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Stabilization for a class of switched neutral systems under asynchronous switching

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Abstract

This paper investigates the problem of stabilization for a class of switched neutral systems under asynchronous switching, where the switching instants of the controller experience delays with respect to those of the system. A state feedback controller is proposed to guarantee exponential stability for switched neutral systems, and the dwell time approach and free weighting matrix scheme are utilized for the stability analysis. A numerical example is given to illustrate the effectiveness of the proposed method.

Keywords

Asynchronous switching, exponential stability, stabilization, switched neutral systems

Introduction

Switched systems are composed of a family of continuous-time or discrete-time subsystems and a switching signal specifying the switching between the subsystems. Such a system has attracted considerable attention because various real-world systems, such as chemical processing (Engell et al., 2000), communication networks, traffic control (Horowitz and Varaiya, 2000; Livadas et al., 2000), control of manufacturing systems (Pepyne and Cassandaras, 2000; Song et al., 2000), automotive engine control and aircraft control (Antsaklis, 2000) can be modelled as switched systems. The past decades have witnessed an enormous interest in analysis and synthesis of switched systems (Cheng et al., 2005; Li et al., 2009; Persisa et al., 2003; Sun, 2006; Wang and Zhao, 2007; Xiang and Chen, 2010).

It is well known that the time-delay phenomenon exists widely in engineering and social systems, which may cause instability or undesirable system performance in feedback systems such as chaos (Ucar, 2003). A neutral system is one of the important branches of time-delay systems, which depend on the delays of state and state derivative. Some practical examples of neutral systems include distributed networks, heat exchanges and processes involving steam (Lien and Yu, 2007).

Recently, the stability and control synthesis issues of switched neutral systems have drawn a lot of attention (see Liu et al., 2008, 2009; Sen et al., 2005; Sun et al., 2005; Xiong et al., 2009; Zhang et al., 2007a, 2007b, 2007c, 2008, and the references cited therein). Because most switched systems do not possess a common Lyapunov function, they may be stable under certain switching laws, and the average dwell time method is employed to choose such switching laws (Liu et al., 2009; Xiong et al., 2009). Besides, the problems of robust non-fragile H_∞ control and reliable H_∞ control for switched neutral systems are investigated in Zhang (2007b) and (2007c), respectively. The issue of robust sliding mode control for uncertain switched neutral systems is discussed in Zhang (2008).

However, as pointed out in Xie and Wang (2005), there inevitably exists asynchronous switching between the controller and the system in actual operation, i.e. the switching instants of the controller exceed or lag behind those of the system. Therefore, it is important to investigate the problem of asynchronous switching. Recently, some results on the stabilization of switched systems with delayed controller switching have already been considered in many studies (Xie and Wang, 2005; Xie et al., 2001; Ji et al., 2007; Xie and Chen, 2008; Xiang and Wang, 2009a, 2009b; Zhang and Gao, 2010; Zhang and Shi, 2009). The stabilization problem of switched linear systems with time-delay in detection of the switching signal is investigated in Xie and Wang (2005), and the proposed result has been extended the switched linear systems with time-varying delay in the detection of the switching signal (Ji et al., 2007). Robust control problems for uncertain switched non-linear systems with time delay and time-varying delays under asynchronous switching are studied in Xiang and Wang (2009a) and (2009b), respectively. The average dwell time method is utilized to discuss an asynchronously switched control problem of switched linear systems in Zhang and Gao (2010). Furthermore, the asynchronous H_∞ control problem of discrete-time switched systems is proposed

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in Zhang and Shi (2009). To the best of our knowledge, the issue of stabilization of switched neutral systems under asynchronous switching has not been investigated, which motivated the present study.

In this paper, we are interested in designing a stabilizing controller for a switched neutral system with asynchronous switching such that the closed-loop system is exponentially stable. We use the Lyapunov stability method and the average dwell time technique to design the stabilizing controller, and a free weighting matrix scheme is used to reduce the conservatism. The remainder of the paper is organized as follows. In Section 2, problem formulation and some necessary lemmas are given. In Section 3, based on the dwell time approach, the problem of stability and stabilization for switched neutral systems under asynchronous switching are addressed, and sufficient conditions for the existence of a state feedback controller are derived in terms of a set of matrix inequalities. A numerical example is provided to illustrate the effectiveness of the proposed approach in Section 4. Concluding remarks are given in Section 5.

Notation

Throughout this paper, the superscript 'T' stands for matrix transposition, and the notation $X \geqslant Y$ $(X > Y)$ means that matrix $X - Y$ is positive semi-definite (positive definite, respectively). $\|x(t)\|$ denotes the Euclidean norm. $\lambda_{\max}(P)$ and $\lambda_{\min}(P)$ denote the maximum and minimum eigenvalues of matrix P, respectively. I is an identity matrix with appropriate dimension. $diag\{a_i\}$ denotes a diagonal matrix with the diagonal elements a_i, $i = 1, 2, \ldots, n$. The asterisk $*$ in a matrix is used to denote a term that is induced by symmetry. The set of all positive integers is represented by Z^+.

Problem formulation and preliminaries

Consider the following switched neutral system

$$\dot{x}(t) - C_{\sigma(t)}\dot{x}(t-\tau_1) = A_{\sigma(t)}x(t) + B_{\sigma(t)}x(t-\tau_2) + D_{\sigma(t)}u(t) \tag{1}$$

$$x(t_0+\theta) = \varphi(\theta), \quad \theta \in [-\tau, 0] \tag{2}$$

where $x(t) \in R^n$ is the state vector, $u(t) \in R^l$ is the control input, $\tau = \max\{\tau_1, \tau_2\}$, $\varphi(\theta)$ is a continuous vector-valued initial function. The function $\sigma(t) : [0, \infty) \to \underline{N} = \{1, 2, \ldots, N\}$ is a switching signal, which is deterministic, piecewise constant and right continuous, corresponding to the switching sequence $\Sigma = \{(t_0, \sigma(t_0)), (t_1, \sigma(t_1)), \ldots, (t_k, \sigma(t_k)), \ldots\}$, $k = 0, 1, 2, \ldots$, where t_0 is the initial time and t_k denotes the kth switching instant. Moreover, $\sigma(t) = i$ means that the ith subsystem is activated. N denotes the number of subsystems. A_i, B_i, C_i, D_i for $i \in \underline{N}$ are real-valued matrices with appropriate dimensions.

The control input $u(t)$ can be described as

$$u(t) = K_{\sigma(t)}x(t) \tag{3}$$

where $K_{\sigma(t)}$ is the gain matrix of control input, which will be designed.

However, in actual operation, there inevitably exists asynchronous switching between the controller and the system, i.e. the real switching instants of the controller exceed or lag behind those of the system. Without loss of generality, we only consider the case when the switching instants of the controller experience delays with respect to those of the system. Denoting $\sigma'(t)$ the switching signal of the controller, the switching instants of the controller can be described as

$$t_1 + \Delta_1, t_2 + \Delta_2, \ldots, t_k + \Delta_k, \ldots, \; k \in Z^+$$

where $\Delta_k < (t_{k+1} - t_k)$, Δ_k represents the delayed period, and it is said to be a mismatched period.

Remark 1. The mismatched period $\Delta_k < (t_{k+1} - t_k)$ guarantees that there always exists a period when the controller and the system operate synchronously, and this period is said to be a matched period in the later section.

Definition 1 (Sun et al., 2006). The equilibrium $x^* = 0$ of system (1) is said to be exponentially stable under $\sigma(t)$, if the solution $x(t)$ of system (1) satisfies

$$\|x(t)\| \leq \alpha \|x(t_0)\|_h e^{-\beta(t-t_0)}, \; t \geqslant t_0 \tag{4}$$

for constants $\alpha \geqslant 1$ and $\beta > 0$, where $\|x(t_0)\|_h = \sup_{-\tau \leq \theta \leq 0} \{\|x(t_0 + \theta)\|, \; \|\dot{x}(t_0+\theta)\|\}$, and $\|\cdot\|$ denotes the Euclidean norm.

Definition 2 (Liberzon, 2003). For any $T_2 > T_1 \geqslant 0$, let $N_\sigma(T_1, T_2)$ denote the switching number of $\sigma(t)$ on an interval (T_1, T_2). If

$$N_\sigma(T_1, T_2) \leq N_0 + \frac{T_2 - T_1}{\tau_a} \tag{5}$$

hold for given $N_0 \geqslant 0$, $\tau_a > 0$, then the constant τ_a is called the average dwell time and N_0 is the chatter bound.

The following lemma plays an important role in the later development.

Lemma 1 (Gu, 2001). For any positive definite symmetric constant matrix $M \in R^{n\times n}$, a scalar $r > 0$, if there exists a vector function $g : [0, r] \to R^n$ such that the integrations in the following are well defined, then the following inequality holds

$$r\int_0^r g^T(s)Mg(s)ds \geqslant \left[\int_0^r g(s)ds\right]^T M \left[\int_0^r g(s)ds\right] \tag{6}$$

The aim of this paper is to design a switching controller for switched neutral system (1)–(2) with asynchronous switching such that the closed-loop system is exponentially stable.

Main results

Stability analysis

In this subsection, we consider stability analysis of the non-switched neutral system.

Lemma 2. Consider the following neutral system

$$\dot{x}(t) - C\dot{x}(t-\tau_1) = Ax(t) + Bx(t-\tau_2) \tag{7}$$

$$x(t_0+\theta)=\varphi(\theta), \quad \theta\in[-\tau,0] \tag{8}$$

where A, B, C are constant matrices with appropriate dimensions. For a given positive constant α, if there exist positive definite symmetric matrices P, Q, R_1, R_2, and any matrices $W_l\,(l=1,2,\ldots,5)$, $M_l\,(l=1,2,\ldots,5)$ with appropriate dimensions, such that

$$\phi=\begin{pmatrix}\phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} & \phi_{15}\\ * & \phi_{22} & \phi_{23} & \phi_{24} & \phi_{25}\\ * & * & \phi_{33} & \phi_{34} & \phi_{35}\\ * & * & * & \phi_{44} & \phi_{45}\\ * & * & * & * & \phi_{55}\end{pmatrix}<0 \tag{9}$$

then, along the trajectory of system (7)–(8), *there holds the following inequality*

$$V(x(t))<e^{-\alpha(t-t_0)}V(x(t_0)) \tag{10}$$

where

$$\begin{aligned}
\phi_{11}&=P(A+B)+(A+B)^TP+\alpha P+W_1^TA+A^TW_1+R_1\\
&\quad+M_1^T+M_1,\\
\phi_{12}&=-W_1^T+A^TW_2+M_2,\\
\phi_{13}&=A^TW_3+W_1^TB-M_1^T+M_3,\\
\phi_{14}&=PC+W_1^TC+A^TW_4+M_4,\\
\phi_{15}&=-PB+A^TW_5-M_1^T+M_5,\\
\phi_{22}&=\tau_2Q-W_2^T-W_2+R_2,\quad \phi_{23}=W_2^TB-W_3+M_2^T,\\
\phi_{24}&=W_2^TC-W_4,\quad \phi_{25}=-W_5-M_2^T,\\
\phi_{33}&=-e^{-\alpha\tau_2}R_1+W_3^TB+B^TW_3-M_3^T-M_3,\\
\phi_{34}&=W_3^TC+B^TW_4-M_4,\quad \phi_{35}=B^TW_5-M_3^T-M_5,\\
\phi_{44}&=-e^{-\alpha\tau_1}R_2+W_4^TC+C^TW_4,\quad \phi_{45}=C^TW_5-M_4^T,\\
\phi_{55}&=-\frac{e^{-\alpha\tau_2}}{\tau_2}Q-M_5^T-M_5
\end{aligned}$$

Proof. Using the Newton–Leibniz formula, we transform system (7) into

$$\dot{x}(t)-C\dot{x}(t-\tau_1)=(A+B)x(t)-B\int_{t-\tau_2}^{t}\dot{x}(s)ds \tag{11}$$

Consider the Lyapunov–Krasovskii functional candidate

$$V(x(t))=\sum_{i=1}^{4}V_i(x(t)) \tag{12}$$

where

$$\begin{aligned}
V_1(x(t))&=x^T(t)Px(t),\ V_2(x(t))\\
&=\int_{-\tau_2}^{0}\int_{t+\theta}^{t}\dot{x}^T(s)e^{-\alpha(t-s)}Q\dot{x}(s)dsd\theta,\\
V_3(x(t))&=\int_{t-\tau_2}^{t}x^T(s)e^{-\alpha(t-s)}R_1x(s)ds,\\
V_4(x(t))&=\int_{t-\tau_1}^{t}\dot{x}^T(s)e^{-\alpha(t-s)}R_2\dot{x}(s)ds
\end{aligned}$$

Along the trajectory of (7)–(8), we have

$$\dot{V}(x(t))=\sum_{i=1}^{4}\dot{V}_i(x(t)) \tag{13}$$

where

$$\dot{V}_1(x(t))=2x^T(t)P\left((A+B)x(t)-B\int_{t-\tau_2}^{t}\dot{x}(s)ds+C\dot{x}(t-\tau_1)\right)$$

$$\begin{aligned}
\dot{V}_2(x(t))&=\tau_2\dot{x}^T(t)Q\dot{x}(t)-\int_{t-\tau_2}^{t}\dot{x}^T(s)e^{-\alpha(t-s)}Q\dot{x}(s)ds\\
&\quad-\alpha\int_{-\tau_2}^{0}\int_{t+\theta}^{t}\dot{x}^T(s)e^{-\alpha(t-s)}Q\dot{x}(s)dsd\theta\\
&\le\tau_2\dot{x}^T(t)Q\dot{x}(t)-e^{-\alpha\tau_2}\int_{t-\tau_2}^{t}\dot{x}^T(s)Q\dot{x}(s)ds\\
&\quad-\alpha\int_{-\tau_2}^{0}\int_{t+\theta}^{t}\dot{x}^T(s)e^{-\alpha(t-s)}Q\dot{x}(s)dsd\theta
\end{aligned}$$

From Lemma 1, we know that

$$\int_{t-\tau_2}^{t}\dot{x}^T(s)Q\dot{x}(s)ds\geqslant\frac{1}{\tau_2}\left[\int_{t-\tau_2}^{t}\dot{x}(s)ds\right]^TQ\left[\int_{t-\tau_2}^{t}\dot{x}(s)ds\right]$$

thus

$$\begin{aligned}
\dot{V}_2(x(t))&\le\tau_2\dot{x}^T(t)Q\dot{x}(t)-\frac{e^{-\alpha\tau_2}}{\tau_2}\left[\int_{t-\tau_2}^{t}\dot{x}(s)ds\right]^TQ\left[\int_{t-\tau_2}^{t}\dot{x}(s)ds\right]\\
&\quad-\alpha\int_{-\tau_2}^{0}\int_{t+\theta}^{t}\dot{x}^T(s)e^{-\alpha(t-s)}Q\dot{x}(s)dsd\theta\\
\dot{V}_3(x(t))&=x^T(t)R_1x(t)-x^T(t-\tau_2)e^{-\alpha\tau_2}R_1x(t-\tau_2)\\
&\quad-\alpha\int_{t-\tau_2}^{t}x^T(s)e^{-\alpha(t-s)}R_1x(s)ds\\
\dot{V}_4(x(t))&=\dot{x}^T(t)R_2\dot{x}(t)-\dot{x}^T(t-\tau_1)e^{-\alpha\tau_1}R_2\dot{x}(t-\tau_1)\\
&\quad-\alpha\int_{t-\tau_1}^{t}\dot{x}^T(s)e^{-\alpha(t-s)}R_2\dot{x}(s)ds
\end{aligned}$$

Notice that the following equations hold for any matrices $W_l\,(l=1,2,\ldots,5)$ and $M_l\,(l=1,2,\ldots,5)$ with appropriate dimensions

$$\begin{aligned}
&2\{x^T(t)W_1^T+\dot{x}^T(t)W_2^T+x^T(t-\tau_2)W_3^T+\dot{x}^T(t-\tau_1)W_4^T\\
&\quad+\int_{t-\tau_2}^{t}\dot{x}^T(s)dsW_5^T\}\{Ax(t)-\dot{x}(t)+Bx(t-\tau_2)\\
&\quad+C\dot{x}(t-\tau_1)\}=0
\end{aligned}\tag{14}$$

$$\begin{aligned}
&2\{x^T(t)M_1^T+\dot{x}^T(t)M_2^T+x^T(t-\tau_2)M_3^T+\dot{x}^T(t-\tau_1)M_4^T\\
&\quad+\int_{t-\tau_2}^{t}\dot{x}^T(s)dsM_5^T\}\{x(t)-x(t-\tau_2)-\int_{t-\tau_2}^{t}\dot{x}(s)ds\}=0
\end{aligned}\tag{15}$$

Then, adding the terms on the left sides of (14) and (15) to (13), we have

$$\dot{V}(x(t))+\alpha V(x(t))=X^T(t)\phi X(t)<0$$

where

$$X^T(t) = \left(x^T(t) \quad \dot{x}^T(t) \quad x^T(t-\tau_2) \quad \dot{x}^T(t-\tau_1) \quad \int_{t-\tau_2}^{t} \dot{x}^T(s)ds \right).$$

That is to say, $\dot{V}(x(t)) + \alpha V(x(t)) < 0$. The proof is completed.

Lemma 3. Consider system (7)–(8), *for given positive constant* β, *if there exist positive definite symmetric matrices* P, Q, R_1, R_2, *and any matrices* $W_l\,(l = 1, 2, \ldots, 5)$, $M_l\,(l = 1, 2, \ldots, 5)$ *with appropriate dimensions, such that*

$$\varphi = \begin{pmatrix} \varphi_{11} & \varphi_{12} & \varphi_{13} & \varphi_{14} & \varphi_{15} \\ * & \varphi_{22} & \varphi_{23} & \varphi_{24} & \varphi_{25} \\ * & * & \varphi_{33} & \varphi_{34} & \varphi_{35} \\ * & * & * & \varphi_{44} & \varphi_{45} \\ * & * & * & * & \varphi_{55} \end{pmatrix} < 0 \tag{16}$$

then, along the trajectory of system (7)–(8), *there holds the following inequality*

$$V(x(t)) < e^{\beta(t-t_0)} V(x(t_0)) \tag{17}$$

where

$$\varphi_{11} = P(A+B) + (A+B)^T P - \beta P + W_1^T A + A^T W_1 + R_1 + M_1^T + M_1,$$

$$\varphi_{12} = -W_1^T + A^T W_2 + M_2,$$

$$\varphi_{13} = A^T W_3 + W_1^T B - M_1^T + M_3,$$

$$\varphi_{14} = PC + W_1^T C + A^T W_4 + M_4,$$

$$\varphi_{15} = -PB + A^T W_5 - M_1^T + M_5$$

$$\varphi_{22} = \tau_2 Q - W_2^T - W_2 + R_2,$$

$$\varphi_{23} = W_2^T B - W_3 + M_2^T,$$

$$\varphi_{24} = W_2^T C - W_4,$$

$$\varphi_{25} = -W_5 - M_2^T$$

$$\varphi_{33} = -e^{\beta\tau_2} R_1 + W_3^T B + B^T W_3 - M_3^T - M_3,$$

$$\varphi_{34} = W_3^T C + B^T W_4 - M_4,$$

$$\varphi_{35} = B^T W_5 - M_3^T - M_5,$$

$$\varphi_{44} = -e^{\beta\tau_1} R_2 + W_4^T C + C^T W_4,$$

$$\varphi_{45} = C^T W_5 - M_4^T,$$

$$\varphi_{55} = -\frac{e^{\beta\tau_2}}{\tau_2} Q - M_5^T - M_5$$

Proof. It is similar to the proof line of Lemma 2 and it is omitted here.

Remark 2. Lemmas 2 and 3 provide the methods for the estimation of Lyapunov functional candidate, which will be used to design the controller for the switched neutral system under asynchronous switching.

Stabilization of switched neutral system

Consider system (1)–(2), under an asynchronous switching controller $u(t) = K_{\sigma'(t)} x(t)$, the corresponding closed-loop system is given by

$$\dot{x}(t) - C_{\sigma(t)} \dot{x}(t-\tau_1) = (A_{\sigma(t)} + D_{\sigma(t)} K_{\sigma'(t)}) x(t) + B_{\sigma(t)} x(t-\tau_2) \tag{18}$$

$$x(t_0 + \theta) = \varphi(\theta), \quad \theta \in [-\tau, 0] \tag{19}$$

Suppose that the ith subsystem is activated at the switching instant t_k, the jth subsystem is activated at the switching instant t_{k+1}, then the corresponding switching controller is activated at the switching instant $t_k + \Delta_k$, $t_{k+1} + \Delta_{k+1}$, respectively.

Let $T^{+}(t_0, t)$ denote the total mismatched period during $[t_0, t)$ and $T^{-}(t_0, t)$ denote the total matched period during $[t_0, t)$, then we have the following result.

Theorem 1. Consider system (1)–(2), *for given positive constants* α, β, *if there exist positive definite symmetric matrices* X_{1i}, X_{3i}, X_{4i}, X_{5i}, R_{1ij}, R_{2ij}, P_{ij}, Q_{ij} *and any matrices* X_{2i}, $W_{lij}(l = 1, 2, \ldots, 5)$, $N_{li}(l = 1, 2, \ldots, 5)$, $N_{lij}(l = 1, 2, \ldots, 5)$ *with appropriate dimensions, such that, for* $i, j \in \underline{N}$, $i \neq j$

$$\begin{pmatrix} \Pi_{1i} & -X_{1i} + X_{1i}A_i^T + X_2 i^T D_i^T + N_{2i} & X_{1i}A_i^T + X_2 i^T D_i^T + B_i X_{1i} - N_{1i}^T + N_{3i} & 2C_i X_{1i} + X_{1i}A_i^T + X_2 i^T D_i^T + N_{4i} & -B_i X_{1i} + X_{1i}A_i^T + X_2 i^T D_i^T - N_{1i}^T + N_{5i} \\ * & \tau_2 X_{5i} - 2X_{1i} + X_{4i} & B_i X_{1i} - X_{1i} + N_{2i}^T & C_i X_{1i} - X_{1i} & -X_{1i} - N_{2i}^T \\ * & * & -e^{-\alpha\tau_2} X_{3i} + B_i X_{1i} + X_{1i} B_i^T - N_{3i}^T - N_{3i} & C_i X_{1i} + X_{1i} B_i^T - N_{4i} & X_{1i} B_i^T - N_{3i}^T - N_{5i} \\ * & * & * & -e^{-\alpha\tau_1} X_{4i} + C_i X_{1i} + X_{1i} C_i^T & X_{1i} C_i^T - N_{4i}^T \\ * & * & * & * & -\frac{e^{-\alpha\tau_2}}{\tau_2} X_{5i} - N_{5i}^T - N_{5i} \end{pmatrix} < 0 \tag{20}$$

$$\begin{pmatrix} \Lambda_{1ij} & -W_{1ij}^T + (A_j + D_j X_{2i} X_{1i}^{-1})^T W_{2ij} + N_{2ij} & (A_j + D_j X_{2i} X_{1i}^{-1})^T W_{3ij} + W_{1ij}^T B_j - N_{1ij}^T + N_{3ij} & (A_j + D_j X_{2i} X_{1i}^{-1})^T W_{4ij} + P_{ij} C_j + W_{1ij}^T C_j + N_{4ij} & (A_j + D_j X_{2i} X_{1i}^{-1})^T W_{5ij} - N_{1ij}^T + N_{5ij} - P_{ij} B_j \\ * & \tau_2 Q_{ij} - W_{2ij}^T - W_{2ij} + R_{2ij} & W_{2ij}^T B_j - W_{3ij} + N_{2ij}^T & W_{2ij}^T C_j - W_{4ij} & -W_{5ij} - N_{2ij}^T \\ * & * & -e^{\beta\tau_2} R_{1ij} + W_{3ij}^T B_j + B_j^T W_{3ij} - N_{3ij}^T - N_{3ij} & W_{3ij}^T C_j + B_j^T W_{4ij} - N_{4ij} & B_j^T W_{5ij} - N_{3ij}^T - N_{5ij} \\ * & * & * & -e^{\beta\tau_1} R_{2ij} + W_{4ij}^T C_j + C_j^T W_{4ij} & C_j^T W_{5ij} - N_{4ij}^T \\ * & * & * & * & -\frac{e^{\beta\tau_2}}{\tau_2} Q_{ij} - N_{5ij}^T - N_{5ij} \end{pmatrix} < 0 \tag{21}$$

Then, under the switching controller $u(t) = K_{\sigma'(t)}x(t)$, $K_i = X_{2i}X_{1i}^{-1}$ and the following average dwell time scheme

$$\inf_{t>t_0} \frac{T^-(t_0,t)}{T^+(t_0,t)} \geqslant \frac{\lambda^+ + \lambda^*}{\lambda^- - \lambda^*},\ \tau_a > \tau_a^* = \frac{\ln(\mu_1\mu_2)}{\lambda^*} \tag{22}$$

the corresponding closed-loop system is exponentially stable, where $\lambda^+ = \beta$, $\lambda^- = \alpha$, $0 < \lambda^* < \lambda^-$, $\mu_1, \mu_2 > 1$ satisfying

$$\begin{aligned}
&X_{1i}^{-1} < \mu_1 P_{ij},\ P_{ij} < \mu_2 X_{1i}^{-1},\ X_{1i}^{-1}X_{3i}X_{1i}^{-1} < \mu_1 R_{1ij},\\
&R_{1ij} < \mu_2 X_{1i}^{-1}X_{3i}X_{1i}^{-1},\ X_{1i}^{-1}X_{4i}X_{1i}^{-1} < \mu_1 R_{2ij},\\
&R_{2ij} < \mu_2 X_{1i}^{-1}X_{4i}X_{1i}^{-1},\ X_{1i}^{-1}X_{5i}X_{1i}^{-1} < \mu_1 Q_{ij},\ Q_{ij} < \mu_2 X_{1i}^{-1}X_{5i}X_{1i}^{-1},\\
&\Pi_{1i} = (2A_i + B_i)X_{1i} + X_{1i}(2A_i + B_i)^T + 2D_iX_{2i} + 2X_2 i^T D_i^T\\
&\qquad + \alpha X_{1i} + X_{3i} + N_{1i}^T + N_{1i},\\
&\Lambda_{1ij} = P_{ij}(A_j + B_j + X_{2i}X_{1i}^{-1}) + (A_j + B_j + X_{2i}X_{1i}^{-1})^T P_{ij}\\
&\qquad - \beta P_{ij} + W_{1ij}^T(A_j + D_jX_{2i}X_{1i}^{-1}) + (A_j + D_jX_{2i}X_{1i}^{-1})^T W_{1ij}\\
&\qquad + R_{1ij} + N_{1ij}^T + N_{1ij}.
\end{aligned}$$

Proof. When $t \in [t_k + \Delta_k, t_{k+1})$, the closed-loop system can be written as

$$\dot{x}(t) - C_i\dot{x}(t-\tau_1) = (A_i + D_iK_i)x(t) + B_ix(t-\tau_2) \tag{23}$$

Consider the Lyapunov functional candidate as follows

$$V_i(x(t)) = V_{1i}(x(t)) + V_{2i}(x(t)) + V_{3i}(x(t)) + V_{4i}(x(t))$$

where,

$$\begin{aligned}
V_{1i}(x(t)) &= x^T(t)P_ix(t)\\
V_{2i}(x(t)) &= \int_{-\tau_2}^{0}\int_{t+\theta}^{t} \dot{x}^T(s)e^{-\alpha(t-s)}Q_i\dot{x}(s)dsd\theta\\
V_{3i}(x(t)) &= \int_{t-\tau_2}^{t} x^T(s)e^{-\alpha(t-s)}R_{1i}x(s)ds\\
V_{4i}(x(t)) &= \int_{t-\tau_1}^{t} \dot{x}^T(s)e^{-\alpha(t-s)}R_{2i}\dot{x}(s)ds
\end{aligned}$$

By Lemma 2, we can know that if there exist positive definite symmetric matrices P_i, Q_i, R_{1i}, R_{2i}, and any matrices $W_{li}(l = 1,\ 2,\ldots,5)$, $M_{li}(l = 1,2,\ldots,5)$ with appropriate dimensions, such that

$$\begin{pmatrix}
\phi_{111i} & -W_{1i}^T + (A_i + D_iK_i)^T W_{2i} + M_{2i} & (A_i + D_iK_i)^T W_{3i} + W_{1i}^T B_i - M_{1i}^T + M_{3i} & P_iC_i + W_{1i}^T C_i + (A_i + D_iK_i)^T W_{4i} + M_{4i} & -P_iB_i + (A_i + D_iK_i)^T W_{5i} - M_{1i}^T + M_{5i}\\
* & \tau_2 Q_i - W_{2i}^T - W_{2i} + R_{2i} & W_{2i}^T B_i - W_{3i} + M_{2i}^T & W_{2i}^T C_i - W_{4i} & -W_{5i} - M_{2i}^T\\
* & * & -e^{-\alpha\tau_2} R_{1i} + W_{3i}^T B_i + B_i^T W_{3i} - M_{3i}^T - M_{3i} & W_{3i}^T C_i + B_i^T W_{4i} - M_{4i} & B_i^T W_{5i} - M_{3i}^T - M_{5i}\\
* & * & * & -e^{-\alpha\tau_1} R_{2i} + W_{4i}^T C_i + C_i^T W_{4i} & C_i^T W_{5i} - M_{4i}^T\\
* & * & * & * & -\frac{e^{-\alpha\tau_2}}{\tau_2} Q_i - M_{5i}^T - M_{5i}
\end{pmatrix} < 0 \tag{24}$$

where

$$\begin{aligned}
\phi_{111i} = {} & P_i(A_i + B_i + D_iK_i) + (A_i + B_i + D_iK_i)^T P_i + \alpha P_i\\
& + W_{1i}^T(A_i + D_iK_i) + (A_i + D_iK_i)^T W_{1i} + R_{1i} + M_{1i}^T + M_{1i}.
\end{aligned}$$

Then the following matrix inequalities hold

$$V_i(x(t)) < e^{-\alpha(t-t_0^i)} V_i(x(t_0^i)) \tag{25}$$

where t_0^i represents the initial time of the ith subsystem.

From (25), we can obtain

$$\|x(t)\| < \sqrt{\frac{b_1}{a_1}} \cdot e^{-\alpha(t-t_0^i)/2}\left\|x(t_0^i)\right\|_h,\ t \in [t_k + \Delta_k, t_{k+1}) \tag{26}$$

where

$$\begin{aligned}
a_1 &= \min_{i\in \underline{N}}\{\lambda_{\min}(P_i)\},\\
b_1 &= \max_{i\in \underline{N}}\{\lambda_{\max}(P_i) + \tau_2^2\lambda_{\max}(Q_i) + \tau_2\lambda_{\max}(R_{1i}) + \tau_1\lambda_{\max}(R_{2i})\},
\end{aligned}$$

and $t \in [t_{k+1}, t_{k+1} + \Delta_{k+1})$; the closed-loop system can be written as

$$\dot{x}(t) - C_j\dot{x}(t-\tau_1) = (A_j + D_jK_i)x(t) + B_jx(t-\tau_2) \tag{27}$$

For system (27), we consider the Lyapunov functional candidate as follows:

$$\begin{aligned}
V_{ij}(x(t)) = {} & x^T(t)P_{ij}x(t) + \int_{-\tau_2}^{0}\int_{t+\theta}^{t} \dot{x}^T(s)e^{\beta(t-s)}Q_{ij}\dot{x}(s)dsd\theta\\
& + \int_{t-\tau_2}^{t} x^T(s)e^{\beta(t-s)}R_{1ij}x(s)ds\\
& + \int_{t-\tau_1}^{t} \dot{x}^T(s)e^{\beta(t-s)}R_{2ij}\dot{x}(s)ds
\end{aligned}$$

By Lemma 3, we can know that if there exist positive definite symmetric matrices P_{ij}, Q_{ij}, R_{1ij}, R_{2ij}, and any matrices $W_{lij}(l = 1,2,\ldots,5)$, $M_{lij}(l = 1,2,\ldots,5)$ with appropriate dimensions, such that

$$\begin{pmatrix}
\varphi_{11j} & -W_{1ij}^T + (A_j + D_jK_i)^T W_{2ij} + M_{2ij} & (A_j + D_jK_i)^T W_{3ij} + W_{1ij}^T B_j - M_{1ij}^T + M_{3ij} & P_{ij}C_j + W_{1ij}^T C_j + (A_j + D_jK_i)^T W_{4ij} + M_{4ij} & -P_{ij}B_j + (A_j + D_jK_i)^T W_{5ij} - M_{1ij}^T + M_{5ij}\\
* & \tau_2 Q_{ij} - W_{2ij}^T - W_{2ij} + R_{2ij} & W_{2ij}^T B_j - W_{3ij} + M_{2ij}^T & W_{2ij}^T C_j - W_{4ij} & -W_{5ij} + M_{2ij}^T\\
* & * & -e^{\beta\tau_2} R_{1ij} + W_{3ij}^T B_j + B_j^T W_{3ij} - M_{3ij}^T - M_{3ij} & W_{3ij}^T C_j + B_j^T W_{4ij} - M_{4ij} & B_j^T W_{5ij} - M_{3ij}^T - M_{5ij}\\
* & * & * & -e^{\beta\tau_1} R_{2ij} + W_{4ij}^T C_j + C_j^T W_{4ij} & C_j^T W_{5ij} - M_{4ij}^T\\
* & * & * & * & -\frac{e^{\beta\tau_2}}{\tau_2} Q_{ij} - M_{5ij}^T - M_{5ij}
\end{pmatrix} < 0 \tag{28}$$

where

$$\varphi_{11j} = P_{ij}(A_j + B_j + D_jK_i) + (A_j + B_j + D_jK_i)^T P_{ij} - \beta P_{ij} + W_{1ij}^T(A_j + D_jK_i) + (A_j + D_jK_i)^T W_{1ij} + R_{1ij} + M_{1ij}^T + M_{1ij}.$$

Then the following inequality holds

$$V_{ij}(x(t)) < e^{\beta(t - t_0^{ij})} V_{ij}(x(t_0^{ij})) \tag{29}$$

where t_0^{ij} represents the initial time of the jth subsystem.

From (29), we can obtain

$$\|x(t)\| < \sqrt{\frac{b_2}{a_2}} \cdot e^{\beta(t - t_0^{ij})/2} \left\| x(t_0^{ij}) \right\|_h, \; t \in [t_{k+1}, t_{k+1} + \Delta_{k+1}) \tag{30}$$

where

$$a_2 = \min_{i,j \in \underline{N},\, i \neq j} \{\lambda_{\min}(P_{ij})\},$$

$$b_2 = \max_{i,j \in \underline{N},\, i \neq j} \{\lambda_{\max}(P_{ij}) + \tau_2^2 \lambda_{\max}(Q_{ij}) + \tau_2 \lambda_{\max}(R_{1ij}) + \tau_1 \lambda_{\max}(R_{2ij})\}.$$

Denoting $t_0, \; t_1, \; \ldots, \; t_k$ the switching instants in $[t_0, \; t)$, we consider the following piece-wise Lyapunov functional candidate for the closed-loop system

$$V(t) = \begin{cases} x^T(t)P_ix(t) + \int_{-\tau_2}^0 \int_{t+\theta}^t \dot{x}^T(s)e^{-\alpha(t-s)}Q_i\dot{x}(s)dsd\theta + \int_{t-\tau_2}^t x^T(s)e^{-\alpha(t-s)}R_{1i}x(s)ds + \int_{t-\tau_1}^t \dot{x}^T(s)e^{-\alpha(t-s)}R_{2i}\dot{x}(s)ds \\ \qquad t \in [t_n + \Delta_n, t_{n+1}) \cup [t_0, t_1), \quad n = 1, 2, \ldots, k \\ x^T(t)P_{ij}x(t) + \int_{-\tau_2}^0 \int_{t+\theta}^t \dot{x}^T(s)e^{\beta(t-s)}Q_{ij}\dot{x}(s)dsd\theta + \int_{t-\tau_2}^t x^T(s)e^{\beta(t-s)}R_{1ij}x(s)ds + \int_{t-\tau_1}^t \dot{x}^T(s)e^{\beta(t-s)}R_{2ij}\dot{x}(s)ds \\ \qquad t \in [t_n, t_n + \Delta_n), \quad n = 1, 2, \ldots, k \end{cases} \tag{31}$$

From (25) and (29), for $t_k + \Delta_k \le t < t_{k+1}$, we have

$$\begin{aligned} V(t) &< e^{-\alpha(t - t_k - \Delta_k)} V(t_k + \Delta_k) \\ &< \mu_1 e^{-\alpha(t - t_k - \Delta_k)} V((t_k + \Delta_k)^-) \\ &< \mu_1 e^{-\alpha(t - t_k - \Delta_k)} e^{\beta \Delta_k} V(t_k) \\ &< \mu_1 \mu_2 e^{-\alpha(t - t_k - \Delta_k)} e^{\beta \Delta_k} V(t_k^-) \\ &< \cdots \\ &< (\mu_1\mu_2)^k e^{-\alpha[(t - t_k - \Delta_k) + (t_k - t_{k-1} - \Delta_{k-1}) + \cdots + (t_1 - t_0 - \Delta_0)]} \\ &\qquad + \beta(\Delta_k + \Delta_{k-1} + \cdots + \Delta_0) V(t_0) \\ &= (\mu_1\mu_2)^k e^{-\alpha T^-(t_0,t) + \beta T^+(t_0,t)} V(t_0) \end{aligned} \tag{32}$$

By Definition 2, we know that $k = N_\sigma$, then

$$k \le N_0 + \frac{t - t_0}{\tau_a} \tag{33}$$

From (22), we can obtain

$$-T^-(t_0, t)\lambda^- + T^+(t_0, t)\lambda^+ \le -\lambda^*(t - t_0) \tag{34}$$

substituting (33) and (34) into (32), we have

$$\begin{aligned} V(t) &< (\mu_1\mu_2)^{N_0 + (t - t_0)/\tau_a} e^{-\lambda^*(t - t_0)} V(t_0) \\ &= (\mu_1\mu_2)^{N_0} e^{[\ln(\mu_1\mu_2)/\tau_a - \lambda^*](t - t_0)} V(t_0) \end{aligned}$$

Thus it can be obtained that

$$\|x(t)\| < \sqrt{\frac{b}{a}} \cdot (\mu_1\mu_2)^{N_0/2} e^{[\ln(\mu_1\mu_2)/\tau_a - \lambda^*](t - t_0)/2} \|x(t_0)\|_h$$

where

$$a = \min_{i,j \in \underline{N},\, i \neq j} \{\lambda_{\min}(P_i), \lambda_{\min}(P_{ij})\},$$

$$b = \max_{i,j \in \underline{N},\, i \neq j} \{\lambda_{\max}(P_i) + \tau_2^2\lambda_{\max}(Q_i) + \tau_2\lambda_{\max}(R_{1i}) + \tau_1\lambda_{\max}(R_{2i}), \lambda_{\max}(P_{ij}) + \tau_2^2\lambda_{\max}(Q_{ij}) + \tau_2\lambda_{\max}(R_{1ij}) + \tau_1\lambda_{\max}(R_{2ij})\}.$$

Denoting $W_{1i} = W_{2i} = W_{3i} = W_{4i} = W_{5i} = P_i$, and substituting them into (24), then we have

$$\begin{pmatrix} \phi_{211i} & -P_i + (A_i + D_iK_i)^T P_i + M_{2i} & (A_i + D_iK_i)^T P_i + P_iB_i - M_{1i}^T + M_{3i} & 2P_iC_i + (A_i + D_iK_i)^T P_i + M_{4i} & -P_iB_i + (A_i + D_iK_i)^T P_i - M_{1i}^T + M_{5i} \\ * & \tau_2 Q_i - 2P_i + R_{2i} & P_iB_i - P_i + M_{2i}^T & P_iC_i - P_i & -P_i - M_{2i}^T \\ * & * & -e^{-\alpha\tau_2} R_{1i} + P_iB_i + B_i^T P_i - M_{3i}^T - M_{3i} & P_iC_i + B_i^T P_i - M_{4i} & B_i^T P_i - M_{3i}^T - M_{5i} \\ * & * & * & -e^{-\alpha\tau_1} R_{2i} + P_iC_i + C_i^T P_i & C_i^T P_i - M_{4i}^T \\ * & * & * & * & -\frac{e^{-\alpha\tau_2}}{\tau_2} Q_i - M_{5i}^T - M_{5i} \end{pmatrix} < 0 \tag{35}$$

where

$$\phi_{211i} = P_i(A_i + B_i + D_iK_i) + (A_i + B_i + D_iK_i)^T P_i + \alpha P_i + P_i(A_i + D_iK_i) + (A_i + D_iK_i)^T P_i + R_{1i} + M_{1i}^T + M_{1i}.$$

Using $diag\{P_i^{-1}, P_i^{-1}, P_i^{-1}, P_i^{-1}, P_i^{-1}\}$ to pre- and post-multiply the left term of (35), and denoting $P_i^{-1} = X_{1i}$, $K_iP_i^{-1} = X_{2i}$, $P_i^{-1}R_{1i}P_i^{-1} = X_{3i}$, $P_i^{-1}R_{2i}P_i^{-1} = X_{4i}$, $P_i^{-1}Q_i^{-1}P_i^{-1} = X_{5i}$, $P_i^{-1}M_{li}P_i^{-1} = N_{li}(l = 1, 2, \ldots, 5)$,we can obtain (20).

Similarly, substituting $K_i = X_{2i}X_{1i}^{-1}$ into (28) and denoting $M_{lij} = N_{lij}(l = 1, 2, \ldots, 5)$ leads to (21).

The proof is completed.

Remark 3. It can be noticed that the matrix inequalities (20) and (21) are not LMIs. To solve the problem, we can firstly solve the LMI (20) to obtain the solutions of matrices X_{1i}, X_{2i}. Then (21) can be transformed into the LMI by substituting X_{1i}, X_{2i} into (21). By adjusting the parameters α, β, we can find the feasible solutions of X_{1i}, X_{2i}, X_{3i}, X_{4i}, X_{5i}, P_{ij}, R_{1ij}, R_{2ij}, Q_{ij} and W_{lij}, N_{li}, $N_{lij}(l = 1, 2, \ldots, 5)$ such that (20) and (21) hold.

Numerical example

In this section, we present an example to illustrate the effectiveness of the proposed approach. Consider system (1)–(2) with parameters as follows:

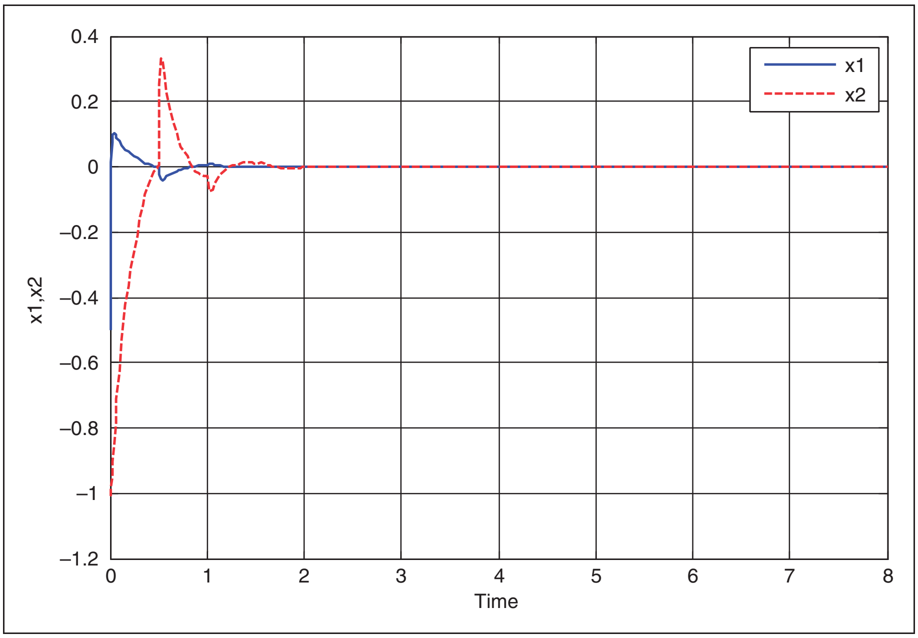

Figure 1 State trajectories of the closed-loop system.

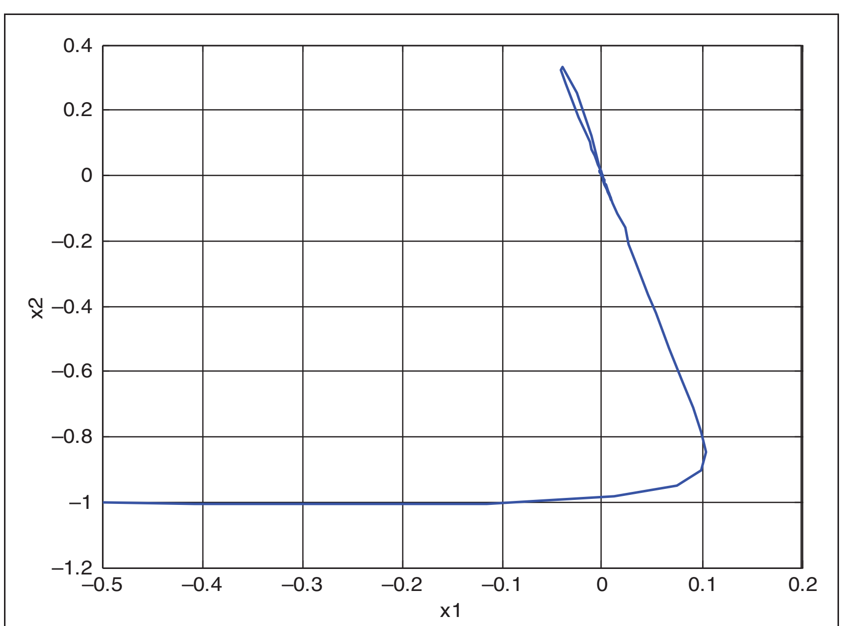

Figure 2 Phase plane portrait.

$$A_1 = \begin{bmatrix} -3 & -6 \\ 4 & -5 \end{bmatrix}, \quad B_1 = \begin{bmatrix} -1 & 0 \\ -1 & -1 \end{bmatrix}, \quad C_1 = \begin{bmatrix} -0.04 & 0 \\ 0.5 & -0.1 \end{bmatrix}, \quad D_1 = \begin{bmatrix} -4 & -1 \\ 1 & 1 \end{bmatrix}$$
$$A_2 = \begin{bmatrix} -2 & 3 \\ -4 & -5 \end{bmatrix}, \quad B_2 = \begin{bmatrix} -1 & -2 \\ 0 & -1 \end{bmatrix}, \quad C_2 = \begin{bmatrix} -0.1 & 0 \\ -0.5 & -0.05 \end{bmatrix}, \quad D_2 = \begin{bmatrix} -2 & 1 \\ -1 & -1 \end{bmatrix}$$

Choosing $\tau_1 = 0.5$, $\tau_2 = 0.3$, $\alpha = 4$, $\beta = 12$, by solving the matrix equalities in Theorem 1, we obtain K_1, K_2 as follows

$$K_1 = \begin{bmatrix} 0.9308 & -2.9176 \\ -2.7734 & 5.2955 \end{bmatrix}, K_2 = \begin{bmatrix} 33.5196 & 2.2653 \\ -21.4826 & -1.0548 \end{bmatrix}$$

The state trajectories of the closed-loop system under asynchronous switching ($\Delta_k = 0.1,\ k = 1, 2$) are shown in Figures 1 and 2, where the initial condition $x(0) = [-0.5 \quad -1]^T$, $\tau^* = 0.5$.

Conclusions

This paper focuses on designing the controller for a class of switched neutral systems with asynchronous switching. The dwell time approach and free weighting matrix scheme are utilized for the stability analysis, and a kind of controller design methodology is proposed to guarantee the exponential stability of the switched neutral systems. An illustrative example is also given to illustrate the applicability of the proposed approach.

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