Letter

Disturbance Observer-Based Predictive Tracking Control of Uncertain HOFA Cyber-Physical Systems

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Dear Editor,

In this letter, an output tracking control problem of uncertain cyber-physical systems (CPSs) is considered in the perspective of high-order fully actuated (HOFA) system theory, where a lumped disturbance is used to denote the total uncertainties containing parameters perturbations and external disturbances. A disturbance observer-based HOFA predictive control (DOB-HOFAPC) is adopted to achieve the desired tracking control performance and compensate for the communication delays in the forward and backward channels. The further discussion gives a criterion to analyze the tracking performance and stability of closed-loop CPSs. An example of long distance power transmission line is shown to verify the feasibility of the proposed DOB-HOFAPC.

The study on CPSs has become an important research hotspot with the progress of industrial Internet of Things. Because of complicated and varied working site, the uncertainties are always here to damage the control performances of CPSs. In the past, [1] gave an adaptive fuzzy control to cope with the unmodeled dynamics of CPSs. Reference [2] also designed a novel adaptive fuzzy control to implement the finite-time secure control for uncertain nonlinear CPSs under deception attacks. Reference [3] proposed a fractional-order sliding-mode control to overcome the model uncertainties and external disturbances of tele-operated CPSs. Meanwhile, [4]–[6] also focused on this research area.

HOFA system theory is firstly presented in [7], which involves the modeling, analysis, design and application of control systems and has obtained many theoretical and practical progresses. It focuses on the control design instead of the analysis of state responses, such that a simple way is given to simplify the complexities of design processes. Among them, HOFAPC plays an important role in the control design based on HOFA system theory and has obtained some results in the analysis and control of CPSs (see [8], [9]). Following this idea, this letter continues to develop a DOB-HOFAPC to implement the output tracking of uncertain CPSs, where a technical difficulty is to design the disturbance observer and predictive control in HOFA forms and another is to maintain the tracking control performance and stability by using this DOB-HOFAPC. Concretely, an HOFA system model is applied to describe the CPSs, which is called the HOFACPSs. Meanwhile, a lumped disturbance is used to indicate the total uncertainties, and then an HOFA disturbance observer is designed to estimate this lumped disturbance. Furthermore, an incremental prediction model (IPM) is constructed in an HOFA form with the help of Diophantine equation, so that multi-step output ahead predictions can be developed to optimize the tracking control performance and compensate for the communication delays in the forward and backward channels. Finally, a simple criterion is proposed to ensure the tracking performance and stability of closed-loop HOFACPSs. Comparing to the existing work, a highlight is that both disturbance observer and predictive control are directly designed in HOFA forms without model reduction. However, the existing work should convert the high-order system into a first-order one, and then completes the related control design, so that the computational loads and complexities can be obviously increased.

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Notations: $\aleph_y > \aleph_v$ are the output and control prediction horizons. q is a time operator satisfied $\varpi(k+i) = q^i \varpi(k)$, $i \in \mathbb{Z}$. $\Delta = 1 - q^{-1}$ is a difference operator. $\hat{\varpi}(k+i|k-j)$ is the i-th ahead prediction of $\varpi(k)$ based on time $k-j$.

Problem statement: Consider a class of uncertain HOFACPSs as

$$x(k+n) = -\sum_{l=0}^{n-1}(A_l + \delta A_l)x(k+l) + (B + \delta B)u(k) + d(k) \tag{1a}$$

$$y(k) = Cx(k) \tag{1b}$$

where $x(k) \in \mathbb{R}^{\tilde{n}}$, $u(k) \in \mathbb{R}^{\tilde{n}}$, $y(k) \in \mathbb{R}^m$, $d(k) \in \mathbb{R}^{\tilde{n}}$ are the state, input, output and external disturbance vectors, $A_l \in \mathbb{R}^{\tilde{n}\times\tilde{n}}$, $B \in \mathbb{R}^{\tilde{n}\times\tilde{n}}$, $C \in \mathbb{R}^{m\times\tilde{n}}$ are the related known coefficient matrices, δA_l and δB are the perturbations of A_l and B. For HOFACPS (1), it is assumed that: 1) $\det(B) \neq 0$; 2) The state vector is available; 3) $d(k)$ is unknown but is bounded in relation to time k.

Following [10], a lumped disturbance $w(k)$ is applied to denote the total uncertainties and is represented as $w(k) = -\sum_{l=0}^{n-1}\delta A_l x(k+l) + \delta Bu(k) + d(k)$, such that HOFACPS (1a) can be rewritten as:

$$x(k+n) = -\sum_{l=0}^{n-1} A_l x(k+l) + Bu(k) + w(k). \tag{2}$$

Based on Remark 4 in [10], it is assumed that $w(k)$ is slowly time-varying, that is, $\Delta w(k+1) \approx 0$.

The control structure of uncertain HOFACPSs is shown in Fig. 1, where τ_a and τ_s indicate the upper bounds of random communication delays in the forward and backward channels. From [9], τ_a and τ_s are the positive integral multiples of sampling period, and $\tau = \tau_a + \tau_s$.

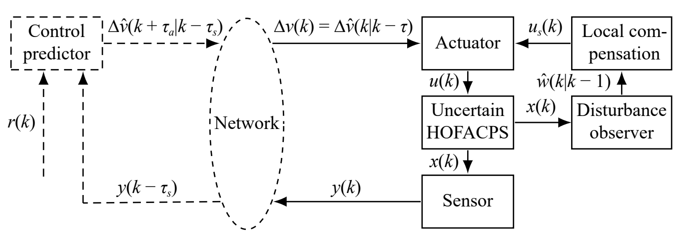

Fig. 1. Tracking control of uncertain HOFACPSs via DOB-HOFAPC.

For HOFACPS (2), a DOB-HOFAPC is proposed as

$$u(k) = B^{-1}(u_s(k) + v(k)),\ \ u_s(k) = \sum_{l=0}^{n-1} K_{c,l}x(k+l) - \hat{w}(k|k-1) \tag{3}$$

where $u_s(k) \in \mathbb{R}^{\tilde{n}}$ is a local feedback with disturbance compensation and $K_{c,l} \in \mathbb{R}^{\tilde{n}\times\tilde{n}}$ indicates the related feedback gain, $\hat{w}(k|k-1)$ is the estimation of $w(k)$ generated by HOFA disturbance observer, $v(k) \in \mathbb{R}^{\tilde{n}}$ is a tracking control part designed by HOFA predictive control. By applying (3), a closed-loop HOFACPS is achieved as

$$x(k+n) = -\sum_{l=0}^{n-1} A_{l,c}x(k+l) + v(k) + e_w(k) \tag{4}$$

with $A_{l,c} = A_l - K_{c,l}$ and $e_w(k) = w(k) - \hat{w}(k|k-1)$. For tracking control performance, a cost function $J(k)$ is given as

$$J(k) = \|\hat{Y}(k+\tau_a+\aleph_y|k-\tau_s) - R(k+\tau_a+\aleph_y)\|_{W_1}^2 + \|\Delta\hat{V}(k+\tau_a+\aleph_v|k-\tau_s)\|_{W_2}^2 \quad (5)$$

with

$$\hat{Y}(k+\tau_a+\aleph_y|k-\tau_s) = \begin{bmatrix} \hat{y}(k+\tau_a+\aleph_y|k-\tau_s) \\ \vdots \\ \hat{y}(k+\tau_a+1|k-\tau_s) \end{bmatrix}$$

$$\Delta\hat{V}(k+\tau_a+\aleph_v|k-\tau_s) = \begin{bmatrix} \Delta\hat{v}(k+\tau_a+\aleph_v|k-\tau_s) \\ \vdots \\ \Delta\hat{v}(k+\tau_a|k-\tau_s) \end{bmatrix}$$

$$R(k+\tau_a+\aleph_y) = \begin{bmatrix} r(k+\tau_a+\aleph_y) \\ \vdots \\ r(k+\tau_a+1) \end{bmatrix}$$

where $\hat{y}(k+\mu|k-\tau_s)$ and $\Delta\hat{v}(k+\mu|k-\tau_s)$ denote the μ-th ahead predictions of $y(k)$ and tracking control increment $\Delta v(k)$ based on time $k-\tau_s$, $r(k)$ represents the reference input, and W_1, W_2 are two positive definite weighting matrices. In (5), the first part focuses on the tracking control performance and the second part is concerned with the changing rate and amplitude of tracking control increment.

Problem 1: For HOFACPS (2), this research is to present a predictive tracking control (3) by minimizing (5), such that the tracking performance and stability of closed-loop HOFACPS (4) can be achieved, that is, the following conditions are held.

1) $\|r(k)\| < \infty$, $\|y(k)\| < \infty$, where $r(k)$ is a known reference;

2) $\lim_{k\to\infty}\|y(k) - r(k)\| = 0$.

Main results: 1) Design of HOFA disturbance observer: By applying the time operator q, system (2) is equivalently transformed as

$$x(k+1) = -\mathcal{A}_o(q^{-1})x(k) + \mathcal{B}_o(q^{-1})u(k) + \mathcal{D}_o(q^{-1})w(k) \quad (6)$$

with $\mathcal{A}_o(q^{-1}) = \sum_{l=0}^{n-1} A_l q^{l+1-n}$, $\mathcal{B}_o(q^{-1}) = Bq^{1-n}$, $\mathcal{D}_o(q^{-1}) = q^{1-n}$. To estimate the $w(k)$, a disturbance observer is presented as

$$\begin{aligned}\hat{z}(k+1|k) &= \hat{w}(k|k-1) + \mathcal{K}_{\rm do}(q)(\mathcal{A}_o(q^{-1})x(k) - \mathcal{B}_o(q^{-1})u(k)) \\ &\quad - \mathcal{K}_{\rm do}(q)\mathcal{D}_o(q^{-1})(\hat{z}(k|k-1) + \mathcal{K}_{\rm do}(q)x(k)) \\ \hat{w}(k|k-1) &= \hat{z}(k|k-1) + \mathcal{K}_{\rm do}(q)x(k) \end{aligned} \quad (7)$$

where $\mathcal{K}_{\rm do}(q) = \sum_{l=0}^{n-1} K_{{\rm do},l}q^l$, $K_{{\rm do},l} \in \mathbb{R}^{\tilde{n}\times\tilde{n}}$ is an observer gain. Then, Theorem 1 is provided to obtain the disturbance observer (7).

Theorem 1: HOFA disturbance observer (7) is held if $\mathcal{A}_{wo}(q^{-1})$ is a Schur polynomial matrix, where $\mathcal{A}_{wo}(q^{-1}) = I - \mathcal{K}_{\rm do}(q)\mathcal{D}_o(q^{-1})$.

Proof: From (4), $e_w(k) = w(k) - \hat{w}(k|k-1)$ so that $e_w(k+1) = w(k+1) - \hat{w}(k+1|k)$, then the error system is derived that

$$\begin{aligned} e_w(k+1) &= w(k) - \hat{z}(k+1|k) - \mathcal{K}_{\rm do}x(k+1) \\ &= w(k) - \hat{w}(k|k-1) - \mathcal{K}_{\rm do}(\mathcal{A}_o x(k) - \mathcal{B}_o u(k)) \\ &\quad + \mathcal{K}_{\rm do}\mathcal{D}_o(\hat{z}(k|k-1) + \mathcal{K}_{\rm do}x(k)) \\ &\quad - \mathcal{K}_{\rm do}(-\mathcal{A}_o x(k) + \mathcal{B}_o u(k) + \mathcal{D}_o w(k)) \\ &= (I - \mathcal{K}_{\rm do}\mathcal{D}_o)e_w(k) = \mathcal{A}_{wo}e_w(k). \end{aligned}$$

Because $\mathcal{A}_{wo}(q^{-1})$ is a Schur polynomial matrix, $e_w(k) \to 0$ with $k \to \infty$. Hence, disturbance observer (7) is held. ■

2) Design of HOFA predictive control: With the help of q operator, closed-loop system (4) is rewritten as

$$\mathcal{A}_{l,c}(q^{-1})x(k) = \mathcal{D}_o(q^{-1})v(k-1) + \mathcal{D}(q^{-1})e_w(k) \quad (8)$$

with $\mathcal{A}_{l,c}(q^{-1}) = I + \sum_{l=0}^{n-1} A_{l,c}q^{l-n}$ and $\mathcal{D}(q^{-1}) = q^{-1}\mathcal{D}_o(q^{-1})$. From [11], a Diophantine equation is given as $I = \mathcal{E}_\mu\mathcal{A}_{l,c}\Delta + q^{-\mu}\mathcal{F}_\mu$, where $\mathcal{E}_\mu(q^{-1})$ and $\mathcal{F}_\mu(q^{-1})$ represent two polynomial matrices in relation to the prediction horizon μ and polynomial coefficient matrix $\mathcal{A}_{l,c}(q^{-1})$, and they are expressed as $\mathcal{E}_\mu(q^{-1}) = e_{\mu,0} + e_{\mu,1}q^{-1} + \cdots + e_{\mu,\mu-1}q^{-(\mu-1)}$, $\mathcal{F}_\mu(q^{-1}) = f_{\mu,0} + f_{\mu,1}q^{-1} + \cdots + f_{\mu,n}q^{-n}$. Then, multiplying $\mathcal{E}_\mu\Delta q^\mu$ at (8) obtains that

$$\mathcal{E}_\mu\mathcal{A}_{l,c}\Delta x(k+\mu) = \mathcal{E}_\mu\mathcal{D}_o\Delta v(k+\mu-1) + q^\mu\mathcal{E}_\mu\mathcal{D}\Delta e_w(k).$$

Based on the idea in [11], taking the above into Diophantine equation establishes an IPM in an HOFA form as

$$x(k+\mu) = \mathcal{F}_u x(k) + \mathcal{L}_u\Delta e_w(k) + \mathcal{G}_\mu\Delta v(k+\mu-1) \quad (9)$$

where $\mathcal{L}_u(q^{-1}) = q^\mu\mathcal{E}_\mu(q^{-1})\mathcal{D}(q^{-1})$ and $\mathcal{G}_\mu = \mathcal{E}_\mu(q^{-1})\mathcal{D}_o(q^{-1})$. Considering the communication delays in the forward and backward channels, IPM (9) is rewritten as

$$\hat{x}(k-\tau_s+\mu|k-\tau_s) = \mathcal{F}_\mu x(k-\tau_s) + \mathcal{L}_\mu\Delta e_w(k-\tau_s) + \mathcal{G}_\mu\Delta\hat{v}(k-\tau_s+\mu-1|k-\tau_s)$$

with $\mu = 1, 2, \ldots, \tau+\aleph_y$. From $\mu = 1+\tau$ to $\mu = \aleph_y+\tau$,

$$\begin{aligned} \hat{x}(k+\tau_a+1|k-\tau_s) &= \mathcal{F}_{1+\tau}x(k-\tau_s) + \mathcal{L}_{1+\tau}\Delta e_w(k-\tau_s) \\ &\quad + \mathcal{G}_{1+\tau}\Delta\hat{v}(k+\tau_a|k-\tau_s) \\ &\vdots \\ \hat{x}(k+\tau_a+\aleph_y|k-\tau_s) &= \mathcal{F}_{\aleph_y+\tau}x(k-\tau_s) + \mathcal{L}_{\aleph_y+\tau}\Delta e_w(k-\tau_s) \\ &\quad + \mathcal{G}_{\aleph_y+\tau}\Delta\hat{v}(k+\tau_a+\aleph_y-1|k-\tau_s) \end{aligned}$$

based on (1b), output prediction is constructed as $\hat{y}(k+\tau_a+\mu|k-\tau_s) = C\hat{x}(k+\tau_a+\mu|k-\tau_s)$ with $\mu = 1, 2, \ldots, \aleph_y$. For $\mu = \aleph_v+1, \aleph_v+2, \ldots, \aleph_y$, $\hat{v}(k+\tau_a+\mu|k-\tau_s) = \hat{v}(k+\tau_a+\aleph_v|k-\tau_s)$ so that $\Delta\hat{v}(k+\tau_a+\aleph_v|k-\tau_s) = 0$, hence output predictions are compactly written as

$$\hat{Y}(k+\tau_a+\aleph_y|k-\tau_s) = P_1x(k-\tau_s) + P_2\Delta e_w(k-\tau_s) + P_3\Delta\hat{V}(k+\tau_a+\aleph_v|k-\tau_s) \quad (10)$$

with

$$P_1 = \begin{bmatrix} C\mathcal{F}_{\aleph_y+\tau} \\ \vdots \\ C\mathcal{F}_{1+\tau} \end{bmatrix}, \quad P_2 = \begin{bmatrix} C\mathcal{L}_{\aleph_y+\tau} \\ \vdots \\ C\mathcal{L}_{1+\tau} \end{bmatrix}$$

$$P_3 = \begin{bmatrix} C\mathcal{G}_{\aleph_y+\tau} & 0 & \ldots & 0 \\ \vdots & \vdots & \ldots & \vdots \\ C\mathcal{G}_{1+\aleph_v+\tau} & 0 & \ldots & 0 \\ 0 & C\mathcal{G}_{\aleph_v+\tau} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \ldots & 0 & C\mathcal{G}_{1+\tau} \end{bmatrix}.$$

In order to solve the optimal HOFA predictive control increment, let $\frac{\partial J(k)}{\partial\Delta\hat{V}(k+\tau_a+\aleph_v|k-\tau_s)} = 0$, taking (10) into the above yields that

$$P_3^TW_1\Big(P_1x(k-\tau_s) + P_2\Delta e_w(k-\tau_s) + P_3\Delta\hat{V}(k+\tau_a+\aleph_v|k-\tau_s) - R(k+\tau_a+\aleph_y)\Big) + W_2\Delta\hat{V}(k+\tau_a+\aleph_v|k-\tau_s) = 0$$

so that $\Delta\hat{V}(k+\tau_a+\aleph_v|k-\tau_s) = M_1^{-1}M_2x(k-\tau_s) + M_1^{-1}M_3\Delta e_w(k-\tau_s) + M_1^{-1}M_4R(k+\tau_a+\aleph_y)$ with $M_1 = P_3^TW_1P_3 + W_2$, $M_2 = -P_3^TW_1P_1$, $M_3 = -P_3^TW_1P_2$, $M_4 = P_3^TW_1$. For the network node, the optimal HOFA predictive control increment is set as $\Delta\hat{v}(k+\tau_a|k-\tau_s) = H\Delta\hat{V}(k+\tau_a+\aleph_v|k-\tau_s)$ with $H = [0 \ \cdots \ 0 \ I]$. For the actuator node, it is generated by $\Delta v(k) = \Delta\hat{v}(k|k-\tau)$, which is completely formulated as

$$\Delta v(k) = HM_1^{-1}M_2x(k-\tau) + HM_1^{-1}M_3\Delta e_w(k-\tau) + HM_1^{-1}M_4R(k+\aleph_y) \quad (11)$$

where $R(k+\aleph_y) = [r^T(k+\aleph_y) \ \cdots \ r^T(k+1)]^T$.

3) Closed-loop system analysis: Based on [9], let $r(\cdot) = r$, and denote $\mathcal{A}_c = \mathcal{A}_{l,c}^{-1}\mathcal{D}_o$, $\mathcal{A}_d = \mathcal{A}_{l,c}^{-1}\mathcal{D}$, then system (8) is converted as

$$\Delta x(k+1) = \mathcal{A}_c\Delta v(k) + \mathcal{A}_d\Delta e_w(k+1)$$

by taking (11) and error system into the above, it is derived that

$$\begin{aligned}\Delta x(k+1) &= \mathcal{A}_{c,1}x(k-\tau)+\mathcal{A}_{c,2}\Delta e_w(k-\tau)\\ &\quad+\mathcal{A}_{c,3}R(k+\aleph_y)+\mathcal{A}_{c,4}\Delta e_w(k)\\ &=\Delta x(k)+\mathcal{A}_{c,1}\Delta x(k-\tau)\\ &\quad+\mathcal{A}_{c,2}\tilde{\mathcal{A}}_{wo}\Delta e_w(k-\tau-1)+\mathcal{A}_{c,4}\tilde{\mathcal{A}}_{wo}\Delta e_w(k-1)\end{aligned}$$

where $\mathcal{A}_{c,1}=\mathcal{A}_cHM_1^{-1}M_2$, $\mathcal{A}_{c,2}=\mathcal{A}_cHM_1^{-1}M_3$, $\mathcal{A}_{c,3}=\mathcal{A}_cHM_1^{-1}M_4$, $\mathcal{A}_{c,4}=\mathcal{A}_d\mathcal{A}_{wo}$ and $\tilde{\mathcal{A}}_{wo}=I-\mathcal{A}_{wo}$. Further, denote $\Delta X(k)=[\Delta x^T(k)\ \cdots\ \Delta x^T(k-\tau)]^T$ and $\Delta E_w(k-1)=[\Delta e_w^T(k-1)\ \cdots\ \Delta e_w^T(k-\tau-1)]^T$, the above system is drawn as

$$\begin{bmatrix}\Delta X(k+1)\\ \Delta E_w(k)\end{bmatrix}=\Phi\begin{bmatrix}\Delta X(k)\\ \Delta E_w(k-1)\end{bmatrix},\ \Phi=\begin{bmatrix}\Phi_{11} & \Phi_{12}\\ \Phi_{21} & \Phi_{22}\end{bmatrix} \tag{12}$$

with $\Phi_{11}=[I\ 0\ \cdots\ 0\ \mathcal{A}_{c,1}]$, $\Phi_{12}=\left[\mathcal{A}_{c,4}\tilde{\mathcal{A}}_{wo}\ 0\ \cdots\ 0\ \mathcal{A}_{c,2}\tilde{\mathcal{A}}_{wo}\right]$, $\Phi_{21}=\begin{bmatrix}I_{\tau\tilde{n}} & 0_{\tau\tilde{n}\times\tilde{n}}\\ 0_{(\tau+1)\tilde{n}\times\tau\tilde{n}} & 0_{\tau\tilde{n}\times\tilde{n}}\end{bmatrix}$ and $\Phi_{22}=\begin{bmatrix}\mathcal{A}_{wo} & 0_{\tilde{n}\times\tau\tilde{n}}\\ I_{\tau\tilde{n}} & 0_{\tau\tilde{n}\times\tilde{n}}\end{bmatrix}$. Summarizing the above derives the Theorem 2.

Theorem 2: The stability and tracking performance of closed-loop HOFACPS (4) can be realized if and only if the asymptotic stability of system (12) can be guaranteed.

Illustrative example: An example of long distance power transmission line is provided here, whose equivalent circuit is a typical RLC one (as shown in Fig. 2). By means of Kirchhoff law, a uncertain second-order fully actuated model for RLC circuit is presented as

$$LC\ddot{x}+RC\dot{x}+x+\delta(k)=u \tag{13}$$

with $x=u_c$ V, $\dot{x}=\frac{du_c}{dt}$ V/t, $\ddot{x}=\frac{d^2u_c}{dt^2}$ V/t^2, $u=u_r$ V, $L=0.5$ H, $C=0.01$ F, $R=1.5\,\Omega$, $\delta(k)=-500\sin(0.005k)$ V. The communication delays are set as $\tau_a=5$ and $\tau_s=6$. By using $\dot{x}=\frac{x(k+1)-x(k)}{T}$, system (13) can be transformed into a discrete-time expression in the form of (2) as

$$\begin{aligned}x(k+2)+(3T-2)x(k+1)+(1-3T+200T^2)x(k)\\ =200T^2u(k)+w(k)\end{aligned} \tag{14}$$

where $w(k)=200T^2\delta(k)$ and T is a sampling period. Choose $T=0.01$ s. For system (14), an HOFA disturbance observer is designed in the form of (7) with $\mathcal{K}_{\rm do}(q)=0.0199+1.02q$, then a DOB-HOFAPC is proposed in the form of (3) with $K_{c,0}=-0.69$, $K_{c,1}=-0.87$, $\aleph_y=5$, $\aleph_v=3$, $W_1=I$, $W_2=30I$, the simulation results are shown in Fig. 3. It implies that DOB-HOFAPC can realize the accurate estimation of lumped disturbance and the desired tracking control performance, which fully demonstrates the feasibility of the proposed DOB-HOFAPC.

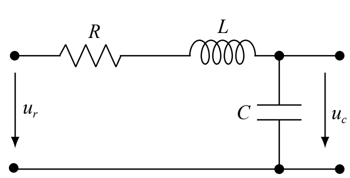

Fig. 2. RLC circuit.

Conclusions: This letter has investigated the output tracking problem of HOFACPSs with lumped disturbances. A DOB-HOFAPC has been proposed to implement the desired tracking control performance. The simulated results of long distance transmission line have been shown to illustrate the feasibility of the proposed DOB-HOFAPC. The future work will further develop the DOB-HOFAPC for tracking control of uncertain CPSs against fast time-varying lumped disturbances.

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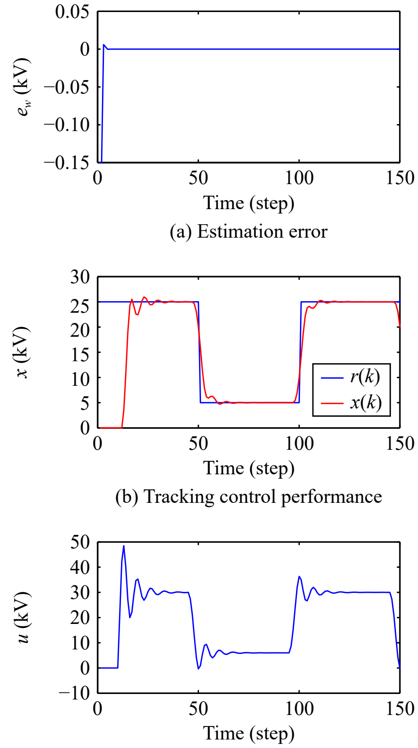

(a) Estimation error
(b) Tracking control performance
(c) Control input

Fig. 3. The simulated results of long distance power transmission line via DOB-HOFAPC.

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