

New Stability Conditions for Nonlinear Systems Described by Multiple Model Approach

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ABSTRACT

This paper studies the global asymptotic stability and the tracking control problem of an uncertain non stationary continuous system described by the multiple model approach. It is based on the construction of a basis of models containing four extreme models and possibility of addition of an average model. Once the basis of models is generated, an operation of fusion of these different models is made to the level of the elementary control law and the partial output using the geometric method. New sufficient conditions for the stability are derived via Lyapunov technique. The matrices of feedback gains and tracking gains are determined while solving systems of LMI constraints (Linear Matrix Inequalities). The case of an unstable continuous nonlinear model of electrical circuit operating in pseudo-periodic system is considered to illustrate the proposed approach.

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1. INTRODUCTION

The multiple model approach is proving very interesting whenever we are confronted with complex systems and/or nonlinear. It is to represent the system studied by a family of simpler and easier to manipulate mathematical models [1], [2], [3]. This approach has been recently developed in several science and engineering domains, with typical applications in the electrical and mechanical engineering areas, with application to modelling, control and/or fault detection. It was introduced as an efficient and powerful method to cope with modelling and control difficulties when complex non linear and/or uncertain processes are concerned. The multiple model approach assumes that it is possible to replace a unique non linear representation by a combination of simpler models thus building a so-called model-base. Usually, each model of this base describes the considered process at a specific operating point [4]. The interaction between the different models of the base through normalized activation functions allows the modelling of the global non-linear and complex system. The stability of these models is, most of the time, studied using the quadratic Lyapunov approach [5], [6], [7], [8], [9], [10]. The obtained conditions are given in terms of Linear Matrix Inequalities (LMI) and can be efficiently solved by convex programming techniques [11], [12], [13], [14].

The stability conditions based on the use of the quadratic Lyapunov function are conservative as a single common symmetric positive definite matrix verifying all Lyapunov inequalities is required [13]. It is also rejected by certain systems such as the saturated systems, the piecewise linear systems, etc. Some works show the contribution of the polyquadratic and the piecewise quadratic Lyapunov functions, [15], [16], [17].

The study proposed in this paper focuses on a class of uncertain systems and complex continuing bounded parameters [18], [19]. The global model can be obtained either by using the switching operation or fusion. In this study, we are interested in the fusion using the geometric method [19].

This method is seen at both the elementary controls at the level of partial outputs and driven by validity indices.

Our new stability conditions are proposed in the case of multiple model stabilizing state feedback control with reference, permits to locally find a symmetric positive definite matrix to each model of the basis. At the entrance to each base model in closed loop control is applied overall inferred weights of elementary linear feedback control with reference state and to converge the global output of the controlled system to a desired trajectory. Matrices gains by state feedback and tracking are determined by solving systems stability conditions given in terms of LMI [20], [21], [22], [23].

This paper is organized as follows. In Section 2, we introduce briefly some basic notions of multiple model approach and the theoretical tool used in this work, namely the algebraic method. In section 3, the strategies of multiple model control based on geometric method is proposed. Stability conditions using new LMI approach based on state feedback with reference are provided in section 4. In the section 5 an example of an unstable second order continuous model of electrical circuit operating in pseudo-periodic system is studied to illustrate the efficiency of this approach. Conclusion is drawn in section 6.

Notations

- The symbol (*) denotes the transpose elements in the symmetric positions, for example,

$$X + (*) < 0 \Leftrightarrow X + X^T < 0 \text{ and } \begin{pmatrix} A & B \\ (*) & C \end{pmatrix} < 0 \Leftrightarrow \begin{pmatrix} A & B \\ B^T & C \end{pmatrix} < 0$$

- LMI: Linear Matrix Inequalities

2. PROBLEM STATEMENT

The evolution of a continuous non-stationary uncertain parameters and bounded complex system is described by the following differential equation:

$$a_0(.) y(t) + a_1(.) y^{(1)}(t) + \dots + a_{n-1}(.) y^{(n-1)}(t) + y^{(n)}(t) = u(t) \quad (1)$$

with the symbol (.) represents the set of variables, uncertainties, noise or disturbances acting on the coefficients of this system as, for: $i = 0, 1, \dots, n-1$, $\underline{a}_i \leq a_i(.) \leq \bar{a}_i$ with $\underline{a}_i = \min_i(a_i(.))$ and $\bar{a}_i = \max_i(a_i(.))$.

Model (1) may be given in the following controllability companion form [15]:

$$\begin{cases} \dot{x}(t) = A(.) x(t) + B u(t) \\ y(t) = C x(t) \end{cases} \quad (2)$$

where A , B and C are respectively the state matrices, control and output with:

$$A(.) = \begin{pmatrix} 0 & 1 & 0 & \dots & 0 \\ \vdots & 0 & 1 & & \vdots \\ & & \vdots & \ddots & \\ & & & \vdots & \ddots & 0 \\ 0 & 0 & 0 & & 1 \\ -a_0(.) & -a_1(.) & -a_2(.) & \dots & -a_{n-1}(.) \end{pmatrix}, \quad B = (0 \quad \dots \quad 0 \quad 1)^T \text{ and } C = (1 \quad 0 \quad \dots \quad 0).$$

The state matrices characterizing the four models M_i of the base are given by $A_1(\underline{a}_0, \underline{a}_1, \bar{a}_2, \bar{a}_3, \dots)$, $A_2(\underline{a}_0, \bar{a}_1, \bar{a}_2, \underline{a}_3, \dots)$, $A_3(\bar{a}_0, \bar{a}_1, \underline{a}_2, \underline{a}_3, \dots)$ and $A_4(\bar{a}_0, \underline{a}_1, \underline{a}_2, \bar{a}_3, \dots)$.

In addition to these models, it is worth adding the average model as a fifth in the database, it somehow represents the barycentre of the extreme models and parameters are defined by the arithmetic mean of the four parameters extreme models with $a_{5i} = \frac{\underline{a}_i + \bar{a}_i}{2}$ for $i = 0, 1, \dots, n-1$.

A comprehensive description of the studied system can be defined from an interpolation model M_i based on the following state representation [18]:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^r \lambda_i(t) (A_i x(t) + B_i u(t)) \\ y(t) = \sum_{i=1}^r \lambda_i(t) C_i x(t) \end{cases} \quad (3)$$

where A_i , B_i and C_i are respectively the state matrices, control and output of each of the M_i basic model.

In this paper, the main objective is to converge the output $y(t)$ of the global system (3) to a desired trajectory $y_d(t)$, i.e., $y(t) - y_d(t) \rightarrow 0$ as $t \rightarrow +\infty$ with:

$$y_d(t) = \sum_{i=1}^r \lambda_i(t) C_i x_d(t) \quad (4)$$

$x_d(t)$ is the desired state vector.

3. MULTIPLE MODEL CONTROL STRATEGY USING GEOMETRIC APPROACH

The geometric method is used to calculate the distance $d_i(t)$ between the partial outputs $y_i(t)$ and the desired trajectory $y_d(t)$, such as [10],[11]:

$$d_i(t) = |y_d(t) - y_i(t)| \quad (5)$$

The normalized distance n_i is given by:

$$n_i(t) = d_i(t) \left(\sum_{j=1}^r d_j(t) \right)^{-1} \quad (6)$$

The geometric validities λ_i are given by:

$$\lambda_i(t) = \gamma_i(t) \left(\sum_{j=1}^r \gamma_j(t) \right)^{-1} \quad (7)$$

with:

$$\gamma_i(t) = (1 - n_i(t)) \prod_{\substack{j=1 \\ j \neq i}}^r \left(1 - \exp \left(- \left(\frac{n_j(t)}{\sigma} \right)^2 \right) \right) \quad (8)$$

σ represents a variable regulating parameter with $0 < \sigma < 0.9$.

The validities λ_i satisfy the following conditions of convexity:

$$0 \leq \lambda_i \leq 1 \text{ and } \sum_{i=1}^r \lambda_i = 1.$$

The strategy of multiple model control described by geometric approach is given in Figure 1. The block "Fusion of elementary controls" aims to calculate the global control $u(t)$ of the fusion of n elementary controls $u_i(t)$.

The global control is driven by the indices of validity $\lambda_i(t)$.

In our case, inputs e refers to the state vector $x(t) = [x_1(t), x_2(t), \dots, x_n(t)]$ and the desired state vector $x_d(t) = [x_{1d}(t), x_{2d}(t), \dots, x_{nd}(t)]$ of system in the closed loop. These inputs are relevant to the determination of validities.

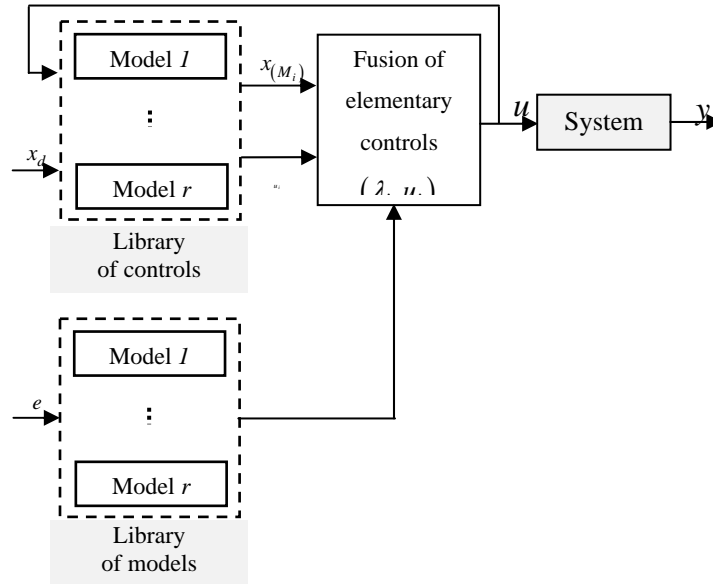


Figure 1. Block diagram of the proposed multiple model control strategy

The global control resulting of the fusion is written as follows:

$$u(t) = \sum_{i=1}^r \lambda_i(t) u_i(t) \quad (9)$$

The global output of system is given by:

$$y(t) = \sum_{i=1}^r \lambda_i(t) x_i(t) \quad (10)$$

4. NEW STABILITY CONDITIONS BASED ON STATE FEEDBACK WITH REFERENCE

The objective in this section is to find from such a formulation LMI matrices state feedback gains K_i and those tracking N_i for which the state vector $x(t) = [x_1(t) \ x_2(t) \ \dots \ x_n(t)]$ of complex continuous system described by (3) converge to a desired state vector $x_d(t) = [x_{1d}(t) \ x_{2d}(t) \ \dots \ x_{nd}(t)]$, n is the order of the controlled system [5], [9].

For each base model is applied a basic control $u_i(t)$ state feedback with reference to the form:

$$u_i(t) = -K_i x(t) + N_i x_d(t) \quad (11)$$

The global control low $u(t)$ is given by:

$$u(t) = \sum_{i=1}^r \lambda_i(t) (-K_i x(t) + N_i x_d(t)) \quad (12)$$

The relations (3) and (10) allow to have the representation of multiple model and can be writing as follows:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^r \sum_{j=1}^r \lambda_i(t) \lambda_j(t) \left(\begin{bmatrix} G_{ij} & H_{ij} \end{bmatrix} \begin{bmatrix} x(t) \\ x_d(t) \end{bmatrix} \right) \\ y(t) = \sum_{i=1}^r \lambda_i(t) C_i x(t) \end{cases} \quad (13)$$

with $G_{ij} = A_i - B_i K_j$ and $H_{ij} = B_i N_j$.

Whether $e(t)$ is the tracking error between the state vector $x(t)$ of continuous system (13) and the desired steady state vector $x_d(t)$ with:

$$e(t) = x(t) - x_d(t) \quad (14)$$

The derivative of the tracking error $\dot{e}(t) = \frac{de(t)}{dt}$ is written as follows:

$$\begin{aligned} \dot{e}(t) = \sum_{i=1}^r \sum_{j=1}^r \lambda_i(t) \lambda_j(t) \left(\begin{bmatrix} G_{ij} & H_{ij} \end{bmatrix} \begin{bmatrix} x(t) \\ x_d(t) \end{bmatrix} \right) \\ - \dot{x}_d(t) \end{aligned} \quad (15)$$

For a constant desired steady state vector $x_d(t)$, the expression (15) can be written:

$$\dot{e}(t) = \sum_{i=1}^r \sum_{j=1}^r \lambda_i(t) \lambda_j(t) \left(\begin{bmatrix} G_{ij} & Z_{ij} \end{bmatrix} \begin{bmatrix} e(t) \\ x_d(t) \end{bmatrix} \right) \quad (16)$$

with $Z_{ij} = G_{ij} + H_{ij}$

In case the control matrices B_i are square and invertible, there are new stability conditions, formulated in terms of LMI, are developed.

If we used the following constraints:

$$\begin{cases} Z_{ij} = 0 & i, j = 1, 2, \dots, r \\ x_d(t) & \text{constant} \end{cases} \quad (17)$$

The derivative $\dot{e}(t)$ is written as follows:

$$\dot{e}(t) = \sum_{i=1}^r \sum_{j=1}^r \lambda_i(t) \lambda_j(t) G_{ij} e(t) \quad (18)$$

Theorem: The equilibrium of the continuous system (10) is globally asymptotically stable if exists a matrix $Q = P^{-1}$ such that $Q = Q^T > 0$ and square matrices R_i with size n , such as:

$$A_i Q - B_i R_i + (*) < 0 \quad \text{for } i = 1, 2, \dots, r \quad (19)$$

$$\frac{1}{2} (A_i + A_j) Q - \frac{1}{2} B_i R_j - \frac{1}{2} B_j R_i + (*) \leq 0 \quad (20)$$

for $1 \leq i < j \leq r$

The gains by stabilizing feedback K_i state are calculated by:

$$K_i = R_i P \text{ for } i = 1, 2, \dots, r \quad (21)$$

The tracking gains N_i are given by:

$$N_i = -B_j^{-1} (A_j - B_j K_i) \text{ for } i, j = 1, 2, \dots, r \quad (22)$$

Proof: Based on the Lyapunov stability conditions can be written:

$$V(e(t)) = e^T(t) P e(t) > 0 \quad (23)$$

$$\dot{V}(e(t)) = \dot{e}^T(t) P e(t) + e^T(t) P \dot{e}(t) < 0 \quad (24)$$

The development of $\dot{V}(e(t))$ gives:

$$\dot{V}(e(t)) = e^T(t) \left(\sum_{i=1}^r \sum_{j=1}^r \lambda_i(t) \lambda_j(t) (P G_{ij} + (*)) \right) e(t) < 0 \quad (25)$$

From the constraint $Z_{ij} = 0$ for $i, j = 1, 2, \dots, r$, it follows that:

$$A_i - B_i K_j + B_i N_j = 0 \text{ for } i, j = 1, 2, \dots, r \quad (26)$$

whence the relation (22).

5. CASE OF STUDY : ELECTRICAL CIRCUIT

Consider an electric circuit, Figure 2, may models a different dynamic process (thermal, mechanical, hydraulic,...), which includes two resistors (R_1, R_2) and two capacitors (C_1, C_2) supplied by two voltages ($u_1(t), u_2(t)$).

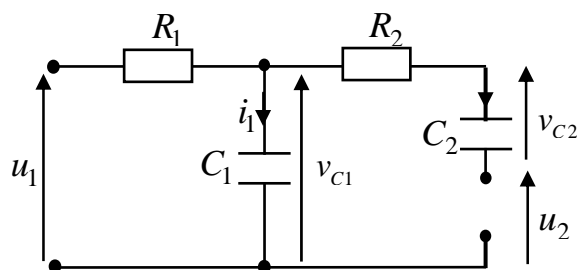


Figure 2. Electrical Circuit

5.1. System Modeling

The main objective is to converge $v_{C1}(t)$ and $v_{C2}(t)$ to constant values 5v and 24v respect. Following characteristics:

$C_1 = C_2 = 100 \mu F$, $R_1 = 1 K\Omega$ and $R_2 = 10 K\Omega$.

The differential equations describing the circuit are given by:

$$u_1(t) = R_1(i_1(t) + i_2(t)) + v_{C1}(t) \quad (27.a)$$

$$v_{C1}(t) = R_2 i_2(t) + v_{C2}(t) + u_2(t) \quad (27.b)$$

$$\dot{v}_{C1}(t) = \frac{d v_{C1}(t)}{dt} = \frac{1}{C_1} i_1(t) \quad (27.c)$$

$$\dot{v}_{C2}(t) = \frac{d v_{C2}(t)}{dt} = \frac{1}{C_2} i_2(t) \quad (27.d)$$

By choosing the state vector $x(t) = (v_{C1}(t) \ v_{C2}(t))^T$ and the control vector $u(t) = (u_1(t) \ u_2(t))^T$, we can write the electric circuit in the following matrix form:

$$\begin{cases} \dot{x}(t) = A x(t) + B u(t) \\ y(t) = C x(t) \end{cases} \quad (28)$$

with:

$$A = \begin{pmatrix} -\frac{R_1 + R_2}{R_1 R_2 C_1} & \frac{1}{R_2 C_1} \\ \frac{1}{R_2 C_2} & -\frac{1}{R_2 C_2} \end{pmatrix}, \quad B = \begin{pmatrix} \frac{1}{R_1 C_1} & \frac{1}{R_2 C_1} \\ 0 & -\frac{1}{R_2 C_2} \end{pmatrix} \quad \text{and} \quad C = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

For the construction of model's library, we assume that the resistors R_1 and R_2 have an uncertainty such as $\underline{R}_1 \leq R_1 \leq \bar{R}_1$ and $\underline{R}_2 \leq R_2 \leq \bar{R}_2$ with: $\underline{R}_1 = 0.8 \text{ K}\Omega$, $\bar{R}_1 = 1.2 \text{ K}\Omega$, $\underline{R}_2 = 8.5 \text{ K}\Omega$, $\bar{R}_2 = 11.5 \text{ K}\Omega$. The four models in the database are defined for combinations $(\underline{R}_1, \underline{R}_2)$, $(\underline{R}_1, \bar{R}_2)$, $(\bar{R}_1, \underline{R}_2)$ and (\bar{R}_1, \bar{R}_2) .

The following matrices A_i and B_i are calculated:

$$A_1 = \begin{pmatrix} -13.6765 & 1.1765 \\ 1.1765 & -1.1765 \end{pmatrix}, \quad A_2 = \begin{pmatrix} -13.3696 & 0.8696 \\ 0.8696 & -0.8696 \end{pmatrix}, \quad A_3 = \begin{pmatrix} 9.5098 & 1.1765 \\ 1.1765 & -1.1765 \end{pmatrix} \quad \text{and} \quad A_4 = \begin{pmatrix} -9.2029 & 0.8696 \\ 0.8696 & -0.8696 \end{pmatrix}.$$

$$B_1 = \begin{pmatrix} 12.5 & 1.1765 \\ 0 & -1.1765 \end{pmatrix}, \quad B_2 = \begin{pmatrix} 12.5 & 0.8696 \\ 0 & -0.8696 \end{pmatrix}, \quad B_3 = \begin{pmatrix} 8.3333 & 1.1765 \\ 0 & -1.1765 \end{pmatrix} \quad \text{and} \quad B_4 = \begin{pmatrix} 8.3333 & 0.8696 \\ 0 & -0.8696 \end{pmatrix}.$$

Solving the proposed LMI system stability conditions presented in Theorem, the matrices of feedback gains K_i defined in (21) are given by:

$$K_1 = \begin{pmatrix} -0.2666 & -0.6545 \\ -8.3751 & 0.5770 \end{pmatrix}, \quad K_2 = \begin{pmatrix} -0.4467 & -0.4749 \\ -8.3839 & 0.4354 \end{pmatrix}, \quad K_3 = \begin{pmatrix} -0.2534 & -0.6320 \\ -5.8736 & 0.5839 \end{pmatrix} \quad \text{and} \quad K_4 = \begin{pmatrix} -0.4335 & -0.4525 \\ -5.8769 & 0.4431 \end{pmatrix}.$$

The matrices of tracking gains N_i defined in (22) are given by:

$$N_1 = \begin{pmatrix} 0.7334 & -0.6545 \\ -7.3751 & -0.4230 \end{pmatrix}, \quad N_2 = \begin{pmatrix} 0.5533 & -0.4749 \\ -7.3839 & -0.5646 \end{pmatrix}, \quad N_3 = \begin{pmatrix} 0.7466 & -0.6320 \\ -4.8736 & -0.4161 \end{pmatrix}, \quad N_4 = \begin{pmatrix} 0.5665 & -0.4525 \\ -4.8769 & -0.5569 \end{pmatrix}.$$

5.2. Simulation Results

In this section, the proposed control is applied to regulate uncertain non stationary nonlinear systems of electrical circuit described by multiple model approach. In the simulations, we employed *Simulink* of MATLAB® and the Solver option is "ode45".

The objective is to stabilize the voltages $v_{C1}(t)$ and $v_{C2}(t)$ across the capacitors C_1 and C_2 of electrical circuit to constant desired voltages $x_{1d} = 5\text{v}$ and $x_{2d} = 24\text{v}$.

The evolutions of state variables $x_{1i}(t)$ and $x_{2i}(t)$ for each base model are given in Figures 3 and 4 respectively.

The performance of trajectory tracking of the state variables $x_1(t)$ and $x_2(t)$ starting system in closed loop, and desired state variables constant, x_{1d} and x_{2d} are illustrated in Figure 5.

Figure 6 shows the evolutions of the voltage $u_1(t)$ to the input of electrical circuit and four basic voltages $u_{1i}(t)$.

Figure 7 shows the evolutions of the voltage $u_2(t)$ and four basic voltages $u_{2i}(t)$.

The state variables $x_1(t)$ and $x_2(t)$ of the starting system in closed loop converge respectively to desired voltage constants values $x_{1d} = 5v$ and $x_{2d} = 24v$ with small oscillations (Figure 5). This is a so-called pseudo-periodic oscillations whose amplitude, expressed in volts, is not constant and decreases (The oscillations are damped).

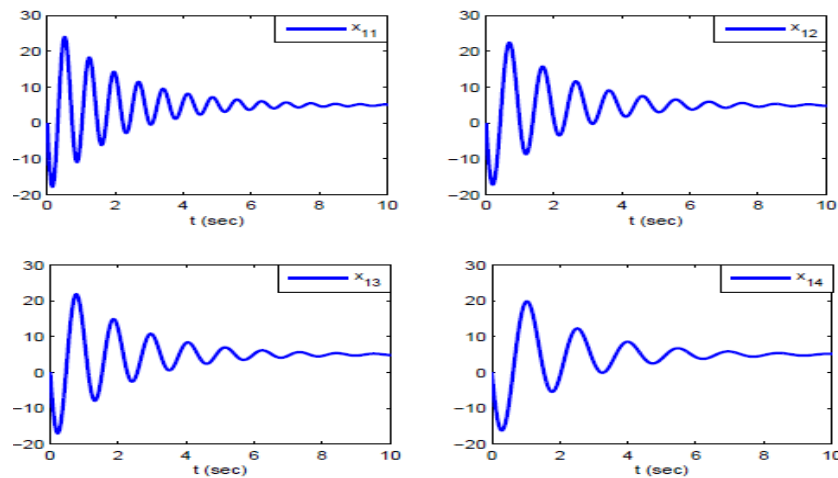


Figure 3. Evolutions of the state variable $x_1(t)$ for each model of the base

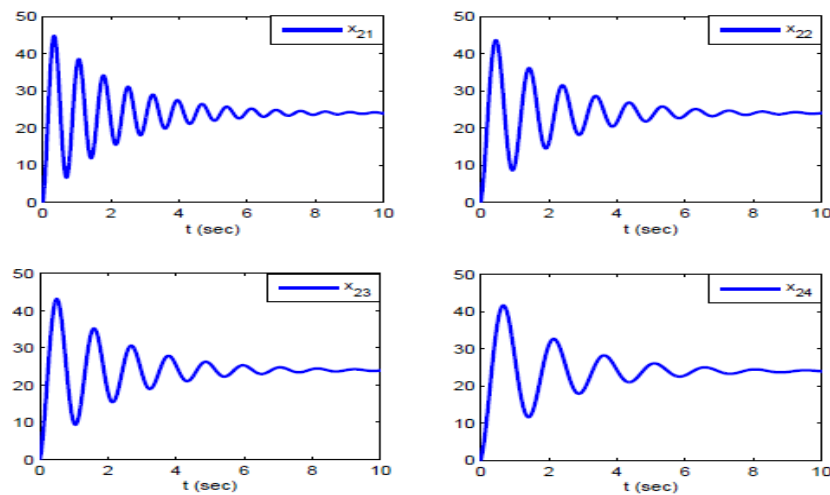


Figure 4. Evolutions of the state variable $x_2(t)$ for each model of the base

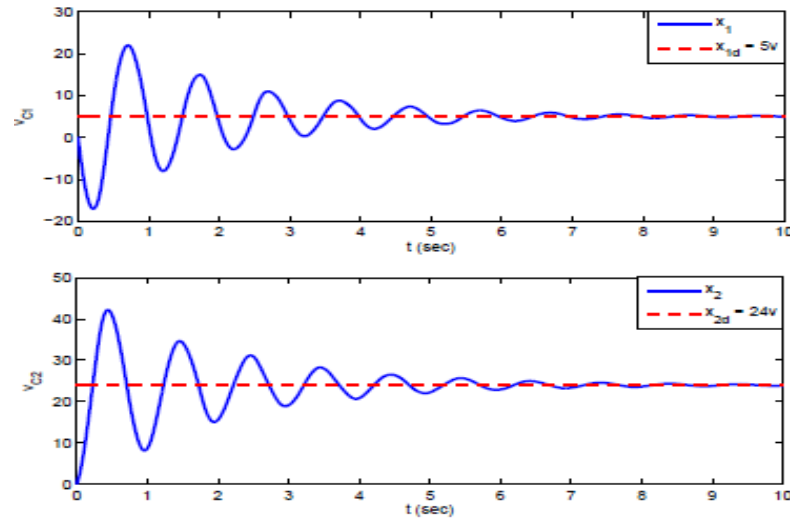


Figure 5. The performance of trajectory tracking of $v_{C1}(t)$ and $v_{C2}(t)$ with the desired constant voltages

The multiple model control in which we will be interested consists in the fusion of partial controls. For that we have to compute the validities of each partial model and associate the sub controls weighted by the correspondent coefficients.

The obtained result will control the global process (29).

The global voltages $u_1(t)$ and $u_2(t)$ are given by the following relations:

$$\begin{cases} u_1(t) = \sum_{i=1}^r \lambda_i(t) u_{1i}(t) \\ u_2(t) = \sum_{i=1}^r \lambda_i(t) u_{2i}(t) \end{cases} \quad (29)$$

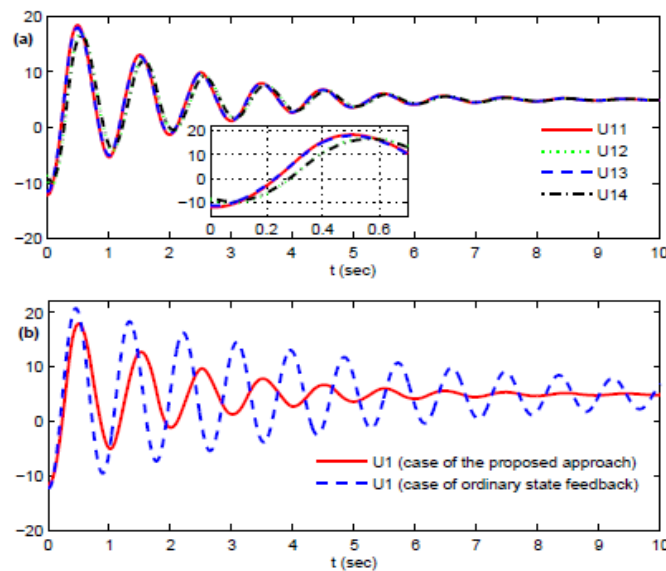


Figure 6. Simulation results of new LMI approach, (a) Evolutions of four basic voltages $u_{1i}(t)$, (b) Evolution of the voltage $u_1(t)$ with the proposed state feedback with reference

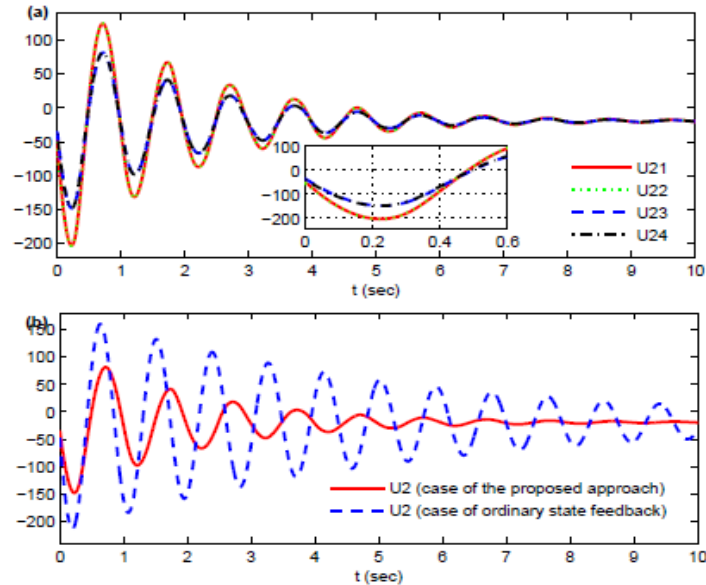


Figure 7. Simulation results of new LMI approach, (a) Evolutions of four basic voltages $u_{2i}(t)$,
(b) Evolution of the voltage $u_2(t)$ with the proposed state feedback with reference

When the new conditions of stability are used, the feedback K_i and the tracking N_i gains guarantee the stability of the continuous system of electrical circuit, initially unstable, described by the multiple model approach. Thus, all the trajectories of the voltages $v_{C1}(t)$ and $v_{C2}(t)$ across the capacitors C_1 and C_2 can track the desired constant voltages x_{1d} and x_{2d} very well and the global model response is better in the new approach (state feedback with reference) case than in the ordinary state feedback control.

We can conclude that each capacitor discharges and recharges with small oscillations around the value of the desired constant voltages.

6. CONCLUSION

In this paper, a contribution in tracking control for a class of continuous non stationary uncertain system with limited parameters is considered. Based on the geometric approach, a library of four models was built. New stability conditions have been developed in the case of multiple model control in the case of state feedback with reference. These conditions allow to reaching the state variables of the closed-loop multiple model describing the complex system starting to the desired state variables. The Matrices gains by state feedback and the matrices of tracking gains are given by solving a system of LMI conditions. Case study of an electrical circuit of second order operative in mode pseudo-periodic is conducted to compare the proposed approach with the ordinary state feedback. Finally, the result of computer simulation has demonstrated the effectiveness of the proposed approach.

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