Acta Technica 62, No. 3B/2017, 593–602

Adaptive sliding mode reliable excitation control design for power systems

Xueting Liu[1,3], Yanchao Yan[2]

Abstract. In this paper, the problem of adaptive sliding mode reliable excitation control design procedure was considered for multi-machine power systems with possible actuator faults, which the upper bound is not exactly known, using linear matrix inequality technique and Lyapunov stability theory. The control objective is to investigate the reliable design on both passive and adaptive sliding mode excitation controllers. Finally, the numerical simulation results based 2-area 4-machine power system validated the effectiveness of the proposed method in terms of improvement of the system stability and reliability effectively.

Key words. Sliding mode excitation control, adaptive, electric power system, stability, reliable.

1. Introduction

With the development of science and technology, the power industry is an important pillar of the national economy in every country in the world. In recent years, the continuous development of power system and safe and stable operation to the world each country's national economic and social development, the tremendous power and efficiency. So how to ensure the stable and efficient operation of the power system and the reliable quality of the power supply for the users is the basic problem to be considered. However, historical experience shows that once the multi-machine power system of natural and man-made fault, if not promptly and effectively control and lose stability, and even the collapse of the power grid, will lead to blackouts, will bring serious influence to the society and the consequences.

With the rapid growth of the power demand of each country in the world, the scale of the power grid and the degree of interconnection are increasing. The safe

[1]College of Electrical and Electronic Engineering, Shandong University of Technology, Zibo 255049, China

[2]School of Science, Shandong University of Technology, Zibo 255049, China

[3]Corresponding author; e-mail: lhk8068@163.com

and reliable operation of power system is becoming more and more serious. How to evaluate the grid during operation, especially the reliability level in the fault state and special operation mode of the power system has become an urgent problem in the world, the majority of electricity workers concerned [1–6].

The so-called reliable control refers to the stability of the closed-loop system and the other performance in the acceptable range of control when the actuator or sensor failure occurs. Reliable control research has always been an active research area [7–14] . In this paper, the problem of adaptive sliding mode reliable excitation control design procedure was considered for multi-machine power systems which allows the actuator failure using linear matrix inequality technique and Lyapunov stability theory. The control objective is to investigate the reliable design on both passive and adaptive sliding mode excitation controllers. Finally, the numerical simulation results based 2-area 4-machine power system validated the effectiveness of the proposed method in terms of improvement of the system stability and reliability effectively.

2. Mathematical model

In this paper, a multi-machine power system with possible actuator faults, external disturbances and uncertain parameters, is considered, assuming that the input mechanical power is constant. Neglecting the equivalent damping windings ($E'_d = 0,\ X_q = X'_q$) and transient salient pole effect of q axis ($X'_d = X'_q$). Then the state equation of the N-machine power system i can be described as

$$\begin{cases} \dot{\delta}_i = \omega_i - \omega_0, \\ \dot{\omega}_i = -\frac{\xi_i}{T_i}\omega_i - \frac{\omega_0 I_{qi}}{T_i}E'_{qi} + \frac{\omega_0}{T_i}P_{mi} + \frac{\xi_i}{T_i}\omega_0 + d_{i1}(t), \\ \dot{E}'_{qi} = -\frac{1}{T'_{d0i}}E'_{qi} + \frac{I_{di}(x_{di} - x'_{di})}{T'_{d0i}} - \frac{1}{T'_{d0i}}E_{fi} + d_{i2}(t), \end{cases} \tag{1}$$

where $i = 1, 2, \cdots, N$, $d_{i1}(t)$ and $d_{i2}(t)$ represent the errors and external disturbances existing in the model, but the upper bound is not exactly known; ξ_i represents the damping coefficient and is an uncertain parameter, δ_i represents the power angle, ω_i represents the rotor angular velocity, ω_0 represents the rated angular velocity where $\omega_0 = 2\pi f$. Symbol T_i represents the inertia time constant, P_{mi} is the mechanical power that is assumed constant, E_{fi} represents the excitation voltage, that is, the design of the control, I_{di} and I_{qi} represent the d-axis and the q-axis components of the armature current, and can be regarded as the implicit functions of the system state.

The COI signal is defined as follows

$$\delta_{\mathrm{COI}} = \frac{\sum_{i=1}^{M} T_i\delta_i}{\sum_{i=1}^{M} T_i}, \qquad \omega_{\mathrm{COI}} = \frac{\sum_{i=1}^{M} T_i\omega_i}{\sum_{i=1}^{M} T_i}.$$

Take the following coordinate transformation for (1):

$$\begin{cases} x_{i1} = (\delta_i - \delta_0) - (\delta_{\mathrm{COI}} - \delta_{\mathrm{COI0}}), \\ x_{i2} = \omega_i - \omega_{\mathrm{COI}}, \\ x_{i3} = \frac{\omega_0}{T_i}\left(P_{mi} - E'_{qi} I_{qi}\right) - \dot{\omega}_{\mathrm{COI}}. \end{cases}$$

The formula (1) can be transformed to

$$\dot{x}_i(t) = A x_i(t) + \xi_i f_i(x_i(t)) + B_1 u_i^F(t) + B_2 d_{i1} + B_3 d_{i3}\,, \tag{2}$$

where

$$A = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix},\ B_1 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix},\ B_2 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix},\ f_i(x_i(t)) = \begin{pmatrix} 0 \\ \omega_i - \omega_0 \\ 0 \end{pmatrix}.$$

Suppose that system (2) may be actuator failure, and failure modes satisfy

$$u_i^F(t) = (I - \Lambda_i(t))\, u_i(t)\,, \tag{3}$$

where

$$\Lambda_i(t) = \mathrm{diag}(\ \delta_{i1}(t),\quad \delta_{i2}(t),\quad \delta_{i3}\ (t)),\quad 0 \le \underline{\delta}_{ij} \le \delta_{ij}(t) \le \overline{\delta}_{ij} < 1\ ,\quad j = 1, 2, 3\,,$$

and I is three-order unit matrix.

If the failure (3) occurs, the system (2) can be changed as

$$\dot{x}_i(t) = A x_i(t) + \xi_i f_i(x_i(t)) + B_1 u_i^F(t) + B_2 d_{i1} + B_1 d_{i3}. \tag{4}$$

For system (3) the objective of this paper is to design the adaptive sliding mode reliable excitation control law, which makes the state trajectory tend to the specified sliding surface, and the sliding mode motion along the specified sliding surface is asymptotically stable even if the actuator failure occurs.

The sliding surface of the sliding mode is

$$s_i(t) = G_i x_i(t) = 0\,, \tag{5}$$

where $G_i = B_1^{\mathrm{T}} P_i^{-1}$ and $P_i > 0$. It is easy to see that $G_i B_1$ is nonsingular.

The aim of this paper is that the sliding mode control law can make the state trajectory tend to the specified sliding surface, and asymptotically tends to zero along the sliding surface. Because of the possible failure of the system, this paper studies the adaptive sliding mode control

3. Controller design

In order to achieve the purpose of this paper, the adaptive sliding mode reliable excitation controller is designed as follows

$$u_i(t) = -(I - \widehat{\Lambda}_i(t))^{-1}(K_i + G_iA)x_i(t) - \rho_i(t)\,\mathrm{sgn}(\mathrm{s}_i(t)), \tag{6}$$

$$\rho_i(t) = \frac{1}{1-\overline{\delta}_{max}} \cdot \left[\mu + B_2^T\widehat{\xi}_i + \left\|(G_iB_1)^{-1}G_i\right\| \|Ax_i(t)\| + \|(K_i + G_iA)\,x_i(t)\|\right]. \tag{7}$$

The update rates are defined as follows

$$\dot{\widehat{\theta}} = l_{i1}x_i^{\mathrm{T}}P_i^{-1}B_1 f_i(x_i(t)), \quad \dot{\widehat{\varepsilon}}_1 = l_{i2}x_i^TP_i^{-1}B_2d_{i1}, \ \dot{\widehat{\varepsilon}}_2 = l_{i3}x_i^TP_i^{-1}B_1d_{i2}, \tag{8}$$

$$\dot{\widehat{\delta}}_{ij}(t) = \underset{[\underline{\delta}_{ij},\overline{\delta}_{ij}]}{Pr}\{U_{ij}\} = \begin{cases} 0, & \widehat{\delta}_{ij}(t) = \underline{\delta}_{ij} \text{ and } U_{ij} \le 0, \text{ or } \widehat{\delta}_{ij}(t) = \overline{\delta}_{ij} \text{ and } U_{ij} \ge 0, \\ U_{ij}, & \text{other cases,} \end{cases}$$

where

$$U_{ij} = \eta_{ij}x_i^{\mathrm{T}}(P^{-1}B_1)_j\left(1 - \widehat{\delta}_{ij}(t)\right)^{-1}(K_i + G_iA)^jx_i(t),$$

and l_{i1}, l_{i2}, l_{i3}, η_{ij} are adaptive gain coefficients. Symbol

$$\widehat{\Lambda}_i(t) = \mathrm{diag}\left\{\widehat{\delta}_{i1}(t), \ \widehat{\delta}_{i2}(t), \ \cdots, \ \widehat{\delta}_{im}(t)\right\},$$

M^j and M_j are row j and column j of the matrix M respectively. Pr$\{\bullet\}$ represents the projection operator, whose function is to project the estimate value $\widehat{\delta}_{ij}(t)$ onto the interval $[\underline{\delta}_{ij}, \overline{\delta}_{ij}]$.

Theorem 3.1: For system (4), the adaptive sliding mode controller is designed as (6), (7), (8). If there exist matrices $L_i \in \mathcal{R}^{m\times n}$, $P_i > 0$, such that the following linear matrix inequality is established

$$\begin{bmatrix} \aleph_i & B_1B_1^{\mathrm{T}} & P_iA^{\mathrm{T}} \\ * & -P_i & 0 \\ * & * & -P_i \end{bmatrix} < 0, \tag{9}$$

where $\aleph_i = AP_i + P_iA^{\mathrm{T}} - B_1K_iP_i - P_iK_i^{\mathrm{T}}B_i^{\mathrm{T}} = AP_i + P_iA^{\mathrm{T}} - B_1L_i - P_iL_i^{\mathrm{T}}$, $K_i = L_iP_i^{-1}$, then even if the actuator (3) shows the fault, the closed-loop system is asymptotically stable.

Proof: Substituting (6) into (4)

$$\dot{x}_i(t) = Ax_i(t) + \xi_if_i(x_i(t)) - B_1(I - \Lambda_i)[(I - \widehat{\Lambda}_i(t))^{-1}(K_i + G_iA)x_i(t) + \rho_i(t)\,\mathrm{sgn}(\mathrm{s}_i(t))] + B_2d_{i1} + B_1d_{i3}$$

$$= Ax_i(t) + \xi_i f_i(x_i(t)) - B_1\widetilde{\Lambda}_i[(I - \widehat{\Lambda}_i(t))^{-1}(K_i + G_iA)x_i(t)$$

$$-B_1(K_i + G_iA)x_i(t) - B_1(I - \Lambda_i)\rho_i(t)\,\mathrm{sgn}(\mathrm{s}_i(t))] + B_2d_{i1} + B_1d_{i3}, \qquad (10)$$

where $\widetilde{\Lambda_i}(t) = \mathrm{diag}\left\{\widetilde{\delta}_{i1}(t),\ \widetilde{\delta}_{i2}(t),\ \cdots,\ \widetilde{\delta}_{im}(t)\right\}$, $\widetilde{\delta}_{ij}(t) = \widehat{\delta}_{ij}(t) - \delta_{ij}(t)$ being the estimation error.

Construct now the Lyapunov function

$$V_{i1} = x_i^T P_i^{-1} x_i + \sum_{j=1}^{m} \frac{1}{\eta_{ij}}\left(\widehat{\delta}_{ij} - \delta_{ij}\right)^2 +$$

$$+\frac{1}{l_{i1}}\left(\widehat{\theta} - \theta\right)^2 + \frac{1}{l_{i2}}(\widehat{\varepsilon}_1 - \varepsilon_1)^2 + \frac{1}{l_{i3}}(\widehat{\varepsilon}_2 - \varepsilon_2)^2. \qquad (11)$$

Taking the derivative on both sides of (11),

$$\dot{V}_{i1} = 2x_i^{\mathrm{T}} P_i^{-1}(Ax_i + \xi_i f_i(x_i) - B_1(I - \Lambda_i)[(I - \widehat{\Lambda}_i)^{-1}(K_i + G_iA)x_i$$

$$+\rho_i(t)\,\mathrm{sgn}(\mathrm{s}_i(t))] + B_2d_{i1} + B_1d_{i3}) + \sum_{j=1}^{m}\frac{2}{\eta_{ij}}\dot{\widehat{\delta}}_{ij}\left(\widehat{\delta}_{ij} - \delta_{ij}\right)$$

$$+\frac{2}{l_{i1}}\dot{\widehat{\theta}}\left(\widehat{\theta} - \theta\right) + \frac{2}{l_{i2}}\dot{\widehat{\varepsilon}}_1(\widehat{\varepsilon}_1 - \varepsilon_1) + \frac{2}{l_{i3}}\dot{\widehat{\varepsilon}}_2(\widehat{\varepsilon}_2 - \varepsilon_2)^2$$

$$= 2x_i^{\mathrm{T}} P_i^{-1}(Ax_i - B_1(K_i + G_iA)x_i) - 2x_i^{\mathrm{T}} P_i^{-1} B_1\widetilde{\Lambda}_i[(I - \widehat{\Lambda}_i)^{-1}(K_i + G_iA)x_i)$$

$$-2x_i^{\mathrm{T}} P_i^{-1} B_1(I - \Lambda_i)\rho_i(\rho_i(t)\,\mathrm{sgn}(\mathrm{s}_i(t)) - \xi_i f_i(x_i))$$

$$+\sum_{j=1}^{m}\frac{2}{\eta_{ij}}\dot{\widehat{\delta}}_{ij}\left(\widehat{\delta}_{ij} - \delta_{ij}\right) + \frac{2}{l_{i1}}\dot{\widehat{\theta}}\left(\widehat{\theta} - \theta\right) + \frac{2}{l_{i2}}\dot{\widehat{\varepsilon}}_1(\widehat{\varepsilon}_1 - \varepsilon_1) + \frac{2}{l_{i3}}\dot{\widehat{\varepsilon}}_2(\widehat{\varepsilon}_2 - \varepsilon_2)^2, \qquad (12)$$

where $G_i = B_1^T P_i^{-1}$.

It is easy to deduce that

$$2x_i^{\mathrm{T}} P_i^{-1} B_1 G_i A x_i \le x_i^{\mathrm{T}}(P_i^{-1} B_1 B_1^{\mathrm{T}}) P_i^{-1}(B_1 B_1^{\mathrm{T}} P_i^{-1}) x_i + x_i^{\mathrm{T}} A^{\mathrm{T}} P_i^{-1} A x_i, \qquad (13)$$

$$-2x_i^{\mathrm{T}} P_i^{-1} B_1(I - \Lambda_i)\rho_i(t)\,\mathrm{sgn}(\mathrm{s}_i(t)) = -2\rho_i(t)\sum_{j=1}^{m}(1 - \delta_{ij})|\mathrm{s}_{ij}(t)|$$

$$\le -2\rho_i(t)\left(1 - \overline{\delta}_{i,max}\right)\|\mathrm{s}_i(t)\|_1 \le -2\rho_i(t)\left(1 - \overline{\delta}_{i,max}\right)\|\mathrm{s}_i(t)\| \le 0, \qquad (14)$$

$$2x_i^{\mathrm{T}} P_i^{-1}(\xi_i f_i(x_i) - 2x_i^{\mathrm{T}} P_i^{-1} B_1\widetilde{\Lambda}(I - \widehat{\Lambda}_i)^{-1}(K_i + G_iA)x_i + B_2d_{i1} + B_1d_{i3})$$

$$+\sum_{j=1}^{m}\frac{2}{\eta_{ij}}\dot{\hat{\delta}}_{ij}\left(\hat{\delta}_{ij}-\delta_{ij}\right)+\frac{2}{l_{i1}}\dot{\hat{\theta}}\left(\hat{\theta}-\theta\right)+\frac{2}{l_{i2}}\dot{\hat{\varepsilon}}_1\left(\hat{\varepsilon}_1-\varepsilon_1\right)+\frac{2}{l_{i3}}\dot{\hat{\varepsilon}}_2(\hat{\varepsilon}_2-\varepsilon_2)^2\leq 0\,. \quad (15)$$

By means of Schur's Lemma and (9),

$$\Psi_i = P_i^{-1}A + A^{\mathrm{T}}P_i^{-1} - P_i^{-1}B_1K_i - K_i^{\mathrm{T}}B_1^{\mathrm{T}}P_i^{-1} +$$

$$+ (P_i^{-1}B_1B_1^{\mathrm{T}})P_i^{-1}(B_1B_1^{\mathrm{T}}P_i^{-1}) + A^{\mathrm{T}}P_i^{-1}A < 0\,. \quad (16)$$

Substituting (13), (14), (15) and (16) into (12), we have

$$\dot{V}_{i1} < 0\,. \quad (17)$$

Thus system (10) is asymptotically stable, the estimation errors are bounded.

The following conclusion proves that the controller is able to make the system (3) the state trajectory tend to be specified by the sliding surface

Theorem 3.2 For system (2), the adaptive sliding mode controller is designed as (6),(7),(8). If there exist matrices $L_i \in \mathcal{R}^{m\times n}$, $P_i > 0$, such that the linear matrix inequality (9) is established, then even if the actuator (3) shows the fault, the designed adaptive sliding mode controller is still able to guarantee the sliding mode surface $s_i\left(t\right) = 0$.

Proof: Constructing Lyapunov function

$$V_{i2} = s_i^T(G_iB_1)^{-1}s_i+\sum_{j=1}^{m}\frac{1}{\eta_{ij}}\left(\hat{\delta}_{ij}-\delta_{ij}\right)^2+\frac{1}{l_{i1}}\left(\hat{\theta}-\theta\right)^2+\frac{1}{l_{i2}}(\hat{\varepsilon}_1-\varepsilon_1)^2+\frac{1}{l_{i3}}(\hat{\varepsilon}_2-\varepsilon_2)^2\,. \quad (18)$$

Taking the derivative on both sides of (18),

$$\dot{V}_{i2} = 2s_i^{\mathrm{T}}(G_iB_1)^{-1}G_i(Ax_i+\xi_if_i\left(x_i\right)-B_1\left(I-\Lambda_i\right)[(I-\hat{\Lambda}_i)^{-1}\left(K_i+G_iA\right)x_i$$

$$+\rho_i\left(t\right)\operatorname{sgn}\left(\mathrm{s}_i\left(t\right)\right)]+B_2d_{i1}+B_1d_{i3})+\sum_{j=1}^{m}\frac{2}{\eta_{ij}}\dot{\hat{\delta}}_{ij}\left(\hat{\delta}_{ij}-\delta_{ij}\right)$$

$$+\frac{2}{l_{i1}}\dot{\hat{\theta}}\left(\hat{\theta}-\theta\right)+\frac{2}{l_{i2}}\dot{\hat{\varepsilon}}_1(\hat{\varepsilon}_1-\varepsilon_1)+\frac{2}{l_{i3}}\dot{\hat{\varepsilon}}_2(\hat{\varepsilon}_2-\varepsilon_2)^2$$

$$= 2s_i^{\mathrm{T}}(G_iB_1)^{-1}G_i\cdot$$

$$\cdot\left(Ax_i-B_1\left(K_i+G_iA\right)x_i\right)-2x_i^{\mathrm{T}}P_i^{-1}B_1\tilde{\Lambda}_i[(I-\hat{\Lambda}_i)^{-1}\left(K_i+G_iA\right)x_i)$$

$$-2s_i^{\mathrm{T}}(G_iB_1)^{-1}G_iB_1(I-\Lambda_i)\left(\rho_i\left(t\right)\mathrm{T}\left(\mathrm{s}_i\left(t\right)\right)-\xi_if_i\left(x_i\right)\right)$$

$$+\sum_{j=1}^{m}\frac{2}{\eta_{ij}}\dot{\hat{\delta}}_{ij}\left(\hat{\delta}_{ij}-\delta_{ij}\right)+\frac{2}{l_{i1}}\dot{\hat{\theta}}\left(\hat{\theta}-\theta\right)+\frac{2}{l_{i2}}\dot{\hat{\varepsilon}}_1\left(\hat{\varepsilon}_1-\varepsilon_1\right)+\frac{2}{l_{i3}}\dot{\hat{\varepsilon}}_2(\hat{\varepsilon}_2-\varepsilon_2)^2, \quad (19)$$

where $G_i = B_1^T P_i^{-1}$.

It is easy to deduce that

$$-2s_i^{\mathrm{T}}(G_iB_1)^{-1}G_iB_1\left(I-\Lambda_i\right)\rho_i\left(t\right)\operatorname{sgn}\left(\mathrm{s}_i\left(t\right)\right)=-2\rho_i\left(t\right)\sum_{j=1}^{m}\left(1-\delta_{ij}\right)\left|\mathrm{s}_{ij}\left(t\right)\right|$$

$$\leq -2\rho_i\left(t\right)\left(1-\overline{\delta}_{i,max}\right)\left\|\mathrm{s}_i\left(t\right)\right\|_1 \leq -2\rho_i\left(t\right)\left(1-\overline{\delta}_{i,\max}\right)\left\|\mathrm{s}_i\left(t\right)\right\| \leq 0, \quad (20)$$

$$2s_i^{\mathrm{T}}P_i^{-1}B_1\widetilde{\Lambda}(I-\widehat{\Lambda}_i)^{-1}(\xi_i f_i\left(x_i\right)+B_2d_{i1}+B_1d_{i3})+\sum_{j=1}^{m}\frac{2}{\eta_{ij}}\dot{\hat{\delta}}_{ij}\left(\hat{\delta}_{ij}-\delta_{ij}\right)$$

$$+\frac{2}{l_{i1}}\dot{\hat{\theta}}\left(\hat{\theta}-\theta\right)+\frac{2}{l_{i2}}\dot{\hat{\varepsilon}}_1\left(\hat{\varepsilon}_1-\varepsilon_1\right)+\frac{2}{l_{i3}}\dot{\hat{\varepsilon}}_2(\hat{\varepsilon}_2-\varepsilon_2)^2 \leq 0\,. \quad (21)$$

Substituting (20), (21) into (19), and by means of Schur's Lemma and inequality (9),

$$\dot{V}_{i2} \leq 2\left\|s_i^{\mathrm{T}}\right\|\left\|(G_iB_1)^{-1}G_i\right\|\left\|Ax_i\left(t\right)\right\|+\left\|\left(K_i+G_iA\right)x_i\left(t\right)\right\|$$

$$-2\rho_i\left(t\right)\left(1-\overline{\delta}_{i,\max}\right)\left\|\mathrm{s}_i\left(t\right)\right\| \leq -2\mu\left\|\mathrm{s}_i\left(t\right)\right\| \leq 0\,.$$

4. Simulation results

In this section, the numerical simulation results based 2-area 4-machine power system validated the effectiveness of the proposed method in terms of improvement of the system stability and reliability effectively. Figure 1 shows that the tracking error is acceptable and tends to 0. Obviously, the simulation results verify the theoretical analysis.

5. Conclusion

This paper studies the problem of adaptive sliding mode reliable excitation control design procedure for multi-machine power systems which allows the actuator failure using linear matrix inequality technique and Lyapunov stability theory. The control objective is to investigate the reliable design on both passive and adaptive sliding mode excitation controllers, and the reachability of the specified sliding surface was analyzed.

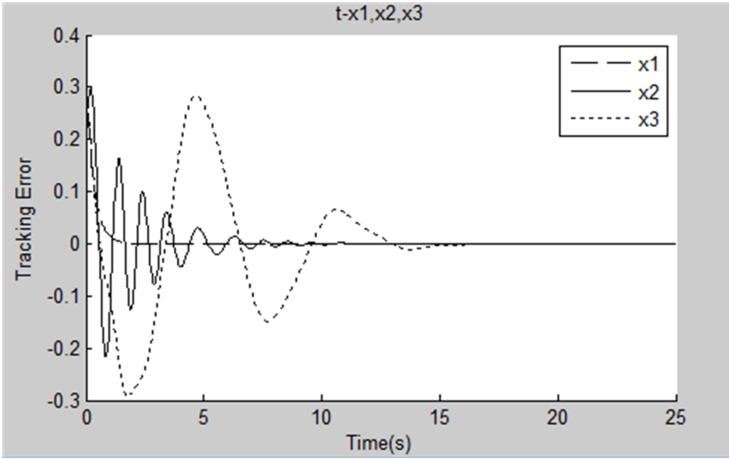

Fig. 1. Tracking error

References

[1] A. Volkanovski, M. Čepin, B. Mavko: *Application of the fault tree analysis for assessment of power system reliability.* Reliability Engineering & System Safety *94* (2009), No. 6, 1116–1127.

[2] A. M. Rei, A. M. L. da Silva, J. L. Jardim, J. C. O. Mello: *Static and dynamic aspects in bulk power system reliability evaluations.* IEEE Transactions on Power Systems *15* (2000), No. 1, 189–195.

[3] R. Billinton, M. Fotuhi-Firuzabad, S. O. Faried, S. Aboreshaid: *Impact of unified power flow controllers on power system reliability.* IEEE Transactions on Power Systems *15* (2000), No. 1, 410–415.

[4] P. Jirutitijaroen, C. Singh: *Comparison of simulation methods for power system reliability indexes and their distributions.* IEEE Transactions on Power Systems *23* (2008), No. 2, 486–493.

[5] B. J. Kirby: *Load response fundamentally matches power system reliability requirements.* IEEE Power Engineering Society General Meeting, 24–28 2007, Tampa, FL, USA, IEEE Conference Publications (2007), 1–6.

[6] V. Miranda, L. de Magalhaes Carvalho, M. A. da Rosa, A. M. L. da Silva, C. Singh: *Improving power system reliability calculation efficiency with EPSO variants.* IEEE Transactions on Power Systems *24* (2009), No. 4, 1772–1779.

[7] D. D. Šiljak: *Reliable control using multiple control systems.* International Journal of Control *31* (1980), No. 2, 303–329.

[8] Z. Wang, B. Huang, H. Unbehauen: *Robust face sketch style synthesis.* Automatica *35* (1999), No. 5, 955–963.

[9] Y. Yang, G. H. Yang, Y. C. Soh: *Reliable control of discrete-time systems with actuator failure.* IEE Proceedings - Control Theory and Applications *147* (2000), No. 4, 428–432.

[10] B. Chen, X. Liu: *Reliable control design of fuzzy dynamic systems with time-varying delay.* Fuzzy Sets and Systems *146* (2004), No. 3, 349–374.

[11] E. Tian, D. Yue, C. Peng: *Reliable control for networked control systems with probabilistic actuator fault and random delays.* Journal of the Franklin Institute *347* (2010), No. 10, 1907–1926.

[12] C. J. Seo, B. K. Kim: *Robust and reliable H' control for linear systems with parameter uncertainty and actuator failure.* Automatica *32* (1996), No. 3, 465–467.

[13] Z. Xiang, Q. Chen: *Robust reliable control for uncertain switched nonlinear systems with time delay under asynchronous switching.* Applied Mathematics and Computation *216* (2010), No. 3, 800–811.

[14] J. Dong, Y. G. Niu: *Reliable control of uncertain systems via adaptive sliding mode technique.* Journal of East China University of Science and Technology (Natural Science Edition) (2014), No. 6, 723–729.

Received April 30, 2017