Based Output Feedback Control for a Class of Markovian Descriptor Jump Systems with Communication Delay

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This paper investigates the problem of quantized dissipative observer-based output feedback control of Markovian descriptor jump systems with unavailable states, appearing networked-induced delay. The descriptor systems are presented as Markovian jump systems which give a more realistic presentation for a variety of nonlinear dynamical systems than conventional state-space representation. To accomplish the objective, a uniform framework is employed to design the delayed Markov observer-based controller and event-triggered scheme. Additionally, we provided the $\mathscr{H}_\infty$ and $\mathscr{L}_2$-$\mathscr{L}_\infty$ and dissipative performance indices which are robust against the disturbances with time-varying delays. Moreover, a novel Lyapunov–Krasovskii functional is considered to guarantee the closed loop for stochastic stability analysis of the Markovian descriptor jump system. The solvability of Lyapunov–Krasovskii functional results in the formation of linear matrix inequalities. The controller and observer gains can be obtained by solving the linear matrix inequalities. Simulations are performed to validate the proposed scheme.

1. Introduction

To appropriately model the physical systems, it is appealing to describe both dynamic and static behaviors simultaneously. Descriptor systems have attained sufficient attention from the researchers in the past decades. In contrast to conventional state-space representation, descriptor systems describe the practical demonstration of real-world applications which include large-scale systems, electric power systems [1–3], and economic systems [4]. Descriptor systems are also known as singular systems whose dynamic part is represented by differential equations and relationship between different sections of the systems and described by algebraic equations. Stability, regularity, and nonimpulsiveness/causality are usually referred to as admissibility of singular systems [5]. Singular systems constitute an important class of dynamic systems, and the admissibility analysis is difficult; the study for singular systems not only has great theoretical significance but also has practical importance. Interest has grown in the analysis and control synthesis of descriptor systems over the past decades, and a lot of important results based on normal systems have been extended to descriptor systems successfully, such as solvability, observability, controllability, regularization, stabilization, normalization, robust control, impulse elimination, and pole assignment [6–8]. The readers are also referred to survey paper [9], for more historical reviews on the admissibility of dynamic systems.

In the past few decades, Markovian jump control is applied in many practical applications. In [10], singular control models present a nonlinear dynamical system into local linear models, which dramatically attracts the attention of a huge number of researchers. Significant research has been carried out for the design of closed-loop Markovian jump systems using the transition matrix approach for input state feedback controllers. In [11, 12], Markovian dynamic output feedback control for discrete time has been investigated. Moreover, in [11–13], the plant and desired feedback controller of Markovian switch systems are based upon this assumption that the information of the nonlinear plant is all the time approachable at the controller side to make sure that the control mode works properly with the system modes, while the space robot manipulator model was investigated with sliding mode control (SMC) in an effective way [14]. Moreover, in practical, working of the controller on this assumption is hard to fulfill [15]. In this regard, fruitful research can be found relating transition probabilities (TPs) in [16–18] which leads to the complication of Markovian switch systems. Therefore, the robustness and design simplicity are increased. Moreover, the properties of Markov jump with fuzzy membership function are codesigned, which gives less conservative results [19]. In [20, 21], authors have been investigating the properties of H_∞ control for Markovian singular jump systems with event-triggered and quantization effect. It is worth mentioning that the obtained results of the abovementioned work are satisfactory conditions, so they could be more improved. Recently, Network control systems (NCSs) are getting too much attention in modern research [22, 23]. In NCS, the data from the sensor to a controller and from the controller to the actuator is transferred through a common network [24, 25]. Such type of mechanism is preferred in distributed control of modern industries including large power systems [26]. Comparing with traditional control NCS, it is unpredictable due to time-varying delays in network and data dropouts. Therefore, match premise requirement is not fulfilled in NCS [27]. As mentioned above, in network-controlled applications with time-varying delays occur due to limited capacities of data analysis and transmission between different sections of plants over a common network. So, delay is considered as a key source of instability [28–31]. Currently, authors investigated the properties of Markov jump systems to get an extension to handle the problem of synchronization for the networked control system [32, 33]. The stability of such type systems is more challenging than normal regular systems because of singular systems required to be stable, regular, and impulse free. Many researchers considered the delay-dependent descriptor system; for details, see [34, 35]. However, still it is open research for large-scale singular systems which is one of the motivations. Furthermore, it is observed that most of the conventional control is time triggered and they waste most of the communication resources and degrade the efficiency, so event-triggered communication over the network got fruitful attention [36, 37].

In most complex systems, sometimes the internal states are unmeasurable. It mostly happens due to the cost of sensors or limited control techniques. In these situations, observer-based output feedback control is mostly adopted [38]. The observer design for singular systems is presented in [39–44]. As far as observer design is concerned and found limited work, a few scholars discussed observer design with delay free [45]. In [46], the author discussed (Q-V-R)-α dissipative observer-based controller design. In [38], a similar problem is considered with uncertainties. On the contrary, some practical examples of the jumping system have been investigated in [47, 48]. In [47], the time-varying formation control problem for a group of quadrotor unmanned aerial vehicles (UAVs) under Markovian switching topologies are investigated. While in [48], authors investigated the properties of $\mathscr{L}_\infty$ control for the semi-Markov jump system with time delays. It is significant to pursue observer-based control design with input and state delays for Markov jump singular systems which are still open and challenging.

One of the important derivations of this research article is the implementation of *Lyapunov–Krasovskii function* (*LKF*), the mode-dependent membership function. Such type of functions possesses additional information about the behavior of the system and helps in decreasing the conservatism of design and analysis for network-based Markovian descriptor systems with event-triggered technique. This special type of *LKF* addresses the limitations of common *LKF* [49] by incorporating mode dependent integral terms which are coupled and its membership functions depends on nonintegral terms in ordinary *LKF*. It is found that event-triggered dissipative observer-based output feedback control for a class of Markovian descriptor systems with time-varying delays with the incorporation such a novel *LKF* is not reported for Markovian descriptor systems. In the light of the abovementioned discussion, the authors are encouraged to pursue currently proposed research with the following listed novelties:

(i) Firstly, a generalized nonlinear system model for the observer-based Markovian descriptor system is derived for delay-dependent NCS with event-triggered control (ETC) and unavailable system states along with quantization effect under the communication delay of the network.

(ii) Secondly, a uniform framework of dissipative control for Markovian descriptor systems having capabilities to analyze performance indices of $\mathscr{H}_\infty$ and $\mathscr{L}_2 - \mathscr{L}_\infty$ is established, which analyses the robust stochastically stability.

(iii) Thirdly, a novel LKF is considered to derive sufficient conditions to make the system stochastically stable and reduce conservatism under delay-dependent conditions. Our suggested scheme gives successful consumption of bandwidth with ETC compared with others. Finally, the DC-motor example is presented to demonstrate the effectiveness of the proposed design methods.

Notations: for real symmetric matrices X and Y, throughout this paper the notation $X \geq Y$ (respectively, $X > Y$) means that the $X - Y$ matrix is positive semidefinite (respectively, positive definite). $|\cdot|$ denotes the Euclidean norm for vectors and $\|\cdot\|$ denotes the spectral norm for matrices. $\mathrm{diag}(\ldots)$ stands for a block-diagonal matrix. The notation "$\bigstar$" is used as an ellipsis for terms that are induced by symmetry. The superscript "T" represents the transpose of the matrix. $\mathscr{L}_2[0,\infty]$ represents the space of square-integrable vector functions over $[0,\infty)$.

2. System Description and Problem Formulation

Consider a continuous class of the Markovian jump system with descriptor model with the time-delayed network control system described as follows:

$$\begin{cases} \mathscr{E}\dot{x}(t) = \mathscr{A}(r_t)x(t) + \mathscr{A}_{\hbar_1}(r_t)x(t-\hbar_1(t)) + \mathscr{B}(r_t)u(t) \\ \quad +\mathscr{D}(r_t)\omega(t), \\ z(t) = \mathscr{C}(r_t)x(t) + \mathscr{C}_{\hbar_1}(r_t)x(t-\hbar_1(t)), \\ y(t) = \mathscr{C}(r_t)x(t), \\ x(t) = \phi(t), \\ t \in [-\overline{\hbar}_1, 0], \end{cases} \tag{1}$$

where $x(t) \in R^{n_x}$, $y(t) \in R^{n_y}$, $z(t) \in R^{n_z}$, and $u(t) \in R^{n_u}$ represents the state variable, output vector, measured output, and control input, respectively, and $\omega(t) \in R^{n_\omega}$ represents the disturbance signal that belongs to $\mathfrak{L}_2[0,\infty]$. $\mathscr{E} \in R^{n_x \times n_x}$ having $\operatorname{rank}(\mathscr{E}) = q \le n_x$. $\phi(t)$ represents the initial condition. $\mathscr{A}(r_t)$, $\mathscr{A}_{\hbar_1}(r_t)$, $B(r_t)$, $D(r_t)$, $\mathscr{C}(r_t)$, $\mathscr{C}(r_t)$, and $\mathscr{C}_{\hbar_1}(r_t)$ are the system matrices with proper dimensions. $\hbar_1(t)$ represents the time-varying delay of the nonlinear system. In the abovementioned discussion, r_t represents the procedure of continuous-time Markovian which takes the values over the finite set $\mathbb{S} = \{1, 2, \ldots, s\}$ with transition probability matrix $\Pi: = [\pi_{ij}]_{s\times s}$ given below:

$$\mathbb{P}r\{r_{(t+\nabla h)} = j \mid r_t = i\} = \begin{cases} \pi_{ij}\nabla h + o(\nabla h), & i \ne j, \\ 1 + \pi_{ii}\nabla h + o(\nabla h), & i = j, \end{cases} \tag{2}$$

where $\nabla h > 0$, $o(\nabla h)$ is greater order infinitesimal of ∇h, and $\lim_{\nabla h \longrightarrow 0}(o(\nabla h)/\nabla h) = 0$.

$$\pi_{ii} = -\sum_{j=1, j\ne i}^{s} \pi_{ij}, \tag{3}$$

and $\pi_{ij} \ge 0$ for $j \ne i$ is the transition mode rate from i at t to mode j at time $t + \Delta h$.

To avoid difficulty, we expressed $\mathscr{A}(r_t) = \mathscr{A}_i$, $\mathscr{A}_{\hbar_1}(r_t) = \mathscr{A}_{\hbar_{1i}}$, $B(r_t) = B_i$, and so on for each $r_t = i \in \mathbb{S}$.

Before proceeding ahead, it is assumed that, in delayed descriptor Markovian jump NCSs (1), the measured output is transmitted through the common network channel.

Definition 1. The delayed Markovian jump descriptor system:

$$\begin{cases} \mathscr{E}\dot{x}(t) = \mathscr{A}_i x(t) + \mathscr{A}_{d_i} x(t - d(t)), \\ x(t) = \phi(t), \\ t \in [-\overline{d}, 0], \end{cases} \tag{4}$$

is known as impulse-free and regular, if the pair $(\mathscr{E}, \mathscr{A}_i, \mathscr{A}_{d_i})$ is impulse free and regular.

2.1. Event-Triggered Control (ETC) Scheme. In this paper, the sampler which samples the measurement output $y(t)$ is time driven with a sampling period. In the traditional method, the sampled data should be sent to the controller in each sampling period, and this would lead to more need of band resources. To solve this issue, we introduced an event-triggered communication-based transmitter which is inserted between the plant and the controller, in order to enhance the communication performance. In addition to deciding, the transmission of the current measured data $y(t)$ to the observer from the ETC transmitter is based on logic function [26]. Network-induced delays are considered between the sensor and controller in our proposed scheme. The ETC is designed to handle the event generated by the instant $(i_k h)$. The error between the current sampled data and the latest transmitted data can be expressed as follows:

$$e^k(t) = y(z_k h) - y(i_k h), \tag{5}$$

where $z_k h = i_k h + mh$, $m \in \mathbb{N}$, and $z_k h$ denotes the sampling instant between two simultaneous instants. The future transmission instants are based on ETC scheme which is expressed as follows:

$$i_{k+1}h = i_k h + \min\{kh \mid e^k(t)^T O e^k(t)\} > \sqrt{\rho}\, y^T(i_k h) O y(i_k h). \tag{6}$$

$\mathcal{O} > 0$ and $0 < \rho < 1$ represents the conditions for triggering which will be determined later. From the abovementioned conditions, it is clear that the next transmitting instants are experienced by two important aspects, which are triggering parameters and output $y(i_k h)$. From (6), it is seen that the transmitted instant $\{i_k h \mid i_k \in N\}$ yielding to sampled instants is denoted as $\{j_k h \mid j_k \in N\}$. $i_0 h = 0$ represents the initial transmitting instant. In this paper, we consider the network-induced transmission delays, τ_{i_k} and $\tau_{i_{k+1}}$, at transmitting instants $i_k h$ and $i_{k+1} h$, respectively. Then, $i_k + \tau_{i_k}$ represents the instant when the transmitted signal arrives at zero-order holder (ZOH).

It is examined that $\tilde{y}(t)$ retains the value of $y(i_k h)$ with interval $[i_k h + \tau_{i_k}, i_{k+1} h + \tau_{i_{k+1}})$ influenced by ZOH:

$$\tilde{y}(t) = y(i_k h), \quad t \in [i_k h + \tau_{i_k}, i_{k+1} h + \tau_{i_{k+1}}). \tag{7}$$

The subset is used to call the holding zone δ of ZOH [26]:

$$\delta = [i_k h + \tau_{i_k}, i_{k+1} h + \tau_{i_{k+1}}) = \bigcup_{p=0}^{o_l} \delta_p, \tag{8}$$

where $\delta_p = [i_k h + \tau_{i_k}, i_{k+1} h + \tau_{i_{k+1}})$, $p = 0, 1, 2, \ldots, o_l$, and $o_l = i_{k+1} - i_k - 1$.

The network delay could be defined as $d(t) = t - i_k h$, satisfying $0 \le d_{i_k} \le h + \overline{d} \doteq d_M$. Based on the abovementioned analysis, the original input of observer could be expressed as follows:

$$\breve{y}(t) = y(i_k h) = y(t - d(t)) - e^k(t). \tag{9}$$

Remark 1. For the Markov jump system, an event-triggering strategy is used corresponding to Markov jump systems. Compared with one common strategy, event-triggering strategies are less conservative and make the event-triggered control design more flexible, especially for the Markov jump system. Moreover, $i_k \in N$ ensures that any interexecution interval is not less than h to avoid Zeno behavior.

2.2. Observer-Based Controller Design through Quantizer. In this paper, due to the appearance of the communication channels between the nonlinear switch plant and controller. First, we consider the output synthesis using quantized measurement, which is received through the communication environment:

$$\check{y}(t) = \mathcal{Q}[\check{y}(t), r_t] = \left[\mathcal{Q}\left[\check{y}^1(t), r(t)\right]\mathcal{Q}\left[\check{y}^2(t), r_t\right] \cdots \mathcal{Q}[\check{y}^p(t), r_t]\right]. \tag{10}$$

$Q[.,.]$ stands for time-variant quantizer and logarithmic static (mode dependent), which is

$$\varrho_j = \left\{\pm\mu_{ij}\colon \mu_{ij} = \lambda_j^i \mu_{0j}, i = \pm 1, \pm 2, \ldots\right\} \cup \left\{\pm\mu_{0j}\right\} \cup \{0\}, \quad \mu_{0j} > 0,\ 1 \le j \le p. \tag{11}$$

The associated quantizer $\mathcal{Q}[\cdot,\cdot]$, for the logarithmic quantizer is well defined as below:

$$\mathcal{Q}\left[\check{y}^j(t), i\right] = \begin{cases} u_{ij}, & \text{if } \dfrac{u_{ij}}{1+\alpha_{f_s}} < \check{y}^j(t) \le \dfrac{u_{ij}}{1-\alpha_{f_s}}, \\ 0, & \text{if } \check{y}^j(t) = 0, \\ -\mathcal{Q}[-\check{y}^j(t), i], & \text{if } \check{y}^j(t) < 0,\ 1 \le j \le p, \end{cases} \tag{12}$$

with

$$\alpha_{f_s} = \frac{1-\rho_{f_s}}{1+\rho_{f_s}}, \quad 0 < \rho_{f_s} < 1. \tag{13}$$

ρ_{f_s} is a given constant, which is called quantization density. It follows from (12) and (13) that

$$-\alpha_{f_s}\check{y}^j(t) \le \mathcal{Q}\left[\check{y}^j(t), i\right] - \left[\check{y}^j(t), i\right] \le \alpha_{f_s}\check{y}^j(t), \quad 1 \le j \le p. \tag{14}$$

The quantized output of the system is also affected by the communication delay, which is considered in the general form of controller design. That is why our approach is more standard than the existing one in [50]. Based on the abovementioned analysis (10)–(14) and using the Sector Bound Approach (SBA) [51, 52], the measured output received by the delayed controller can be expressed as follows:

$$\tilde{y}(t) = \mathcal{Q}[\check{y}(t), i] = \left(I + \Pi_i \nabla_f(t)\right)\check{y}(t), \tag{15}$$

where $\Pi_i = \operatorname{diag}\left\{\Delta_{f_1}, \Delta_{f_2}, \ldots, \Delta_{f_m}\right\}$, $\Delta_{f_s} \in [-\alpha_{f_s}, \alpha_{f_s}]$, and $\Delta_f^T(t)\Delta_f(t) \le I$.

According to the Markovian jump descriptor system (1), we suppose the following observer:

$$\begin{cases} \mathscr{E}\dot{\hat{x}}(t) = \mathscr{A}_i\hat{x}(t) + \mathscr{A}_{\hbar_{2i}}\hat{x}\left(t - \hbar_2(t)\right) + B_i u(t) \\ \qquad + L_j\left(\tilde{y}(t) - \hat{y}(t)\right), \\ \hat{z}(t) = \mathscr{C}_i\hat{x}(t) + \mathscr{C}_{\hbar_{2i}}\hat{x}\left(t - \hbar_2(t)\right), \\ \hat{y}(t) = \mathscr{C}_i\hat{x}(t), \\ u(t) = K_j\hat{x}(t), \\ \hat{x}(t) = \hat{\phi}(t), \\ t \in \left[-\bar{\hbar}_2, 0\right]. \end{cases} \tag{16}$$

$\hat{x}(t)$ is the approximated observer state and $\tilde{y}(t)$ is the quantized measured signal via ETC for $t \in [i_k h + \tau_{i_k}, i_{k+1}h + \tau_{i_{k+1}})$, where controller gain K_j and L_j is the observer gain which needs to be determined.

Defining the estimation error,

$$e(t) = x(t) - \hat{x}(t). \tag{17}$$

Then, integrate (1) and (15)–(17), and the closed loop form can be obtained as follows:

$$\begin{cases} \bar{\mathscr{E}}\dot{\varsigma}(t) = \bar{\mathscr{A}}\varsigma(t) + \sum\limits_{\ell=1}^{2}\bar{\mathscr{A}}_{\hbar_\ell}\varsigma\left(t - \hbar_\ell(t)\right) + \bar{\mathscr{A}}_d X\varsigma\left(t - d(t)\right) + \bar{D}\omega(t) + \bar{L}_{ej}e^k(t), \\ z(t) = \bar{\mathscr{C}}\varsigma(t) + \sum\limits_{\ell=1}^{2}\bar{\mathscr{C}}_{\hbar_\ell}\varsigma\left(t - \hbar_\ell(t)\right). \end{cases} \tag{18}$$

Compute the error output $\mathbf{z}(t) = z(t) - \hat{z}(t)$ and represent the state augmentation $\varsigma = \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$. Then, the augmented system could be expressed as

$$\begin{aligned}
\widetilde{\mathscr{E}} &= \begin{bmatrix} \mathscr{E} & 0 \\ 0 & \mathscr{E} \end{bmatrix},\\
\overline{\mathscr{A}} &= \begin{bmatrix} \mathscr{A}_i + B_i\mathscr{K}_j & -B_i\mathscr{K}_j \\ 0 & \mathscr{A}_i - L_j\mathscr{C}_i \end{bmatrix},\\
\overline{\mathscr{A}}_{\hbar_1} &= \begin{bmatrix} \mathscr{A}_{\hbar_{1i}} & 0 \\ \mathscr{A}_{\hbar_{1i}} & 0 \end{bmatrix},\\
\overline{\mathscr{A}}_{\hbar_2} &= \begin{bmatrix} 0 & 0 \\ \mathscr{A}_{\hbar_{2i}} & 0 \end{bmatrix},\\
\overline{\mathscr{A}}_{\hbar_2} &= \begin{bmatrix} 0 & 0 \\ \mathscr{A}_{\hbar_{2i}} & 0 \end{bmatrix},\\
\overline{\mathscr{A}}_d &= \begin{bmatrix} 0 \\ -L_j\left(I + \Pi_i\nabla_f(t)\right)\mathscr{C}_i \end{bmatrix},\\
\overline{D} &= \begin{bmatrix} D_i \\ D_i \end{bmatrix},\\
\overline{L}_{ej} &= \begin{bmatrix} 0 \\ -L_j\left(I + \Pi_i\nabla_f(t)\right)\mathscr{C}_i \end{bmatrix},\\
X &= [\, I \ \ 0 \,],\\
\overline{\mathscr{E}} &= [\, 0 \ \ \mathscr{E}_i \,],\\
\overline{\mathscr{E}}_{\hbar_1} &= [\, \mathscr{E}_{\hbar_{1i}} \ \ 0 \,],\\
\overline{\mathscr{E}}_{\hbar_2} &= [\, 0 \ \ \mathscr{E}_{\hbar_{2i}} \,].
\end{aligned} \tag{19}$$

It is observed that the augmented system (18) is experienced by delays with the following bounded conditions:

$$\begin{aligned}
0 \le \hbar_\kappa(t) &\le \overline{\hbar}_\kappa,\\
\dot{\hbar}_\kappa &\le \upsilon_\kappa,\\
\kappa &= 1, 2,
\end{aligned} \tag{20}$$

where υ_κ and $\overline{\hbar}_\kappa > 0$ are fixed scalar values.

In addition, we assume the unforced descriptor Markovian jump system with disturbances under time-varying delays in the following form:

$$\begin{cases}
\mathscr{E}\dot{x}(t) = \mathscr{A}(r_t)x(t) + \mathscr{A}_{\hbar_1}(r_t)x(t - \hbar_1(t)) + D(r_t)\omega(t),\\
z(t) = \mathscr{E}(r_t)x(t) + \mathscr{E}_{\hbar_1}(r_t)x(t - \hbar_1(t)),\\
y(t) = \mathscr{C}(r_t)x(t),\\
x(t) = \phi(t), \quad t \in \left[-\overline{\hbar}_1, 0\right].
\end{cases} \tag{21}$$

Definition 2 (see [19, 53]). Consider matrices $\Theta \ge 0$, $\Phi_1 \le 0$, and Φ_2 and $\Phi_3 > 0$, which fulfill $(\|\Phi_1\| + \|\Phi_2\|)\|\Theta\| = 0$. Then, we can say that system (18) is to be extended dissipative if there exists a scalar ρ such that the following inequality holds for any $t_f \ge 0$ and all $\omega(t) \in \mathfrak{L}_2[0, \infty]$:

$$\int_0^{t_f} J(t)\mathrm{d}t - \sup_{0\le t\le t_f} z(t)^T\Theta z(t) \ge \rho, \tag{22}$$

where

$$J(t) = z(t)^T\Phi_1 z(t) + 2z(t)^T\Phi_2\omega(t) + \omega(t)^T\Phi_3\omega(t). \tag{23}$$

Lemma 1 (see [27]). *Rank of Matrix* $(\mathscr{C}_i) = m$, $\mathscr{C}_i \in R^{m\times n}$, *the single value decomposition (SVD) for* $\mathscr{C}$ *can be expressed as* $\mathscr{C} = O[\, S \ \ 0\,]V^t$, *where* $O.O^T = I$ *and* $V.\mathbb{V}^T = I$. *Assume* $X_i > 0$, $\mathbb{M} \in \mathscr{R}^{m\times m}$. *Then, there exist* $\widetilde{X}_i$ *such that* $\mathscr{C}_i X_i = \widetilde{X}_i\mathscr{C}_i$, *if and only if*

$$X_i = V * \mathrm{diag}\{M, N\} * V^T. \tag{24}$$

3. Main Results

Theorem 1. *For the given scalars* ε_ℓ, *satisfying* $0 < \varepsilon_\ell < 1$ *and* $\varepsilon_0 + \varepsilon_1 + \varepsilon_2 = 1$ *with* $\gamma > 0$, *augmented system (18) is impulse-free with the dissipative performance index which will fulfill the conditions of time-varying delays (20) under event-triggered scheme (6), if there exist matrices* $\mathscr{G} > 0$, $\mathscr{P}_i > 0$, $\mathscr{Q}_{gi} > 0$, $\mathscr{R}_{gi} > 0$, $\mathscr{S}_g > 0$, $\mathscr{Z}_{gi} > 0$, $\mathscr{W}_g > 0$, $O > 0$, *and* M_{gi}, *such that* $g = 1, 2, 3$, $r_t = i \in \mathbb{S}$, *and the following inequality holds:*

$$\mathscr{J}^1_{gi} := \sum_{j=1}^{s} \pi_{ij}\left(Q_{gj} + R_{gj}\right) - S_g < 0, \tag{25}$$

$$\mathscr{J}^2_{gi} := \sum_{j=1}^{s} \pi_{ij}R_{gj} - S_g < 0, \tag{26}$$

$$\mathscr{J}^3_{gi} := \sum_{j=1}^{s} \pi_{ij}Z_{gj} - \frac{1}{\overline{a}_g}W_g < 0, \tag{27}$$

$$\begin{gathered}\mathscr{G}-\mathscr{P}_i<0,\\ \begin{bmatrix}\mathscr{Z}_{gi} & \mathscr{M}_{gi}\\ \star & \mathscr{Z}_{gi}\end{bmatrix}>0,\end{gathered} \tag{28}$$

$$\begin{bmatrix}-\varepsilon_0\mathscr{G} & 0 & 0 & \overline{\mathscr{E}}^T\widetilde{\Theta}^T\\ \star & -\varepsilon_1\mathscr{G} & 0 & \overline{\mathscr{E}}_{\hbar_1}^T\widetilde{\Theta}^T\\ \star & \star & -\varepsilon_2\mathscr{G} & \overline{\mathscr{E}}_{\hbar_2}^T\widetilde{\Theta}^T\\ \star & \star & \star & -I\end{bmatrix}<0, \tag{29}$$

$$\begin{bmatrix}\Xi_{ij} & \Lambda_{ij}^T & \mathscr{A}^T\mathscr{P}_i & \mathscr{E}^T\widetilde{\Phi}_1^T\\ \star & -\Phi_3 & \overline{\mathscr{D}}^T\mathscr{P}_i & 0\\ \star & \star & \widehat{Z}-2\mathscr{P}_i & 0\\ \star & \star & \star & -I\end{bmatrix}<0, \tag{30}$$

where $\widehat{Z}=\sum_{g=1}^{3}(\overline{\hbar}_g^2\mathscr{Z}_{gi}+0.5\overline{\hbar}_g^2\mathscr{W}_g)$ *and*

$$\begin{aligned}
\Xi_{ij} &= \left[(1,1)=\left(\sum_{j=1}^{s}\pi_{ij}\mathscr{E}^T\mathscr{P}_j\mathscr{E}+\mathscr{P}_i\overline{\mathscr{A}}+\overline{\mathscr{A}}^T\mathscr{P}_i+\sum_{g=1}^{3}\left(\mathscr{Q}_{gi}+\mathscr{R}_{gi}-\mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E}+\overline{a}_g\mathscr{S}_g\right)\right)\right],\\
&(1,2)=\mathscr{P}_i\overline{\mathscr{A}}_{\hbar_1}+\mathscr{E}^T\mathscr{Z}_{1i}\mathscr{E}-\mathscr{E}^T\mathscr{M}_{1i}\mathscr{E},\\
&(1,3)=\mathscr{E}^T\mathscr{M}_{1i}\mathscr{E},\\
&(1,4)=\mathscr{P}_i\overline{\mathscr{A}}_{\hbar_2}+\mathscr{E}^T\mathscr{Z}_{2i}\mathscr{E}-\mathscr{E}^T\mathscr{M}_{2i}\mathscr{E},\\
&(1,5)=\mathscr{E}^T\mathscr{M}_{2i}\mathscr{E},\\
&(1,6)=\mathscr{P}_i\overline{\mathscr{A}}_d+\mathscr{E}^T\mathscr{Z}_{3i}\mathscr{E}-\mathscr{E}^T\mathscr{M}_{3i}\mathscr{E},\\
&(1,7)=\mathscr{E}^T\mathscr{M}_{3i}\mathscr{E},\\
&(1,8)=\mathscr{P}_i\overline{\mathscr{L}}_{ej},\\
&(2,2)=(1-\upsilon_l)\mathscr{Q}_{1i}-2\mathscr{E}^T\mathscr{Z}_{1i}\mathscr{E}+\mathscr{E}^T\mathscr{M}_{1i}\mathscr{E}+\mathscr{E}^T\mathscr{M}_{1i}^T\mathscr{E},\\
&(2,3)=\mathscr{E}^T\mathscr{Z}_{1i}\mathscr{E}-\mathscr{E}^T\mathscr{M}_{1i}\mathscr{E},\\
&(3,3)=-\mathscr{E}^T\mathscr{Z}_{1i}\mathscr{E}-\mathscr{E}^T\mathscr{R}_{1i}\mathscr{E},\\
&(4,4)=(1-\upsilon_2)\mathscr{Q}_{2i}-2\mathscr{E}^T\mathscr{Z}_{2i}\mathscr{E}+\mathscr{E}^T\mathscr{M}_{2i}\mathscr{E}+\mathscr{E}^T\mathscr{M}_{2i}^T\mathscr{E},\\
&(4,5)=\mathscr{E}^T\mathscr{Z}_{2i}\mathscr{E}-\mathscr{E}^T\mathscr{M}_{2i}\mathscr{E},\\
&(5,5)=-\mathscr{E}^T\mathscr{Z}_{2i}\mathscr{E}-\mathscr{E}^T\mathscr{R}_{2i}\mathscr{E},\\
&(6,6)=(1-d_M)\mathscr{Q}_{3i}-2\mathscr{E}^T\mathscr{Z}_{3i}\mathscr{E}+\mathscr{E}^T\mathscr{M}_{3i}\mathscr{E}+\mathscr{E}^T\mathscr{M}_{3i}^T\mathscr{E}+\mathscr{C}_i^T\mathscr{O}\mathscr{C}_i,\\
&(6,7)=\mathscr{E}^T\mathscr{Z}_{3i}\mathscr{E}-\mathscr{E}^T\mathscr{M}_{3i}\mathscr{E},\\
&(7,7)=-\mathscr{E}^T\mathscr{Z}_{3i}\mathscr{E}-\mathscr{E}^T\mathscr{R}_{3i}\mathscr{E},\\
&(8,8)=-\mathscr{O},\\
\Lambda_{ij} &= \begin{bmatrix}-\Phi_2^T\overline{\mathscr{E}}+\overline{\mathscr{D}}^T\mathscr{P}_i & -\Phi_2^T\overline{\mathscr{E}}_{\hbar_1} & 0 & -\Phi_2^T\overline{\mathscr{E}}_{\hbar_1} & 0 & 0 & 0 & 0\end{bmatrix},\\
\mathscr{A} &= \begin{bmatrix}\overline{\mathscr{A}} & \overline{\mathscr{A}}_{\hbar_1} & 0 & \overline{\mathscr{A}}_{\hbar_2} & 0 & \overline{\mathscr{A}}_d & 0 & \overline{\mathscr{L}}_{ej}\end{bmatrix},\\
\mathscr{E} &= \begin{bmatrix}\overline{\mathscr{E}} & \overline{\mathscr{E}}_{\hbar_1} & 0 & \overline{\mathscr{E}}_{\hbar_2} & 0 & 0 & 0 & 0\end{bmatrix}.
\end{aligned} \tag{31}$$

Proof. First, we present that networked Markovian descriptor system (18) is regular and impulse-free. Since, $\operatorname{rank}(\mathscr{E}) = q$, then the $\operatorname{rank}(\widetilde{\mathscr{E}}) = 2q$, and we select two nonsingular matrices $\widehat{G}$ and $\widehat{H}$ such that

$$\begin{aligned}
\widetilde{\mathscr{E}} &= \widehat{G}\mathscr{E}\widehat{H} = \begin{bmatrix} I_{2q} & 0 \\ 0 & 0 \end{bmatrix}, \\
\widehat{G}\overline{\mathscr{A}}\widehat{H} &= \begin{bmatrix} \overline{\mathscr{A}}_{11} & \overline{\mathscr{A}}_{12} \\ \overline{\mathscr{A}}_{21} & \overline{\mathscr{A}}_{22} \end{bmatrix}, \\
\widehat{G}^{-1}\mathscr{P}_i\widehat{H} &= \begin{bmatrix} \mathscr{P}_{i_{11}} & \mathscr{P}_{i_{12}} \\ \mathscr{P}_{i_{21}} & \mathscr{P}_{i_{22}} \end{bmatrix}.
\end{aligned} \tag{32}$$

Same procedure is adopted in [21, 54], and we identify that $\overline{\mathscr{A}}_{22}$ is nonsingular, which yields that the pair of $(\mathscr{E}, \overline{\mathscr{A}})$ is regular and impulse-free; it follows that the networked Markovian descriptor system (18) is regular and impulse-free. In the same consequences, we will prove that the networked Markovian descriptor system (18) is stable under the quantized event-triggering scheme (6).

At this point, we implement the Lyapunov–Krasovskii function candidate for system (18):

$$\mathscr{V}(x_t, r_t, t) = \varsigma(t)^T\mathscr{E}^T\mathscr{P}_i\mathscr{E}\varsigma(t) + \sum_{l=1}^{3}\mathscr{V}_l(t), \tag{33}$$

where

$$\begin{aligned}
\mathscr{V}_1(t) &= \sum_{g=1}^{3}\left(\int_{t-a_g}^{t}\varsigma(s)^T\mathscr{Q}_{gi}\varsigma(s)\right)\mathrm{d}s + \sum_{g=1}^{3}\left(\int_{t-\overline{a}_g}^{t}\varsigma(s)^T\mathscr{R}_{gi}\varsigma(s)\right)\mathrm{d}s, \\
\mathscr{V}_2(t) &= \sum_{g=1}^{2}\overline{a}_g\int_{-\overline{a}_g}^{0}\int_{t+\gamma}^{t}\dot{\varsigma}(s)^T\mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E}\dot{\varsigma}(s)\mathrm{d}s\,\mathrm{d}\gamma + \sum_{g=1}^{3}\left(\int_{-a_g}^{0}\int_{t+\gamma}^{t}\varsigma(s)^T\mathscr{S}_g\varsigma(s)\right)\mathrm{d}s\,\mathrm{d}\gamma, \\
\mathscr{V}_3(t) &= \sum_{g=1}^{3}\left(\int_{-a_g}^{0}\int_{\theta}^{0}\int_{t+\gamma}^{t}\dot{\varsigma}(s)^T\mathscr{W}_g\dot{\varsigma}(s)\right)\mathrm{d}s\,\mathrm{d}\gamma\,\mathrm{d}\theta.
\end{aligned} \tag{34}$$

Note: throughout the paper, values of $(a_1, a_2, a_3) = (\hbar_1(t), \hbar_2(t), d(t))$, while on the other side $(\overline{a}_1, \overline{a}_2, \overline{a}_3) = (\overline{\hbar}_1, \overline{\hbar}_2, d_M)$.$\mathscr{P}_i > 0$, $\mathscr{Q}_{gi} > 0$, $\mathscr{R}_{gi} > 0$, $\mathscr{Z}_{gi} > 0$, $\mathscr{S}_\ell > 0$, and $\mathscr{W}_g > 0$. Let $\mathscr{F}$ be the weak infinitesimal generator of the random process $\{x_t, r_t\}$. Then, by implementing similar techniques to those in [53], we have that, for $r_t = i \in S$,

$$\begin{aligned}
\mathscr{F}\mathscr{V}(x_t, i, t) = {}& \varsigma(t)^T\left(\sum_{j=1}^{s}\pi_{ij}\mathscr{E}^T\mathscr{P}_j\mathscr{E} + \sum_{g=1}^{3}\left(\mathscr{Q}_{gi} + \mathscr{R}_{gi} + \overline{a}_g\mathscr{S}_g\right)\right)\varsigma(t) + 2\varsigma(t)^T\mathscr{P}_i\dot{\varsigma}(t) \\
& - \sum_{g=1}^{3}\left(1 - \dot{a}_g\right)\varsigma\left(t - a_g\right)^T\mathscr{Q}_{gi}\varsigma\left(t - a_g\right) - \sum_{g=1}^{3}\varsigma\left(t - \overline{a}_g\right)^T\mathscr{R}_{gi}\varsigma\left(t - \overline{a}_g\right) \\
& - \dot{\varsigma}(t)^T\left(\sum_{g=1}^{3}\left(\overline{a}_g^2\mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E} + \frac{1}{2\overline{a}_g^2\mathscr{W}_g}\right)\right)\dot{\varsigma}(t) - \sum_{g=1}^{3}\overline{a}_g\int_{t-\overline{a}_g}^{t}\dot{\varsigma}(s)^T\mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E}\dot{\varsigma}(s)\mathrm{d}s \\
& + \sum_{g=1}^{3}\int_{t-a_g}^{t}\varsigma(s)^T\mathscr{J}_{gi}^1\varsigma(v)\mathrm{d}v + \sum_{g=1}^{3}\int_{t-\overline{a}_g}^{t-a_g}\varsigma(s)^T\mathscr{J}_{gi}^2\varsigma(s)\mathrm{d}s \\
& + \sum_{g=1}^{3}\overline{a_g}\int_{-\overline{a_g}}^{0}\int_{t+\gamma}^{t}\dot{\varsigma}(s)^T\mathscr{J}_{gi}^3\dot{\varsigma}(s)\mathrm{d}s\,\mathrm{d}\gamma + e^k(t)^T\mathscr{O}e^k(t) - e^k(t)^T\mathscr{O}e^k(t).
\end{aligned} \tag{35}$$

Notice that

$$\overline{a}_g\int_{t-\overline{a}_g}^{t}\dot{\varsigma}(s)^TE^T\mathscr{Z}_{gi}E\dot{\varsigma}(s)\mathrm{d}s \geq \zeta^T\begin{bmatrix} -E^T\mathscr{Z}_{gi}E & E^T\mathscr{Z}_{gi}E - E^T\mathscr{M}_{gi}E & E^T\mathscr{M}_{gi}E \\ \star & -2\mathscr{E}^T\mathscr{Z}_{gi}E + E\mathscr{M}_{gi}E + E^T\mathscr{M}_{gi}^TE & E^T\mathscr{Z}_{gi}E - E^T\mathscr{M}_{gi}E \\ \star & \star & -E^T\mathscr{Z}_{gi}E \end{bmatrix}\zeta, \tag{36}$$

where

$$\zeta=\begin{bmatrix}\varsigma(t)\\ \varsigma\left(t-\overline{a}_g\right)(t)\\ \varsigma\left(t-\overline{a}_g\right)\end{bmatrix}. \tag{37}$$

Recalling the triggering condition (6), $t\in[i_kh+\tau_{i_k}, i_{k+1}h+\tau_{i_{k+1}})$ we have

$$e^k(t)^T\mathcal{O}e^k(t)\le\sqrt{\varrho}y(t-d(t))^T\mathcal{O}y(t-d(t)), \tag{38}$$

which is equivalent to

$$y(t-d(t))^T\mathcal{O}y(t-d(t))=\varsigma(t-d(t))^TH^T\mathscr{C}_i^T\mathcal{O}\mathscr{C}_iH\varsigma(t-d(t)). \tag{39}$$

Now, characterize the augmented matrix:

$$\zeta(t)=\mathrm{col}\left[\mathscr{E}\varsigma(t),\varsigma(t-\hbar_1(t),\varsigma(t-\overline{\hbar}_1),\varsigma(t-\hbar_2(t),\varsigma(t-\overline{\hbar}_2),\zeta\left(t-d(t),\zeta(t-d_M),e^k(t),w(t)\right].\tag{40}$$

Combining (36)–(39) with event-triggering mechanism (6), we obtain

$$\begin{aligned}\mathscr{F}\mathscr{V}(x_t,i,t)-\mathscr{J}(t)\le{}&\varsigma(t)^T\left(\sum_{j=1}^{s}\pi_{ij}\mathscr{E}^T\mathscr{P}_j\mathscr{E}+\sum_{g=1}^{3}\left(\mathscr{Q}_{gi}+\mathscr{R}_{gi}+\overline{a}_g\mathscr{S}_g\right)\right)\varsigma(t)+2\varsigma(t)^T\mathscr{P}_i\dot{\varsigma}(t)\\&-\sum_{g=1}^{3}\left(1-\dot{a}_g\right)\varsigma\left(t-a_g\right)^T\mathscr{Q}_{gi}\varsigma\left(t-a_g\right)-\sum_{g=1}^{3}\varsigma\left(t-\overline{a}_g\right)^T\mathscr{R}_{gi}\varsigma\left(t-\overline{a}_g\right)-\dot{\varsigma}(t)^T\\&\cdot\left(\sum_{g=1}^{3}\left(\overline{a}_g^2\mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E}+\frac{1}{2\overline{a_g}^2\mathscr{W}_g}\right)\right)\dot{\varsigma}(t)\\&+\sum_{g=1}^{3}\int_{t-a_g}^{t}\varsigma(s)^T\mathscr{J}_{gi}^1\varsigma(v)\mathrm{d}v+\sum_{g=1}^{3}\int_{t-\overline{a}_g}^{t-a_g}\varsigma(s)^T\mathscr{J}_{gi}^2\varsigma(s)\mathrm{d}s+\sum_{g=1}^{3}\overline{a}_g\int_{-\overline{a}_g}^{0}\int_{t+\gamma}^{t}\dot{\varsigma}(s)^T\mathscr{J}_{gi}^3\dot{\varsigma}(s)\mathrm{d}s\,\mathrm{d}\gamma\\&+\sum_{g=1}^{3}\left(\begin{bmatrix}\varsigma(t)\\ \varsigma\left(t-\overline{a}_g\right)(t)\\ \varsigma\left(t-\overline{a}_g\right)\end{bmatrix}^T\begin{bmatrix}-\mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E} & \mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E}-\mathscr{E}^T\mathscr{M}_{gi}\mathscr{E} & \mathscr{E}^T\mathscr{M}_{gi}\mathscr{E}\\ \star & -2\mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E}+\mathscr{E}\mathscr{M}_{gi}\mathscr{E}+\mathscr{E}^T\mathscr{M}_{gi}^T\mathscr{E} & \mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E}-\mathscr{E}^T\mathscr{M}_{gi}\mathscr{E}\\ \star & \star & -\mathscr{E}^T\mathscr{Z}_{gi}\mathscr{E}\end{bmatrix}\right.\\&\left.\cdot\begin{bmatrix}\varsigma(t)\\ \varsigma\left(t-\overline{a}_g\right)(t)\\ \varsigma\left(t-\overline{a}_g\right)\end{bmatrix}\right)+\sqrt{\varrho}x(t-d(t))^T\mathcal{O}x(t-d(t))-\sqrt{\varrho}e^k(t)^T\mathcal{O}e^k(t).\end{aligned}\tag{41}$$

At that point, it is obtained that

$$\mathscr{V}(x_t,i,t)-\mathscr{J}(t)\le\zeta^T(t)\Xi_{ij}\zeta(t). \tag{42}$$

Note that

$$\mathscr{Z}_i=\mathscr{P}_i\left[\mathscr{P}_i\mathscr{Z}_i^{-1}\mathscr{P}_i\right]\mathscr{P}_i\le\mathscr{P}_i[2\mathscr{P}_i-\mathscr{Z}_i]^{-1}\mathscr{P}_i. \tag{43}$$

This implies that

$$\Xi_{ij}\le\begin{bmatrix}\Gamma_{ij}^{11} & \Lambda_{ij}^T\\ \star & -\Phi_3\end{bmatrix}+\begin{bmatrix}\mathscr{A}^T\\ \mathscr{D}^T\end{bmatrix}\mathscr{P}_i[2\mathscr{P}_i-\mathscr{Z}_i]^{-1}\mathscr{P}_i\begin{bmatrix}\mathscr{A}^T\\ \mathscr{D}^T\end{bmatrix}^T+\begin{bmatrix}\mathscr{E}^T\\ 0\end{bmatrix}\widetilde{\Phi}_1^T\widetilde{\Phi}_1\begin{bmatrix}\mathscr{E}^T\\ 0\end{bmatrix}^T. \tag{44}$$

By applying Schur complement results in theorem LMI, the matrix on the right-hand side of (44) is negative definite which confirms that $\Gamma_{ij} \leq 0$ This along with (36) concludes

$$\mathscr{F}\mathscr{V}(x_t, i, t) - \mathscr{J}(t) \leq 0. \tag{45}$$

Therefore, further calculations are similar to [55], Theorem 1, so it is not difficult to formulate that system error dynamics is extended dissipative from Definition 1. So, this proof is completed. □

3.1. Markovian Controller Designing. For system (18), the main results for the solvability of Markovian observer-based controller is presented as follows.

Theorem 2. *For the given scalars ε_ℓ satisfying $0 < \varepsilon_\ell < 1$, and $\varepsilon_0 + \varepsilon_1 + \varepsilon_2 = 1$ with $\gamma > 0$, augmented system (18) is impulse-free with the dissipative performance index which fulfils the conditions of time-varying delays (20) under event-triggered scheme (6); if there exist matrices $\mathscr{G} > 0$, $\mathscr{P}_i > 0$, $\widetilde{\mathscr{Q}}_{gi} > 0$, $\widetilde{\mathscr{R}}_{gi} > 0$, $\widetilde{\mathscr{S}}_g > 0$, $\widetilde{\mathscr{Z}}_{gi} > 0$, $\widetilde{\mathscr{W}}_g > 0$, $\widetilde{\mathscr{O}} > 0$, and $\widetilde{\mathscr{M}}_{gi}$, Y_j such that $g = 1, 2, 3$ and $r_t = i \in \mathbb{S}$; (29) and the following inequality holds:*

$$\sum_{j=1}^{s} \pi_{ij}\left(\widetilde{\mathscr{Q}}_{gj} + \widetilde{\mathscr{R}}_{gj}\right) - \widetilde{\mathscr{S}}_g < 0, \tag{46}$$

$$\sum_{j=1}^{s} \pi_{ij}\widetilde{\mathscr{R}}_{gj} - \widetilde{\mathscr{S}}_g < 0, \tag{47}$$

$$\sum_{j=1}^{s} \pi_{ij}\widetilde{\mathscr{Z}}_{gj} - \frac{1}{\overline{a}_g}\widetilde{\mathscr{W}}_g < 0, \tag{48}$$

$$\begin{gathered} \widetilde{\mathscr{G}} - \widetilde{\mathscr{P}}_i < 0, \\ \begin{bmatrix} \widetilde{\mathscr{Z}}_{gi} & \widetilde{\mathscr{M}}_{gi} \\ \star & \widetilde{\mathscr{Z}}_{gi} \end{bmatrix} > 0, \end{gathered} \tag{49}$$

$$\begin{bmatrix} \Xi_{ij} & \Lambda_{ij}^T & \widetilde{\mathscr{A}} & \mathscr{E}\widetilde{\Phi}_1^T \\ \star & -\Phi_3 & \exists_{ij}^{16^T} & 0 \\ \star & \star & \widehat{\mathbf{Z}} - 2\widetilde{\mathscr{P}}_i & 0 \\ \star & \star & \star & -I \end{bmatrix} < 0, \tag{50}$$

where $\widehat{\mathbf{Z}} = \sum_{g=1}^{3} (\overline{\hbar}_g^2 \widetilde{\mathscr{Z}}_{gi} + 0.5\overline{\hbar}_g^2 \widetilde{\mathscr{W}}_g)$ *and*

$$\begin{aligned}
\Xi_{ij} = \Bigg[&(1,1) = \left(\sum_{j=1}^{s} \pi_{ij}\mathscr{E}^T\mathscr{P}_j\mathscr{E} + \exists_{ij}^{11} + \exists_{ij}^{11^T} + \sum_{g=1}^{3}\left(\widetilde{\mathscr{Q}}_{gi} + \widetilde{\mathscr{R}}_{gi} - \mathscr{E}^T\widetilde{\mathscr{Z}}_{gi}\mathscr{E} + \overline{a}_g\widetilde{\mathscr{S}}_g\right)\right) \\
&(1,2) = \exists_{ij}^{12} + \mathscr{E}^T\widetilde{\mathscr{Z}}_{1i}\mathscr{E} - \mathscr{E}^T\widetilde{\mathscr{M}}_{1i}\mathscr{E},\ (1,3) = \mathscr{E}^T\widetilde{\mathscr{M}}_{1i}\mathscr{E},\ (1,4) \\
&(1,5) = \mathscr{E}^T\widetilde{\mathscr{M}}_{2i}\mathscr{E},\ (1,6) = \exists_{ij}^{14} + \mathscr{E}^T\widetilde{\mathscr{Z}}_{3i}\mathscr{E} - \mathscr{E}^T\widetilde{\mathscr{M}}_{3i}\mathscr{E},\ (1,7) \\
&(2,2) = \left(1 - v_l\right)\widetilde{\mathscr{Q}}_{1i} - 2\mathscr{E}^T\widetilde{\mathscr{Z}}_{1i}\mathscr{E} + \mathscr{E}^T\widetilde{\mathscr{M}}_{1i}\mathscr{E} + \mathscr{E}^T\widetilde{\mathscr{M}}_{1i}^T\mathscr{E},\ (2,3) = \mathscr{E}^T\widetilde{\mathscr{Z}}_{1i}\mathscr{E} - \mathscr{E}^T\widetilde{\mathscr{M}}_{1i}\mathscr{E} \\
&(3,3) = -\mathscr{E}^T\widetilde{\mathscr{Z}}_{1i}\mathscr{E} - \mathscr{E}^T\widetilde{\mathscr{R}}_{1i}\mathscr{E},\ (4,4) = \left(1 - v_2\right)\widetilde{\mathscr{Q}}_{2i} - 2\mathscr{E}^T\widetilde{\mathscr{Z}}_{2i}\mathscr{E} + \mathscr{E}^T\widetilde{\mathscr{M}}_{2i}\mathscr{E} + \mathscr{E}^T\widetilde{\mathscr{M}}_{2i}^T\mathscr{E} \\
&(4,5) = \mathscr{E}^T\widetilde{\mathscr{Z}}_{2i}\mathscr{E} - \mathscr{E}^T\widetilde{\mathscr{M}}_{2i}\mathscr{E},\ (5,5) = -\mathscr{E}^T\widetilde{\mathscr{Z}}_{2i}\mathscr{E} - \mathscr{E}^T\widetilde{\mathscr{R}}_{2i}\mathscr{E} \\
&(6,6) = \left(1 - d_M\right)\widetilde{\mathscr{Q}}_{3i} - 2\mathscr{E}^T\widetilde{\mathscr{Z}}_{3i}\mathscr{E} + \mathscr{E}^T\widetilde{\mathscr{M}}_{3i}\mathscr{E} + \mathscr{E}^T\widetilde{\mathscr{M}}_{3i}^T\mathscr{E} + \mathscr{C}_i^T\widetilde{\mathscr{O}}\mathscr{C}_i \\
&(6,7) = \mathscr{E}^T\widetilde{\mathscr{Z}}_{3i}\mathscr{E} - \mathscr{E}^T\widetilde{\mathscr{M}}_{3i}\mathscr{E},\ (7,7) = -\mathscr{E}^T\widetilde{\mathscr{Z}}_{3i}\mathscr{E} - \mathscr{E}^T\widetilde{\mathscr{R}}_{3i}\mathscr{E},\ (8,8) = -\widetilde{\mathscr{O}}\Bigg],
\end{aligned}$$

$$\begin{aligned}
\Lambda_{ij} &= \left[\, -\Phi_2^T\Delta_{ij}^{11} + \exists_{ij}^{16} \ \ -\Phi_2^T\Delta_{ij}^{12} \ \ 0 \ \ -\Phi_2^T\Delta_{ij}^{13} \ \ 0 \ \ 0 \ \ 0 \ \ 0 \,\right], \\
\widetilde{\mathscr{A}} &= \operatorname{col}\left[\, \exists_{ij}^{11^T} \ \ \exists_{ij}^{12^T} \ \ 0 \ \ \exists_{ij}^{13^T} \ \ 0 \ \ \exists_{ij}^{14^T} \ \ 0 \ \ \exists_{ij}^{15^T} \,\right], \\
\mathscr{E} &= \operatorname{col}\left[\, \Delta_{ij}^{11} \ \ \Delta_{ij}^{12} \ \ 0 \ \ \Delta_{ij}^{13} \ \ 0 \ \ 0 \ \ 0 \ \ 0 \,\right], \\
\exists_{ij}^{11} &= \begin{bmatrix} \mathscr{A}_iX_i^T + \mathscr{B}_iY_i & -\mathscr{B}_iY_i \\ 0 & \mathscr{A}_iX_i^T - F_j\mathscr{C}_i \end{bmatrix}, \\
\exists_{ij}^{12} &= \begin{bmatrix} \mathscr{A}_{\hbar_1}X_i^T & 0 \\ \mathscr{A}_{\hbar_1}X_i^T & 0 \end{bmatrix}, \\
\exists_{ij}^{13} &= \begin{bmatrix} 0 & 0 \\ \mathscr{A}_{\hbar_2}X_i^T & 0 \end{bmatrix},
\end{aligned}$$

$$\begin{aligned}
\exists_{ij}^{14} &= \begin{bmatrix} 0 & 0 \\ F_j\big(I+\Pi_i\nabla_f(t)\big)\mathscr{C}_i & F_j\big(I+\Pi_i\nabla_f(t)\big)\mathscr{C}_i \end{bmatrix},\\
\exists_{ij}^{15} &= \begin{bmatrix} 0 \\ F_j\big(I+\Pi_i\nabla_f(t)\big)\mathscr{C}_i \end{bmatrix},\\
\exists_{ij}^{16} &= \begin{bmatrix} X_i\mathscr{D}_i \\ X_i\mathscr{D}_i \end{bmatrix},\\
\Delta_{ij}^{11} &= \begin{bmatrix} 0 \\ X_i\mathscr{E}_i^T \end{bmatrix},\\
\Delta_{ij}^{12} &= \begin{bmatrix} X_i\mathscr{E}_{\hbar_{1i}}^T \\ 0 \end{bmatrix},\\
\Delta_{ij}^{13} &= \begin{bmatrix} 0 \\ X_i\mathscr{E}_{\hbar_{2i}}^T \end{bmatrix}.
\end{aligned} \tag{51}$$

From the abovementioned calculation, controller and observer gains are given as follows:

$$\begin{aligned}
\mathscr{K}_j &= Y_jX_i^{-1},\\
\mathscr{L}_j &= F_jOSX_i^{-1}S^{-1}O^{-1}.
\end{aligned} \tag{52}$$

Proof. Define the following matrices to achieve the desired gain: $X_i = \widetilde{\mathscr{P}}_j^{-1}$, $X_i\mathscr{Q}_{gi}X_i^T = \widetilde{\mathscr{Q}}_{gi}$, $X_i\mathscr{R}_{gi}X_i^T = \widetilde{\mathscr{R}}_{gi}$, $X_i\mathscr{Z}_{gi}X_i^T = \widetilde{\mathscr{Z}}_{gi}$, $X_i\mathscr{R}_{Mi}X_i^T = \widetilde{\mathscr{M}}_{gi}$, $X_i\mathscr{S}_gX_i^T = \widetilde{\mathscr{S}}_g$, and $X_i\mathscr{W}_gX_i^T = \widetilde{\mathscr{W}}_g$. For $X_i = \mathscr{V}\begin{bmatrix} X_{1i} & \star \\ \star & X_{2i}\end{bmatrix}\mathscr{V}^T$. As per Lemma 1, which implies $\widetilde{X}_i = OSX_{1i}S^{-1}O^{-1}$, let $\mathscr{C}_iX_i = \widetilde{X}_i\mathscr{C}_i$, where $\widetilde{X}_i^{-1} = OSX_{1i}^{-1}S^{-1}O^{-1}$.

By post- and premultiplication of $\left\{X_i, \underbrace{X_i, \ldots X_i}_{6}, X_i, I, X_i, I\right\}$ and its transpose to (30), which yields to (49), then, it is confirmed that $X_i > 0$, $\mathscr{G} > 0$, $\widetilde{\mathscr{Q}}_{gi} > 0$, $\widetilde{\mathscr{R}}_{gi} > 0$, $\widetilde{\mathscr{Z}}_{gi} > 0$, $\widetilde{\mathscr{S}}_g > 0$, and $\widetilde{\mathscr{W}}_g > 0$. When the LMIs in (46)–(50) are feasible, all the mentioned conditions in Theorem 2 are fulfilled. Proof completed. □

4. Simulation Examples

In this section, we present two examples, first example is presented for the comparison to show the effectiveness of the proposed algorithms, while in Example 2 provide the most motivated practical example of DC motor with ETC-strategy, in which one of the states is composed of time-varying delay.

Example 1. In this example, we considered the descriptor Markov jump system (1) with associated modes $\mathbb{S} = \{1, 2\}$ and $\mathscr{E} = I$. Moreover, the jumping mode is assigned by the following rate matrix:

$$\Pi = \begin{bmatrix} -0.4 & 0.4 \\ 0.8 & -0.8 \end{bmatrix}. \tag{53}$$

To make the comparison, we borrow the example from [58]:

$$\begin{bmatrix} \mathscr{A}_1 & \mathscr{A}_{\hbar_1} & \mathscr{D}_1 & \mathscr{C}_1' \\ \mathscr{A}_2 & \mathscr{A}_{\hbar_2} & \mathscr{D}_2 & \mathscr{C}_2' \end{bmatrix} = \left[\begin{array}{cc|cc|c|c} -3.5 & 0.8 & -0.9 & -1.3 & 0.5 & 0.1 \\ -0.6 & -3.3 & -0.7 & -2.1 & 0.4 & 0.3 \\ \hline -2.5 & 0.3 & -2.8 & 0.5 & 0.3 & 0.2 \\ 1.4 & -0.1 & -0.8 & -1.0 & 0.2 & 0.15 \end{array}\right]. \tag{54}$$

Now, the descriptor Markovian jump system with time delay reduces to a regular Markovian jump time-delay system. Furthermore, we consider system (21) with $\omega(t) = 0$ and $\Pi_{22} = -0.8$. In papers [58–60], we obtained the upper bound delay which is listed in Table 1. We simulate this result together with maximum admissible upper bound for constant delay $\hbar$ with various Π_{11} obtained in this paper. It is worth mentioning that delay-dependent conditions achieved in Theorem 2 yields efficient results rather than those attained in [58–60].

Example 2. In this example, we present the most practical approach example, that is, DC motor driving a load that changes suddenly and randomly, which is given in [56, 57]. The block diagram of the DC motor system is given in Figure 1. Before going to details of the dynamics of the DC motor system, first we define system parameters. Let $u(t)$, $i(t)$, and $\varpi(t)$ present the voltage, electric current, and speed of shaft at time t, respectively. Based on the electrical and mechanical rules, if we ignore the DC motor inductance L_m, we have

$$\begin{cases} \dot{\varpi}(t) = -\dfrac{b_i}{J_i}\varpi(t) + \dfrac{K_t}{J_i}i(t), \\ u(t) = K_{\varpi}\varpi(t) + R_i(t). \end{cases} \tag{55}$$

Table 1: Maximum allowable upper bounds for time delay $\hbar_i$.

Π_{11}	−0.4	−0.55	−0.7	−0.85	−1.00
[59]	0.6078	0.5894	0.5768	0.5675	0.5603
[60]	0.6322	0.6120	0.5918	0.5881	0.5805
[58]	0.8181	0.7815	0.7597	0.7473	0.7377
Theorem 2	1.1208	0.8471	0.8157	0.7941	0.7881

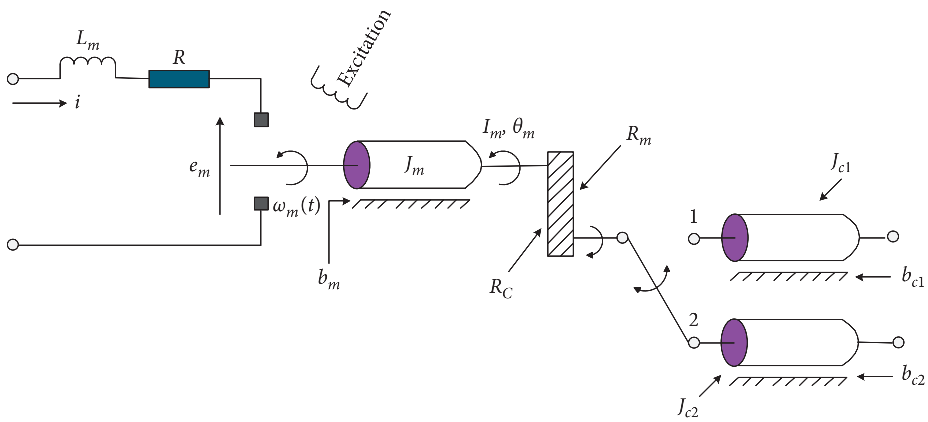

Figure 1: Block diagram of the DC motor [56, 57].

In the abovementioned equations, K_t denotes the torque constant and K_ϖ represents the electromotive force. While, R_i is an electric resistor, b_i and J_i are defined as follows:

$$\begin{cases} b_i = b_m + \dfrac{b_{ci}}{n^2}, \\ J_i = J_m + \dfrac{J_{ci}}{n^2}, \end{cases} \tag{56}$$

where b_m and b_{ci} are the damping ratio with gear ratio n, while J_m and J_{ci} are the moments of motor and load, respectively. Let $x_{1(t)} = \varpi(t)$ and $x_2(t) = i(t)$, then the abovementioned system can be rewritten as follows:

$$\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \dot{x}(t) = \begin{bmatrix} -\dfrac{b_i}{J_i} & \dfrac{K_t}{J_i} \\ K_\varpi & R \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t). \tag{57}$$

For the simulation, we select the suitable time delay for the abovementioned system (57), which becomes

$$\mathscr{E}\dot{x}(t) = \mathscr{A}(r_t)x(t) + \mathscr{A}_{\hbar_1}(r_t)x(t - \hbar_1(t)) + \mathscr{B}\cdot(r_t)u(t). \tag{58}$$

Now, (58) becomes

$$\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \dot{x}(t) = \begin{bmatrix} -\dfrac{b_i}{J_i} & \dfrac{K_t}{J_i} \\ K_\varpi & R \end{bmatrix} x(t) + \mathscr{A}_{\hbar_1}(r_t)x(t - \hbar_1(t)) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t), \tag{59}$$

where

$$\mathscr{A}_{\hbar_1}(1) = \begin{bmatrix} 0 & 0 \\ 0.4 & 0 \end{bmatrix}, \quad \mathscr{A}_{\hbar_1}(2) = \begin{bmatrix} 0 & 0 \\ 0.6 & 0 \end{bmatrix}. \tag{60}$$

Remaining parameters of system (1) are

$$\begin{bmatrix} \mathscr{E}_1 & \mathscr{E}_{\hbar_1} & \mathscr{C}_1 & \mathscr{D}_1 \\ \mathscr{E}_2 & \mathscr{E}_{\hbar_2} & \mathscr{C}_2 & \mathscr{D}_1 \end{bmatrix} = \left[\begin{array}{cc|cc|cc|c} 0.1 & 0 & 0.4 & 0.8 & 1 & 0 & 0.1 \\ \hline -0.2 & -0.5 & 0.2 & 0.5 & 1 & 0 & -0.5 \end{array}\right]. \tag{61}$$

Now, we are in a position to design the state feedback controller such that the abovementioned system (59) is stochastically stable. For the continuous Markovian jump system, the switching mode is driven $t_t, t \geq 0$ getting values over the span $\mathbb{S} = \{1, 2\}$, and transition probability matrix is assigned by

$$\Pi = \begin{bmatrix} -0.0193 & 0.0193 \\ 0.0307 & -0.0307 \end{bmatrix}. \tag{62}$$

We assume that the time-varying delay is given by

$$\hbar_i(t) = \frac{\overline{\hbar}_i + \overline{\hbar}_i \sin(2\mu_i t/\overline{\hbar}_i)}{2}, \quad i = 1, 2, \tag{63}$$

where $(\overline{\hbar}_1, \overline{\hbar}_2) = (1, 1.5)$ and $(\mu_1, \mu_2) = (0.22, 0.45)$. It is seen that the delays satisfy the condition in (20). Moreover, the external disturbance is assumed to be of the following form:

$$\omega(t) = \begin{cases} 1, & 5 \leq t \leq 10, \\ -1, & 15 \leq t \leq 20, \\ 0, & \text{elsewhere}. \end{cases} \tag{64}$$

By choosing the initial condition as $\phi(t) = [0.5, -0.75]^T$ and $\tilde{\phi}(t) = [-0.5, 0.75]^T$ with quantization density ρ_{f_s} as 0.01. Numerical values are $(J_{c1}, J_{c2}) = (50\,\mathrm{kg\,m}, 150\,\mathrm{kg\,m})$, $(J_m, b_m) = (0.5\,\mathrm{kg\,m}, 1)$, $(b_{c1}, b_{c2}) = (100, 240)$, $(R_1, R_2) = (0.3, 0.4)$, $(S_1, S_2, R) = (0.1, 0.1, 1)$, and $(K_t, K_\varpi) = (3\,\mathrm{N\,m/A}, 1\,\mathrm{V\,s/rad})$ with $n = 10$. In the following three cases, we presented the H_∞ control, dissipative control, and $L_2 - L_\infty$ control, respectively. In order to get the feasible solution of Theorem 2, we select $(\varepsilon_1, \varepsilon_2, \varepsilon_3) = 0.25$.

Case 1. $\mathscr{H}_\infty$ controller.

Let $\Theta = 0$, $\Phi_1 = 0$, $\Phi_2 = 0$, and $\Phi_3 = \gamma^2$. γ is chosen to be 2.5. It is observed that the feasible solution of LMI (29) and (46)–(50) with trigger matrix $\widetilde{\mathcal{O}} = 2.8541$ and feasible results in the controller and observer gain are given as follows:

$$\left[\begin{array}{c|c} X_1 & X_2 \\ Y_1 & Y_2 \end{array}\right] = \left[\begin{array}{cc|cc} 83.4843 & -44.9881 & 91.8379 & -47.5966 \\ -44.9881 & 65.0896 & -47.5966 & 64.6817 \\ \hline -53.5655 & -126.6159 & -48.4015 & -173.4393 \end{array}\right],$$

$$\begin{bmatrix} \mathscr{K}_1 \\ \mathscr{K}_2 \end{bmatrix} = \begin{bmatrix} -2.6929 & -3.8065 \\ -3.0984 & -4.9614 \end{bmatrix}, \quad \begin{bmatrix} \mathscr{L}_1 \\ \mathscr{L}_2 \end{bmatrix}^T = \begin{bmatrix} 14.5538 & 23.7956 \\ -25.2628 & -28.3751 \end{bmatrix}^T. \tag{65}$$

The estimated states of the DC motor system are demonstrated in Figures 2 and 3, which means that the closed-loop system is stochastically stable, while quantized control input is presented in Figure 4. These simulation results show that the designed controller and observer meet the specified requirements.

Case 2. Dissipative controller.

Let $\Theta = 0$, $\Phi_1 = 0$, $\Phi_2 = 0$, and $\Phi_3 = \gamma^2$. γ is chosen to be 2.5. It is observed that the feasible solution of LMI (29) and (46)–(50) with trigger matrix $\widetilde{\mathcal{O}} = 2.9761$ and feasible results in the controller and observer gain are given as follows:

$$\left[\begin{array}{c|c} X_1 & X_2 \\ Y_1 & Y_2 \end{array}\right] = \left[\begin{array}{cc|cc} 12.5396 & -6.5088 & 13.7039 & -7.0160 \\ -6.5088 & 9.9039 & -7.0160 & 9.7328 \\ \hline -8.4926 & -19.1462 & -7.5232 & -25.8167 \end{array}\right],$$

$$\begin{bmatrix} \mathscr{K}_1 \\ \mathscr{K}_2 \end{bmatrix} = \begin{bmatrix} -2.5509 & -3.6097 \\ -3.0225 & -4.8313 \end{bmatrix}, \quad \begin{bmatrix} \mathscr{L}_1 \\ \mathscr{L}_2 \end{bmatrix}^T = \begin{bmatrix} 2.1323 & 3.5385 \\ -3.9795 & -4.4256 \end{bmatrix}^T. \tag{66}$$

Then, the dissipative controller parameters can be calculated in the form of (52). The behaviour of the quantized measured output is presented in Figure 5. While in Figure 6, it depicts the transmit instants and the transmit intervals with given the simulation time $T = 30$ sec. Dissipativity represents the ratio of supplied energy from outside the system to energy storage inside the system. So, this factor is very important from the electrical circuit point of view. That is why we considered this analysis for our paper.

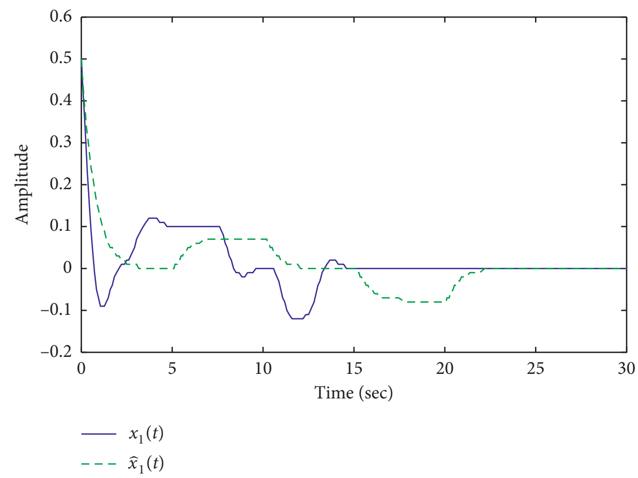

FIGURE 2: Response of state $x_1(t)$ with estimation $\hat{x}_1(t)$ for case-I.

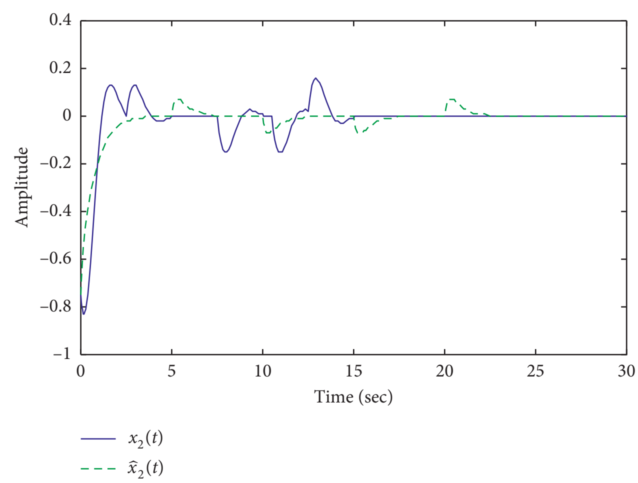

FIGURE 3: Response of state $x_2(t)$ with estimation $\hat{x}_2(t)$ for case-I.

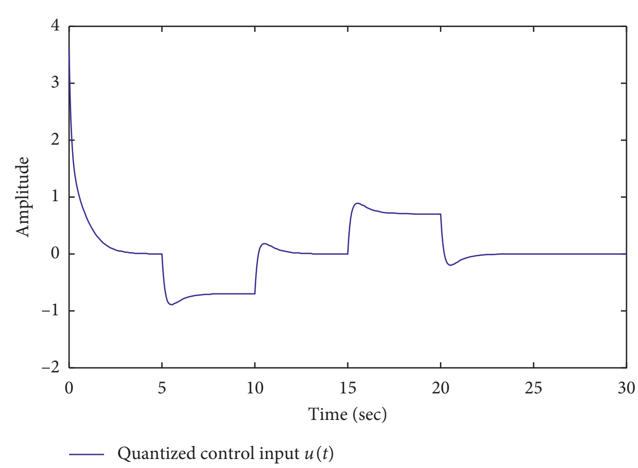

FIGURE 4: Response of the quantized control input for case-I.

Case 3. $\mathscr{L}_2 - \mathscr{L}_\infty$ controller.

Let $\Theta = 0$, $\Phi_1 = 0$, $\Phi_2 = 0$, and $\Phi_3 = \gamma^2$. γ is chosen to be 2.5. It is observed that the feasible solution of LMI (29) and

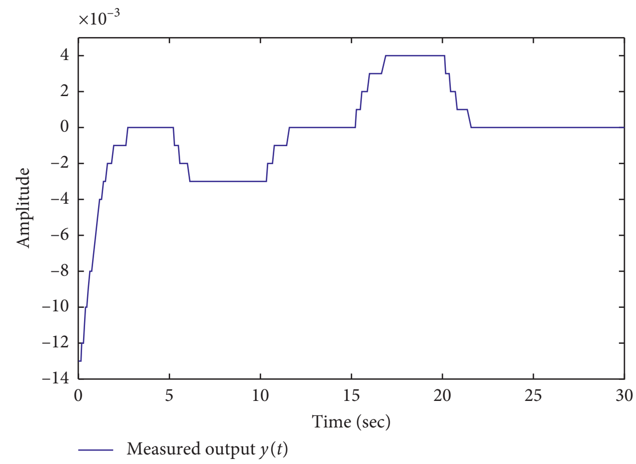

Figure 5: Response of the quantized measured output $y(t)$ for case-II.

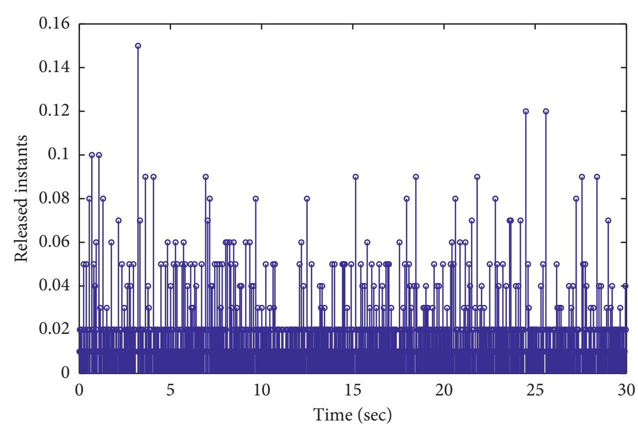

Figure 6: Transmit time and transmit interval for case-II.

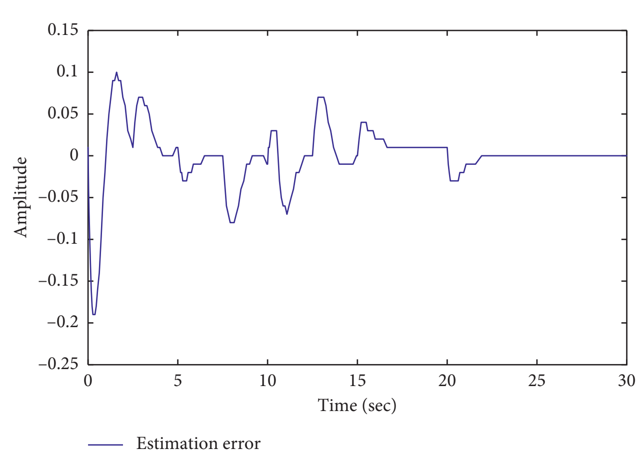

Figure 7: Response of the estimation error for case-III.

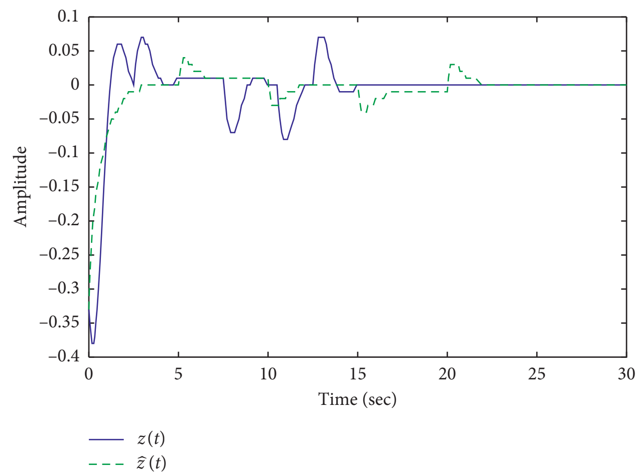

Figure 8: Response of the estimation error for case-III.

(46)–(50) with trigger matrix $\widetilde{\mathcal{O}} = 3.2417$ and feasible results in the controller and observer gain are given as follows:

$$\begin{aligned}
&\left[\begin{array}{c|c} X_1 & X_2 \\ Y_1 & Y_2 \end{array}\right] = \left[\begin{array}{cc|cc} 95.0242 & -51.1864 & 104.5699 & -54.2314 \\ -51.1864 & 74.1306 & -54.2314 & 73.6577 \\ \hline -61.0344 & -144.1278 & -55.1494 & -197.5640 \end{array}\right], \\
&\begin{bmatrix} \mathcal{K}_1 \\ \mathcal{K}_2 \end{bmatrix} = \begin{bmatrix} -2.6902 & -3.8018 \\ -3.1034 & -4.9671 \end{bmatrix}, \begin{bmatrix} \mathcal{L}_1 \\ \mathcal{L}_2 \end{bmatrix}^T = \begin{bmatrix} 16.5625 & 27.0879 \\ -28.7872 & -32.3038 \end{bmatrix}^T.
\end{aligned} \tag{67}$$

Figure 7 illustrates the behavior of estimation error signal $e(t)$, and it is observed that, finally, the error reaches to zero. Response of $z(t)$ and $\hat{z}(t)$ is shown in Figure 8, which shows that these values finally approach to zero.

5. Conclusions

In this paper, a dissipative observer-based output feedback control is considered for Markovian descriptor jump systems with time-varying delay under the networked control system. The event triggered scheme is used for the effective utilization of bandwidth. The control objective is achieved by the successful design of the observer with time-varying delay. The criteria for stability and stabilization are based on communication delays which results in the formation of LMI. The proposed method is validated through a practical simulation example of the DC motor system. One of the important aspects of network control is packet loss which affects the control performance of the systems. Combining the effects of packet loss and delay is an interesting challenging problem to extend the proposed method to T-S fuzzy for multiagent systems. In addition, it is worth mentioning that the scheme developed in this paper can be extended to other dynamic systems, such as neural networks and sampled-data systems with random time-varying delays, which will be our future research. Future work will focus on the filtering problem for networked Markov jump systems with network attack, partially unknown jump information, and packet loss phenomena.

Data Availability

Data used to support the findings of this work are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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