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Robust Stabilization of Singular Markovian Jump Systems with Uncertain Switching

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Abstract: This paper focuses on the robust stabilization problem for a class of singular Markovian jump systems with uncertain switching probabilities. Based on a slack matrix method on transition probabilities, a new criterion for quadratically stochastic admissibility of such an uncertain system is established. Then, two new sufficient conditions for the existence of mode-dependent controller are given as linear matrix inequalities. Especially, a more practical controller named as mode-independent controller is derived by a mode-dependent Lyapunov function. Finally, a numerical example is used to demonstrate the effectiveness of the proposed methods.

Keywords: Linear matrix inequalities (LMIs), singular Markovian jump systems, uncertain switching probability.

1. INTRODUCTION

Many practical dynamics, e.g., aircraft control, solar receiver control, and power systems, experience abrupt changes in their structures, whose parameters are caused by phenomena such as component failures or repairs. This class of system named as Markovian jump systems (MJSs) involves both time-evolving and event-driven mechanisms, which has the advantage of better representing these practical systems with different structures due to random abrupt changes. During the past decades, a lot of attention has been devoted to the study of such system, see e.g., [1-5].

On the other hand, singular systems have convenient representation in the description of practical systems [6,7]. Compared with normal state-space systems, singular systems are more complicated, which have three types of modes, namely, finite dynamic modes, impulsive modes and non-dynamic modes. It is said that the latter two kinds of modes are not included in normal systems. In recent years, many research topics of singular system have been extensively studied, see e.g., [8-11]. When singular systems experience abrupt changes in their structures, it is natural to model them as singular Markovian jump systems (SMJSs) [12,13]. Recently, the control and filtering problems of continuous-time singular systems were proposed in [14-18].

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It is worth pointing out that most of the works done on the analysis and synthesis of MJSs have an important assumption that the switching probabilities of the underlying Markov chain are known precisely. However, in practical applications, these values are often needed to be measured, and it is very hard and higher cost to obtain all the mode transition rates (MTRs) precisely. Instead, only the estimations of MTR are obtained. In this case, measurement errors also referred to switching probability uncertainties are inevitable, and this error can lead to instability or degrade the performance of a system such as uncertainty in system matrices. So, it is important and necessary to consider the robust control and filtering problems of MJSs with uncertain transition rate matrix (TRM) between the actual and estimated values. A model with uncertain switching probabilities has been proposed in [19] and [20], and the desired controllers are given in terms of a set of coupled algebraic Riccati equations. Via considering the inherent probability constraints on rows of TRM, improved results on stabilization and H_∞ filtering were presented in [21] and [22], which were given in terms of a set of LMIs with equation constraints. Because the criteria in references [19-22] on normal state-space MJSs with uncertain TRM are not LMIs, it is meaningful to study the similar problems of MJSs with uncertain switching probabilities under an LMI framework. More importantly, because of singular matrix and Markov property of SMJSs, it makes the system synthesis not easy, and the methods in the afore-referred references about normal state-space MJSs with uncertain switching cannot be applied to SMJSs with uncertain TRM. To the best of our knowledge, the stabilization problem of continuous-time SMJSs with uncertain switching probability has not been fully investigated, which motivates the current research.

In this paper, the aim is to design a controller coming from an LMI condition such that, over all the admissible uncertainties in TRM, the closed-loop system is quadratically stochastically admissible. The main contributions of this paper are follows: (1) a novel condition for quadratically stochastic admissibility of SMJSs with uncertain switching is obtained by using a slack matrix method on transition probabilities; (2) Based on the obtained result, two approaches to a mode-dependent controller stabilizing an SMJSs with uncertain switching are presented in terms of LMIs; (3) A special but more practical case is considered, in which a kind of controller stabilizing the uncertain SMJS without any mode information is proposed.

2. PROBLEM FORMULATION

Consider a class of SMJSs described as

$$E\dot{x}(t) = A(\eta(t))x(t) + B(\eta(t))u(t), \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^m$ is the control input. Matrix $E \in \mathbb{R}^{n\times n}$ may be singular, which is assumed to be rank $\text{rank}(E) = r < n.$ $A(\eta(t))$ and $B(\eta(t))$ are known matrices of compatible dimensions. The mode $\{\eta(t), t \ge 0\}$ is a continuous-time Markov process taking values in a finite set $S = \{1, 2, ..., N\}$ with transition probabilities

$$\Pr\{\eta(t+\Delta) = j \mid \eta(t) = i\} = \begin{cases} \tilde{\pi}_{ij}\Delta + o(\Delta) & i \ne j \\ 1 + \tilde{\pi}_{ii}\Delta + o(\Delta) & i = j, \end{cases} \tag{2}$$

where $\Delta > 0,\ \lim_{\Delta\to 0^+} (o(\Delta)/\Delta) = 0$ and $\tilde{\pi}_{ij} \ge 0,$ for $i, j \in S,\ i \ne j,$ is the transition rate from mode i at time t to mode j at $t+\Delta$ and $\tilde{\pi}_{ii} = -\sum_{j=1, j\ne i}^{N} \tilde{\pi}_{ij}.$

In this paper, the actual TRM $\tilde{\Pi} \triangleq (\tilde{\pi}_{ij})$ cannot be obtained exactly. Instead, we only know that it satisfies the following admissible uncertainty

$$\tilde{\Pi} \triangleq \Pi + \Delta\Pi \text{ with } \left|\Delta\pi_{ij}\right| \le \varepsilon_{ij}, \quad \varepsilon_{ij} \ge 0, \quad j \ne i. \tag{3}$$

In (3), TRM $\Pi \triangleq (\pi_{ij})$ is the known constant estimation of $\tilde{\Pi}$ with $\pi_{ij} \ge 0,\ j \ne i$ and $\pi_{ii} = -\sum_{j=1, j\ne i}^{N} \pi_{ij}.$ In matrix $\Delta\Pi \triangleq (\Delta\pi_{ij}),\ \Delta\pi_{ij} \triangleq \tilde{\pi}_{ij} - \pi_{ij}$ denotes the estimated error, and $\Delta\pi_{ii}$ is also expressed by $\Delta\pi_{ii} = -\sum_{j=1, j\ne i}^{N} \Delta\pi_{ij}.$ It is assumed that $\Delta\pi_{ij},\ j \ne i,$ takes any value in $[-\varepsilon_{ij}, \varepsilon_{ij}],$ and $\alpha_{ij} \triangleq \pi_{ij} - \varepsilon_{ij}$ Then, it is concluded that $\left|\Delta\pi_{ii}\right| \le -\varepsilon_{ii},$ where $\varepsilon_{ii} \triangleq -\sum_{j=1, j\ne i}^{N} \varepsilon_{ij}$ and $\alpha_{ii} \triangleq \pi_{ii} - \varepsilon_{ii}.$

Definition 1: The unforced SMJS (1) is said to be quadratically stochastically admissible, if there exists P_i, such that for all $i \in S$

$$E^T P_i = P_i^T E \ge 0, \tag{4}$$

$$(A_i^T P_i)^\dagger + \sum_{j=1}^{N} \tilde{\pi}_{ij} E^T P_j < 0 \tag{5}$$

hold over the admissible uncertainty in (2), where $(A_i^T P_i)^\dagger \triangleq A_i^T P_i + P_i^T A_i.$

In this paper, a mode-dependent controller (MDC) is developed as follows:

$$u(t) = K(\eta(t))x(t), \tag{6}$$

where $K(\eta(t))$ is the designed controller gain. If the system mode is not available to a controller all time, a mode-independent controller (MIC) is constructed as

$$u(t) = Kx(t), \tag{7}$$

where K is the controller gain to be determined.

3. MAIN RESULTS

Theorem 1: The unforced SMJS (1) is quadratically stochastically admissible, if there exist P_i, $W_i = W_i^T$ and $T_i > 0,$ such that the following LMIs hold for all $i \in S$

$$E^T P_i = P_i^T E \ge 0, \tag{8}$$

$$E^T P_j - E^T P_i - W_i \le 0, \tag{9}$$

$$\begin{bmatrix} \Omega_i & W_i \\ * & -T_i \end{bmatrix} < 0, \tag{10}$$

where

$$\Omega_i = (A_i^T P_i)^\dagger + 0.25\varepsilon_{ii}^2 T_i - \varepsilon_{ii} W_i + \sum_{j=1, j\ne i}^{N} \alpha_{ij} E^T (P_j - P_i).$$

Proof: From Definition 1 and taking into account condition (3), it is concluded that (5) is equivalent to

$$\begin{aligned} &(A_i^T P_i)^\dagger + \sum_{j=1, j\ne i}^{N} \alpha_{ij} E^T (P_j - P_i) - \Delta\pi_{ii} W_i - \varepsilon_{ii} W_i \\ &\quad + \sum_{j=1, j\ne i}^{N} (\Delta\pi_{ij} + \varepsilon_{ij})(E^T P_j - E^T P_i - W_i) < 0, \end{aligned} \tag{11}$$

which could be guaranteed by

$$(A_i^T P_i)^\dagger + \sum_{j=1, j\ne i}^{N} \alpha_{ij} E^T (P_j - P_i) - \Delta\pi_{ii} W_i - \varepsilon_{ii} W_i < 0, \tag{12}$$

$$\sum_{j=1, j\ne i}^{N} (\Delta\pi_{ij} + \varepsilon_{ij})(E^T P_j - E^T P_i - W_i) < 0. \tag{13}$$

On the other hand, it is noted that, for any $T_i > 0$, one has

$$\begin{aligned} -\Delta\pi_{ii} W_i &\le 0.25(\Delta\pi_{ii})^2 T_i + W_i T_i^{-1} W_i \\ &\le 0.25\varepsilon_{ii}^2 T_i + W_i T_i^{-1} W_i. \end{aligned} \tag{14}$$

Taking into account (14), it is concluded that condition (10) implies (12). On the other hand, by (3), it is seen that (9) implies (13). Thus, one has that (4) and (5) can be guaranteed by (8)-(10). This completes the proof.

Remark 1: It should be remarked that for normal state-space MJSs with uncertain switching probabilities, some results such as [19,20] were obtained, which were more conservative and were not LMIs. Via considering the inherent probability constraint on rows of TRM, improved results with less conservatism were proposed in [21,22], which were given in terms of a set of LMIs with equality constraints. An improved cone complementarity linearization (CCL) algorithm was given to deal with such non-convex conditions. In addition, by the given computation method, it is said that the matrix coming from the Lyapunov function needs to be positive-definite. This condition is always satisfied for normal state-space MJSs, but it is not usually true for SMJSs. It is because that the corresponding matrix resulting from the Lyapunov function [12,13] is generally nonsingular. As a result, the afore-mentioned method of normal state-space MJSs with uncertain TRM is unsuitable to SMJSs with uncertain switching probabilities. In this paper, it is seen that for SMJSs with uncertain TRM, Theorem 1 develops a condition for quadratically stochastic admissibility via using a slack variable method on TRM, in which the corresponding Lyapunov matrix is not necessary positive-definite. More importantly, because of singular matrix and Markov property in SMJSs simultaneously, it makes the stabilization problem of SMJSs with uncertain switching cannot be solved directly and simply by using the existing results of normal state-space MJSs with uncertain TRM. However, on the basis of the result in Theorem 1, it makes the designs of both mode-dependent and mode-independent controllers within LMI framework stabilizing the underlying system feasible and easy. Based on the above facts, it is said that Theorem 1 is not obtained via combining the existing results directly and simply.

Now we give an LMI condition for MDC (6).

Theorem 2: Consider the uncertain SMJS (1), there exists an MDC (6) such that the resulting closed-loop system is quadratically stochastically admissible, if there exist $\hat{P}_i$, $\hat{Q}_i$, Y_i, $\overline{W}_i = \overline{W}_i^T$ and $\overline{T}_i > 0$, such that the following LMIs hold for all $i \in S$

$$\begin{bmatrix} -E\hat{P}_iE^T - \overline{W}_i & X_i^T E_R \\ * & -E_R^T\hat{P}_jE_R \end{bmatrix} \le 0, \tag{15}$$

$$\begin{bmatrix} \overline{\Omega}_{i1} & \overline{W}_i & \overline{\Omega}_{i2} \\ * & -\overline{T}_i & 0 \\ * & * & \overline{\Omega}_{i3} \end{bmatrix} < 0, \tag{16}$$

where

$$\overline{\Omega}_{i1} = (A_iX_i + B_iY_i)^{\dagger} + 0.25\varepsilon_{ii}^2\overline{T}_i - \varepsilon_{ii}\overline{W}_i + \alpha_{ii}E\hat{P}_iE^T,$$

$$X_i = \hat{P}_iE^T + V\hat{Q}_iU,$$

$$\overline{\Omega}_{i2} = [\sqrt{\alpha_{i1}}X_i^TE_R \quad \cdots \quad \sqrt{\alpha_{i(i-1)}}X_i^TE_R \quad \sqrt{\alpha_{i(i+1)}}X_i^TE_R \quad \cdots \quad \sqrt{\alpha_{iN}}X_i^TE_R],$$

$$\overline{\Omega}_{i3} = -\mathrm{diag}\{E_R^T\hat{P}_1E_R, \ldots, E_R^T\hat{P}_{i-1}E_R, E_R^T\hat{P}_{i+1}E_R, \ldots, E_R^T\hat{P}_NE_R\}.$$

In this case, the gain of controller (6) is given by

$$K_i = Y_iX_i^{-1}. \tag{17}$$

Proof: Let

$$P_i \triangleq \overline{P}_iE + U^T\overline{Q}_iV^T, \tag{18}$$

where $\overline{P}_i > 0$, $|\overline{Q}_i| \ne 0$, $U \in \mathbb{R}^{(n-r)\times n}$ is any matrix with full row rank and satisfies, $UE = 0$, $V \in \mathbb{R}^{n\times(n-r)}$ is any matrix with full column rank and satisfies $EV = 0$. Then, one has

$$E^TP_i = P_i^TE = E^T\overline{P}_iE \ge 0 \tag{19}$$

always holds. Since $\overline{P}_i > 0$ and $|\overline{Q}_i| \ne 0$, we have $E_L^T\overline{P}_jE_L > 0$, where E is decomposed as $E = E_LE_R^T$ with $E_L \in \mathbb{R}^{n\times r}$ and $E_R \in \mathbb{R}^{n\times r}$ of full column rank. Via the method in [23], it is obtained that

$$X_i = P_i^{-1} = \hat{P}_iE^T + V\hat{Q}_iU, \tag{20}$$

where $\hat{P}_i = \hat{P}_i^T$ and $|\hat{Q}_i| \ne 0$. Denoting $\overline{W}_i = X_i^TW_iX_i$, pre- and post-multiplying (9) with X_i^T and X_i, one gets that it is equivalent to (15). Let $\overline{T}_i = X_i^TT_iX_i$, pre- and post-multiplying (10) with $\mathrm{diag}\{X_i^T, X_i^T\}$ and its transpose, we have

$$\begin{bmatrix} \overline{\Omega}_i & \overline{W}_i \\ * & -\overline{T}_i \end{bmatrix} < 0, \tag{21}$$

where

$$\overline{\Omega}_i = (A_iX_i + B_iK_iX_i)^{\dagger} + 0.25\varepsilon_{ii}^2\overline{T}_i - \varepsilon_{ii}\overline{W} + \sum_{j=1, j\ne i}^{N} \alpha_{ij}X_i^TE^T(P_j - P_i)X_i.$$

Taking into account (17) and (20), it is concluded that (16) implies (21). This completes the proof.

Remark 2: It is worth mentioning that, compared with the similar existing results on both normal state-space and singular MJSs, Theorem 2 has the following advantages: 1) From the method in [21] which is similar to that in [22], it is seen that if one wants to discuss the stabilization problem of SMJSs with uncertain switching via the afore-referred algorithm, another assumption on matrix P_i which is positive-definite should be satisfied firstly. Moreover, even if the additional assumption holds, the corresponding stabilization problem cannot be solved completely. That is because some new problems emerge due to singular matrix E, which must be also dealt with. Thus, it is concluded that the existing methods to deal with the TRM of normal state-space MJSs cannot be applicable to SMJSs with uncertain switching; 2) When the TRM is assumed to be known exactly, some stabilization results for the underlying SMJSs in terms of LMIs were reported in [15-17]. From these criteria, it is seen that the equation condition such as (4) was removed successfully by using the method in [23]. Unfortunately, if there are admissible uncertainties in TRM, the desired controller within LMI framework cannot be constructed by using contragradient transformation directly such as in [15-17]. The reason is that there are some terms having strong correlations among the uncertain transition rates, singular matrix and Lyapunov matrices which make the LMI condition of a controller developed by the methods in the afore-said references impossible. Recently, the robust stabilization problem of SMJSs with full or partial knowledge of TRM was studied in [14], whose uncertainties were in system matrix instead of TRM. Moreover, it is also seen that the algorithm dealing with term E^TP_i is not suitable to the case of uncertain TRM, which has more conservatism and where the equation constraint such as (4) is also included in the established results.

It is seen that the implement of controller (6) requires the system mode available online. However, in many practical applications, the data is transmitted through unreliable networks and suffers packet dropout. As a result, controller (6) is too ideal. Instead, another kind of controller (7) named to be mode-independent can be constructed to deal with the above case. In order to obtain a common K from Theorem 2 directly, X_i in (15)-(17) should be a common matrix. That means the corresponding Lyapunov function should be mode-independent, which is more conservative than mode-dependent ones. In the next, a sufficient condition is given to separate X_i from A_i, which makes the requirements of mode-independent controller and mode-dependent Lyapunov function satisfied simultaneously.

Theorem 3: Consider the uncertain SMJS (1), there exists an MDC (6) such that the resulting closed-loop system is quadratically stochastically admissible, if there exist $\hat{P}_i$, $\hat{Q}_i$, G_i, Y_i, $\bar{W}_i = \bar{W}_i^T$ and $\bar{T}_i > 0$, such that (15) and the following LMIs hold for all $i \in S$

$$\begin{bmatrix} \Phi_{i1} & \Phi_{i2} & \bar{W}_i & \bar{\Omega}_{i2} \\ * & -(G_i)^\dagger & 0 & 0 \\ * & * & -\bar{T}_i & 0 \\ * & * & * & \bar{\Omega}_{i3} \end{bmatrix} < 0, \tag{22}$$

where

$$\Phi_{i1} = (A_iG_i + B_iY_i)^\dagger + 0.25\varepsilon_{ii}^2\bar{T}_i - \varepsilon_{ii}\bar{W}_i + \alpha_{ii}E\hat{P}_iE^T,$$
$$\Phi_{i2} = A_iG_i + B_iY_i + X_i^T - G_i^T.$$

In this case, the gain of controller(6) is given by

$$K_i = Y_iG_i^{-1}. \tag{23}$$

Proof: Pre- and post-multiplying (22) with the following matrix

$$\begin{bmatrix} I & A_i & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \end{bmatrix} \tag{24}$$

and its transpose, respectively. It is directly obtained that (22) implies (16). This completes the proof.

If the conditions in Theorem 3 with $G_i = G$ are satisfied, a corollary is obtained directly.

Corollary 1: Consider the uncertain SMJS (1), there exists an MIC (7) such that the resulting closed-loop system is quadratically stochastically admissible, if there exist $\hat{P}_i$, $\hat{Q}_i$, G, Y, $\bar{W}_i = \bar{W}_i^T$ and $\bar{T}_i > 0$, such that (15) and the following LMIs hold for all $i \in S$

$$\begin{bmatrix} \bar{\Phi}_{i1} & \bar{\Phi}_{i2} & \bar{W}_i & \bar{\Omega}_{i2} \\ * & -(G)^\dagger & 0 & 0 \\ * & * & -\bar{T}_i & 0 \\ * & * & * & \bar{\Omega}_{i3} \end{bmatrix} < 0, \tag{25}$$

where

$$\bar{\Phi}_{i1} = (A_iG + B_iY)^\dagger + 0.25\varepsilon_{ii}^2\bar{T}_i - \varepsilon_{ii}\bar{W}_i + \alpha_{ii}E\hat{P}_iE^T,$$
$$\bar{\Phi}_{i2} = A_iG + B_iY + X_i^T - G^T.$$

In this case, the gain of controller (7) is given by

$$K = YG^{-1}. \tag{26}$$

4. NUMERICAL EXAMPLES

Example 1: Consider an SMJS of form (1) is obtained by

$$A_1 = \begin{bmatrix} -0.2 & 1 & 0.3 \\ 2 & -1.2 & -6 \\ 2 & 1 & -1 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 1.5 \\ 0.4 \\ 1 \end{bmatrix},$$
$$A_1 = \begin{bmatrix} 0.2 & 1.3 & -0.3 \\ 3 & -1.2 & -1 \\ 1 & 2 & 1 \end{bmatrix}, \quad B_1 = \begin{bmatrix} -1 \\ 0 \\ -2 \end{bmatrix}.$$

The singular matrix is given as

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

The transition rate are given as $\tilde{\pi}_{11} = -5$ and $\tilde{\pi}_{22} = -7$, where the uncertainties of TRM Π are such that $|\Delta\pi_{12}| \le \varepsilon_{12} = 0.5\pi_{12}$ and $|\Delta\pi_{21}| \le \varepsilon_{21} = 0.5\pi_{21}$ respectively. Under the initial condition $x_0 = [1 \ \ -1 \ \ 0.6]^T$, the state of the open-loop system with uncertain TRM is illustrated in Fig. 1, which is not stable. When its system mode is always available to controller, it is known that the methods in [15-17] are not applied to such an SMJS with uncertain TRM. That is because the results on continuous-time SMJSs depended on the TRM known exactly. Though [14] considered the stabilization problem of SMJSs with partial knowledge TRM, it is seen that it is different to the problem presented in this paper, and the given method is not suitable to the case of SMJSs with uncertain switching. Instead, by Theorem 2, an MDC can be computed as

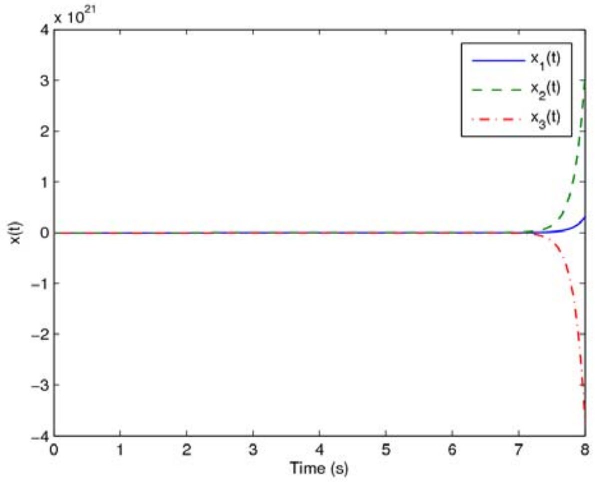

Fig. 1. The simulation of open-loop system.

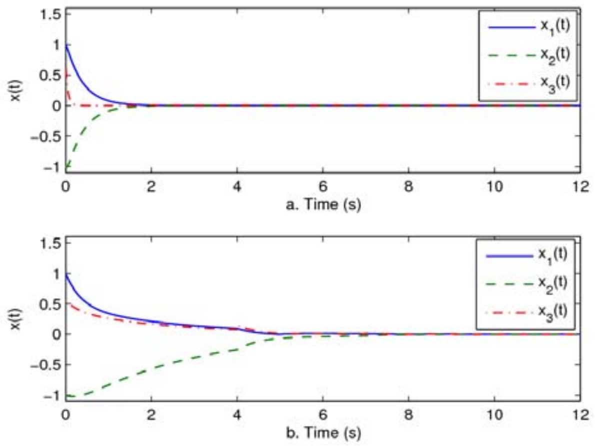

Fig. 2. The simulations of closed-loop system by MDC and MIC.

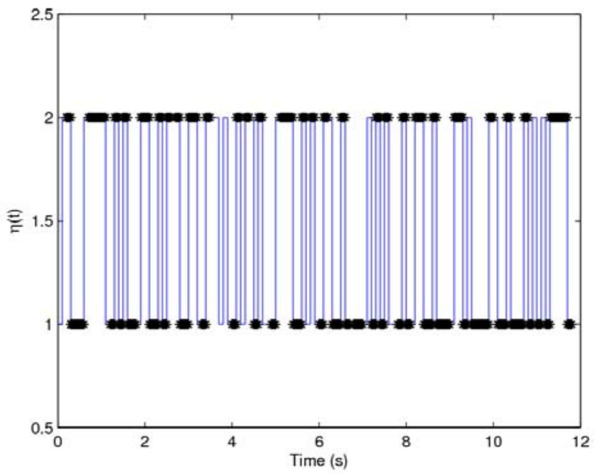

Fig. 3. The simulation of system mode with a percent.

$$K_1 = [-0.3396 \quad 1.2769 \quad -1.1206],$$
$$K_2 = [-0.9982 \quad 0.6619 \quad 1.2338].$$

After applying the desired controller to the above system, the state response of the resulting closed-loop system is shown in Fig. 2(a). It is seen that it is stable over all the admissible uncertainties. On the other hand, if its system mode is not always available to controller, it means the controller mode is accessible with a percent. For this example, the system mode received by a controller is only about 30%, and Fig. 3 gives the corresponding simulation, in which * denotes the current mode inaccessible. In this case, an MDC will fail to stabilize the corresponding system, since its system mode is not always available. However, based on Corollary 1, an MIC can be designed as

$$K = [-0.3346 \quad 0.4602 \quad 0.7148].$$

The response of the resulting closed-loop system is simulated in Fig. 2(b), which shows that the constructed controller can stabilize the system over all the admissible uncertainties, even if the system mode is unavailable.

5. CONCLUSION

In this paper, the stabilization problem for a class of SMJSs with uncertain switching probabilities is considered by using a slack variable method on TRM. Based on this, two sufficient existence conditions of MDC are proposed in terms of LMIs, which could be solved easily and directly. Moreover, the obtained result is further applied to a practical case that the system mode is not necessary to the controller. Finally, the utility of the developed theory is illustrated by a numerical example.

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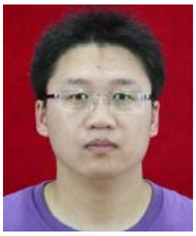

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