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混合时变时滞多机系统气门开度的模糊 H_∞ 控制器设计

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摘 要:研究了带有混合时变时滞的多机电力系统的气门开度模糊 H_∞ 控制器设计问题,混合时变时滞包括区间时滞、中立型时滞和分布时滞,通过建立模糊模型并设计系统的模糊控制器,基于线性矩阵不等式(LMIs)给出了系统满足 H_∞ 性能指标的稳定性条件. 同时,将结论推广到时滞的不同情况,包括带有快时变分布时滞(即分布时滞的导数大于1)的 H_∞ 稳定条件,所得结果减少了保守性. 最后,针对三机无穷大母线的气门开度控制系统建立模糊 H_∞ 控制器,验证了所提出方法的有效性.

关 键 词:混合时变时滞;多机电力系统;模糊控制;LMI;H_∞ 性能
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Fuzzy H_∞ Controllers Design Approach for Steam Valve Opening of Multi-machine Power Systems with Mixed Time-Varying Delays

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Abstract: The fuzzy H_∞ controller design problem was studied for steam valve opening of multi-machine power systems which consisting of turbo-generators with mixed time-varying delays. The mixed time-varying delays include the interval retarded-type discrete delay, the neutral-type discrete delay and the time-varying distributed delays. Fuzzy models were established, and the controllers of the systems were designed. Linear matrix inequalities (LMIs)-based H_∞ stability conditions were derived. Moreover, the results were expanded to different conditions of time-delay, including H_∞ stability condition with the fast time-varying distributed delays (i.e. the derivatives of distributed delay is larger than 1). Therefore, the obtained results are new and less conservative. Finally, simulation results for the steam value opening of three-machine infinite bus systems were provided to verify the effectiveness of the proposed results.

Key words: mixed time-varying delay; multi-machine power systems; fuzzy control; LMI; H_∞ performance

多机电力系统气门开度中存在的混合时滞包括分布时滞和离散型时滞,其中的离散时滞包括区间时滞(即时滞存在于系统状态)和中立型时滞(即时滞存在于系统状态的导数). 文献[1-3]研究了中立型时滞系统稳定性条件;文献[4-6]研究了固定的分布时滞或者分布时滞的导数上界小于1的情况下的系统控制问题;文献[7-8]研究了多机电力系统气门开度的时滞无关分散控制问题.

本文研究了包含混合型时变时滞的多机电力系统的气门开度控制系统的稳定条件,混合时变时滞包括区间时滞,中立型时滞(包括快变时滞)

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和分布时滞. 基于线性矩阵不等式(LMIs)给出了系统满足 H_∞ 性能指标的稳定性条件,并将结论推广到时滞的不同情况,包括带有快时变分布时滞(即分布时滞的导数大于1)的 H_∞ 稳定条件,所得结果减少了保守性,最后针对三机无穷大系统验证了所提方法的有效性.

1 问题描述

定义第 i 台发电机的状态向量为 $\boldsymbol{x}_i(t)=[\Delta\boldsymbol{\delta}_i(t)\quad \Delta\boldsymbol{w}_i(t)\quad \Delta\boldsymbol{P}_{Mi}(t)\quad \Delta X_{Ei}(t)]^{\mathrm{T}}$,其中,转子角增量为 $\Delta\boldsymbol{\delta}_i(t)=\boldsymbol{\delta}_i(t)-\boldsymbol{\delta}_{i0}$,相对角速度为 $\Delta\boldsymbol{w}_i(t)=\boldsymbol{w}_i(t)-w_{i0}$,机械功率增量为 $\Delta\boldsymbol{P}_{Mi}(t)=\boldsymbol{P}_{Mi}(t)-\boldsymbol{P}_{Mi0}$,气门开度增量为 $\Delta X_{Ei}(t)=\boldsymbol{X}_{Ei}(t)-\boldsymbol{X}_{Ei0}$,$i=1,\cdots,N$,考虑系统传输过程中存在多种类型时滞,则其用如下模糊规则描述:

If $\xi_{i1}(t)$ is $M_{i1}^{l}\cdots$ and $\xi_{ig_i}(t)$ is $M_{ig_i}^{l}$,then

$$\begin{aligned}\dot{\boldsymbol{x}}_i(t)&=\boldsymbol{A}_{il}\boldsymbol{x}_i(t)+\sum_{j=1,j\neq i}^{J}\boldsymbol{B}_{ijl}\boldsymbol{x}_j(t-d_{ij}(t))+\boldsymbol{C}_{il}\dot{\boldsymbol{x}}_i(t-\\&\quad\tau_i(t))+\boldsymbol{D}_{il}\int_{t-\eta_i(t)}^{t}\boldsymbol{x}_i(s)\mathrm{d}s+\boldsymbol{B}_i\boldsymbol{u}_i(t)+\\&\quad\boldsymbol{F}_{il}\boldsymbol{\omega}_i(t),\\ \boldsymbol{x}_i(t)&=\boldsymbol{\Phi}_{i0}(t),t\in[-\max(d_{ijM},\tau_{iM},\eta_{iM}),0],\\ z_i(t)&=\boldsymbol{H}_{il}\boldsymbol{x}_i(t)+\boldsymbol{L}_{il}\omega_i(t),l=1,\cdots,r_i.\end{aligned}\tag{1}$$

其中:$\boldsymbol{x}_i(t)\in\mathbb{R}^{n_i}$,$\boldsymbol{u}_i(t)\in\mathbb{R}^{m_i}$,$\boldsymbol{\omega}_i(t)$,$z_i(t)\in\mathbb{R}^{p_i}$ 分别表示系统状态,控制,扰动和输出向量;$\boldsymbol{\Phi}_{i0}(t)$表示初始条件向量;$\xi_{i1}(t),\cdots,\xi_{ig_i}(t)$是前件变量;$M_{ig_i}^{l}$是模糊集. $\boldsymbol{A}_{il}$,$\boldsymbol{C}_{il}$,$\boldsymbol{D}_{il}$,$\boldsymbol{F}_{il}$,$\boldsymbol{H}_{il}$,$\boldsymbol{L}_{il}$代表子系统 S_i 的第 l 条规则的系统矩阵;$\boldsymbol{B}_i$ 为控制量系数矩阵;$\boldsymbol{B}_{ijl}$表示第 i 和第 j 个子系统间第 l 条规则的互联项;$d_{ij}(t)$,$\tau_i(t)$和 $\eta_i(t)$分别代表时变滞后型时滞,中立型离散延迟和分布时滞,且 $d_{ijm}\leqslant d_{ij}(t)\leqslant d_{ijM}$,$\dot d_{ij}\leqslant\bar d_{ij}$,$0\leqslant\eta_i(t)\leqslant\eta_{iM}$,$\dot\eta_i(t)\leqslant\bar\eta_i$,$0\leqslant\tau_i(t)\leqslant\tau_{iM}$,$\underline{\tau}_i\leqslant\dot\tau_i(t)\leqslant\bar\tau_i$.

考虑如下情况:1)$\underline{\tau}\leqslant\dot\tau\leqslant\bar\tau<1$, $0\leqslant\tau(t)\leqslant\tau_{\mathrm{M}}$(纯慢变中立型时滞);2)$1\leqslant\underline{\tau}\leqslant\dot\tau\leqslant\bar\tau$(纯快变中立型时滞);3)$\underline{\tau}\leqslant\dot\tau\leqslant\bar\tau$,$\underline{\tau}<1$,$\bar\tau\geqslant1$,$0\leqslant\tau(t)\leqslant\tau_{\mathrm{M}}$. 在 $\bar\eta_i\geqslant1$(纯快变分布时滞)的情况下,选择 $0\leqslant\alpha_i\leqslant1$ 满足 $0\leqslant\alpha_i\bar\eta_i\leqslant1$.

子系统 S_i 采用如下模糊控制器:

$$\boldsymbol{u}_i(t)=\sum_{l=1}^{r_i}\boldsymbol{h}_i^l(\xi_i(t))\boldsymbol{K}'_{il}\boldsymbol{x}_i(t),\boldsymbol{K}_{il}=\boldsymbol{B}_i\boldsymbol{K}'_{il}.\tag{2}$$

其中,$\boldsymbol{K}'_{il}$为子系统 S_i 的第 l 条规则的控制器增益,$\lambda_i^l(\xi_i(t))=\prod_{q=1}^{g_i}M_{iq}^{l}\xi_{iq}(t)$,$h_i^l(\xi_i(t))=\dfrac{\lambda_i^l(\xi_i(t))}{\sum_{i=1}^{r_i}\lambda_i^l(\xi_i(t))}$.

则闭环模糊互联系统为

$$\begin{aligned}\dot{\boldsymbol{x}}_i=&\sum_{l=1}^{r_i}\sum_{m=i}^{r_i}\sum_{j=1,j\neq i}^{J}\boldsymbol{h}_i^l\boldsymbol{h}_i^m((\boldsymbol{A}_{il}+\boldsymbol{K}_{im})\boldsymbol{x}_i+\\&\boldsymbol{B}_{ijl}\boldsymbol{x}_j(t-d_{ij}(t))+\boldsymbol{C}_{il}\dot{\boldsymbol{x}}_i(t-\tau_i(t))+\\&\boldsymbol{D}_{il}\int_{t-\eta_i(t)}^{t-\alpha_i\eta_i(t)}x_i(s)\mathrm{d}s+\boldsymbol{D}_{il}\int_{t-\alpha_i\eta_i(t)}^{t}\boldsymbol{x}_i(s)\mathrm{d}s+\boldsymbol{F}_{il}\boldsymbol{\omega}_i).\end{aligned}\tag{3}$$

2 主要结果

定理 1 对于给定常数 $\gamma_i>0$,$i=1,\cdots,J$,在 $\bar\eta_i\geqslant1$,$\underline{\tau}_i\leqslant\dot\tau_i(t)\leqslant\bar\tau_i<1$,$0\leqslant\tau_i(t)\leqslant\tau_{iM}$的情况下,如果存在矩阵 $\boldsymbol{M}_i$,$\boldsymbol{Y}_{im}$,$\boldsymbol{S}_{ij2}$,$j=1,2$,$\boldsymbol{P}_{i12}$,$\boldsymbol{P}_{i13}$,$\boldsymbol{P}_{i14}$,$\boldsymbol{P}_{i23}$,$\boldsymbol{P}_{i24}$,$\boldsymbol{P}_{i34}$,正定矩阵 $\boldsymbol{W}_i$,$\boldsymbol{P}_{i11}$,$\boldsymbol{P}_{i22}$,$\boldsymbol{P}_{i33}$,$\boldsymbol{P}_{i44}$,$\boldsymbol{S}_{ij1}$,$\boldsymbol{S}_{ij3}$,$j=1,2$;$\boldsymbol{Q}_{ij}$,$\bar{\boldsymbol{Q}}_{ij}$,$\boldsymbol{R}_{ij}$,$\boldsymbol{T}_{ijk}$,$j=1,\cdots,4$,$k=1,\cdots,5$,满足 LMI(4)~(10),则式(2)使式(3)稳定且满足 H_∞ 性能指标 γ_i.

$$\boldsymbol{\Phi}_{ijlm}=\begin{bmatrix}\boldsymbol{\Phi}_{i11}&\boldsymbol{\Phi}_{i12}&\boldsymbol{\Phi}_{i13}&\boldsymbol{\Phi}_{i14}&\boldsymbol{\Phi}_{i15}&\boldsymbol{\Phi}_{i16}&0&\boldsymbol{\Phi}_{i18}&\boldsymbol{\Phi}_{i19}&\boldsymbol{\Phi}_{i10}&\boldsymbol{\Phi}_{i1,11}&0&\boldsymbol{\Phi}_{i1,13}&\boldsymbol{\Phi}_{i1,14}&\boldsymbol{\Phi}_{i1,15}&0&0&\boldsymbol{\Phi}_{i,18}\\ *&\boldsymbol{\Phi}_{i22}&\boldsymbol{\Phi}_{i23}&0&0&0&0&\boldsymbol{\Phi}_{i28}&\boldsymbol{\Phi}_{i29}&0&\boldsymbol{\Phi}_{i2,11}&0&\boldsymbol{\Phi}_{i2,13}&0&0&0&0&0\\ *&*&\boldsymbol{\Phi}_{i33}&0&0&0&0&\boldsymbol{\Phi}_{i38}&\boldsymbol{\Phi}_{i39}&0&\boldsymbol{\Phi}_{i3,11}&0&\boldsymbol{\Phi}_{i3,13}&0&0&0&0&0\\ *&*&*&\boldsymbol{\Phi}_{i44}&\boldsymbol{\Phi}_{i45}&0&0&\boldsymbol{\Phi}_{i48}&\boldsymbol{\Phi}_{i49}&\boldsymbol{\Phi}_{i40}&\boldsymbol{\Phi}_{i4,11}&0&\boldsymbol{\Phi}_{i4,13}&0&\boldsymbol{\Phi}_{i4,15}&0&0&0\\ *&*&*&*&\boldsymbol{\Phi}_{i55}&\boldsymbol{\Phi}_{i56}&\boldsymbol{\Phi}_{i57}&\boldsymbol{\Phi}_{i58}&0&\boldsymbol{\Phi}_{i50}&0&0&\boldsymbol{\Phi}_{i5,13}&0&\boldsymbol{\Phi}_{i5,15}&0&0&0\\ *&*&*&*&*&\boldsymbol{\Phi}_{i66}&0&0&0&0&0&0&0&0&0&0&0&0\\ *&*&*&*&*&*&\boldsymbol{\Phi}_{i77}&0&0&0&0&0&0&0&0&0&0&0\\ *&*&*&*&*&*&*&\boldsymbol{\Phi}_{i88}&0&\boldsymbol{\Phi}_{i80}&0&0&\boldsymbol{\Phi}_{i8,13}&0&\boldsymbol{\Phi}_{i8,15}&\bar{\boldsymbol{P}}_{i2}&0&0\\ *&*&*&*&*&*&*&*&\boldsymbol{\Phi}_{i99}&0&0&0&0&0&0&0&0&0\\ *&*&*&*&*&*&*&*&*&\boldsymbol{\Phi}_{i00}&0&0&\boldsymbol{\Phi}_{i0,13}&0&\boldsymbol{\Phi}_{i0,15}&0&0&0\\ *&*&*&*&*&*&*&*&*&*&\boldsymbol{\Phi}_{i11,11}&\boldsymbol{\Phi}_{i11,12}&0&0&0&0&\bar{\boldsymbol{P}}_{i4}&0\\ *&*&*&*&*&*&*&*&*&*&*&\boldsymbol{\Phi}_{i12,12}&0&0&0&0&0&0\\ *&*&*&*&*&*&*&*&*&*&*&*&\boldsymbol{\Phi}_{i13,13}&0&\boldsymbol{\Phi}_{i13,15}&0&0&0\\ *&*&*&*&*&*&*&*&*&*&*&*&*&\boldsymbol{\Phi}_{i14,14}&0&0&0&0\\ *&*&*&*&*&*&*&*&*&*&*&*&*&*&\boldsymbol{\Phi}_{i15,15}&0&0&0\\ *&*&*&*&*&*&*&*&*&*&*&*&*&*&*&-\overline{\tau_i\boldsymbol{Q}_i}&0&0\\ *&*&*&*&*&*&*&*&*&*&*&*&*&*&*&*&-\overline{\gamma_i\boldsymbol{Q}_i}&0\\ *&*&*&*&*&*&*&*&*&*&*&*&*&*&*&*&*&-\boldsymbol{I}\end{bmatrix},\tag{4}$$

$$\boldsymbol{\Phi}'_{ijlm} - \boldsymbol{I}_1^{\mathrm T}\boldsymbol{T}_{ij4}\boldsymbol{I}_1 - \boldsymbol{I}_2^{\mathrm T}\boldsymbol{W}_i\boldsymbol{I}_2 < 0 , \tag{5}$$

$$\boldsymbol{\Phi}'_{ijlm} - \boldsymbol{I}_3^{\mathrm T}\boldsymbol{T}_{ij4}\boldsymbol{I}_3 - \boldsymbol{I}_2^{\mathrm T}\boldsymbol{W}_i\boldsymbol{I}_2 < 0 , \tag{6}$$

$$\boldsymbol{\Phi}'_{ijlm} - \boldsymbol{I}_1^{\mathrm T}\boldsymbol{T}_{ij4}\boldsymbol{I}_1 - \boldsymbol{I}_4^{\mathrm T}\boldsymbol{W}_i\boldsymbol{I}_4 < 0 , \tag{7}$$

$$\boldsymbol{\Phi}'_{ijlm} - \boldsymbol{I}_3^{\mathrm T}\boldsymbol{T}_{ij4}\boldsymbol{I}_3 - \boldsymbol{I}_4^{\mathrm T}\boldsymbol{W}_i\boldsymbol{I}_4 < 0 , \tag{8}$$

$$\begin{bmatrix} \boldsymbol{S}_{ij1} & \boldsymbol{S}_{ij2} \\ * & \boldsymbol{S}_{ij3} \end{bmatrix} > 0, j = 1, 2 , \tag{9}$$

$$\boldsymbol{P}_i = \begin{bmatrix} \boldsymbol{P}_{i11} & \boldsymbol{P}_{i12} & \boldsymbol{P}_{i13} & \boldsymbol{P}_{i14} \\ * & \boldsymbol{P}_{i22} & \boldsymbol{P}_{i23} & \boldsymbol{P}_{i24} \\ * & * & \boldsymbol{P}_{i33} & \boldsymbol{P}_{i34} \\ * & * & * & \boldsymbol{P}_{i44} \end{bmatrix} > 0 . \tag{10}$$

其中：

$$\bar{\boldsymbol{I}}_1 = [0\ 0\ 0\ 0\ \ -\boldsymbol{I}\ 0\ \boldsymbol{I}\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0],$$

$$\bar{\boldsymbol{I}}_2 = [-\boldsymbol{I}\ \boldsymbol{I}\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0],$$

$$\bar{\boldsymbol{I}}_3 = [0\ 0\ 0\ 0\ \ -\boldsymbol{I}\ \boldsymbol{I}\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0],$$

$$\bar{\boldsymbol{I}}_4 = [0\ \ -\boldsymbol{I}\ \boldsymbol{I}\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0],$$

$$\boldsymbol{I}_1 = [\bar{\boldsymbol{I}}_1\quad 0], \boldsymbol{I}_2 = [\bar{\boldsymbol{I}}_2\quad 0], \boldsymbol{I}_3 = [\bar{\boldsymbol{I}}_2\quad 0],$$

$$\boldsymbol{I}_4 = [\bar{\boldsymbol{I}}_4\quad 0], \bar{\boldsymbol{P}}_{i2} = [\boldsymbol{P}_{i12}^{\mathrm T}\quad \boldsymbol{P}_{i22}\quad \boldsymbol{P}_{i23}\quad \boldsymbol{P}_{i24}],$$

$$\bar{\boldsymbol{P}}_{i4} = [\boldsymbol{P}_{i14}^{\mathrm T}\quad \boldsymbol{P}_{i24}^{\mathrm T}\quad \boldsymbol{P}_{i34}^{\mathrm T}\quad \boldsymbol{P}_{i44}],$$

$$\overline{\tau_i \boldsymbol{Q}_i} = \mathrm{diag}[\bar{\tau}_i^{-1}\boldsymbol{Q}_{i1}\quad \bar{\tau}_i^{-1}\boldsymbol{Q}_{i2}\quad \bar{\tau}_i^{-1}\boldsymbol{Q}_{i3}\quad \bar{\tau}_i^{-1}\boldsymbol{Q}_{i4}],$$

$$\overline{\eta_i \boldsymbol{Q}_i} = \mathrm{diag}[\bar{\eta}_i^{-1}\boldsymbol{Q}_{i1}\quad \bar{\eta}_i^{-1}\boldsymbol{Q}_{i2}\quad \bar{\eta}_i^{-1}\boldsymbol{Q}_{i3}\quad \bar{\eta}_i^{-1}\boldsymbol{Q}_{i4}],$$

去掉 $\boldsymbol{\Phi}_{ijlm}$ 的最后三行三列为 $\boldsymbol{\Phi}'_{ijlm}$.

$\boldsymbol{\Phi}_{i11} = \boldsymbol{S}_{i11} - \boldsymbol{W}_i + \alpha_i^2\eta_{iM}^2\boldsymbol{R}_{i1} + \eta_{iM}^2\boldsymbol{R}_{i2} - (1-\alpha_i\bar{\eta}_i)\boldsymbol{R}_{i3} - \dfrac{1}{\alpha_i}\boldsymbol{R}_{i4} + \bar{\tau}_i\boldsymbol{Q}_{i1} + \bar{\eta}_i\bar{\boldsymbol{Q}}_{i1} + \boldsymbol{P}_{i14} + \boldsymbol{P}_{i14}^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{A}_{il}^{\mathrm T} + \boldsymbol{A}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{Y}_{im} + \boldsymbol{Y}_{im}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i12} = \boldsymbol{P}_{i24}^{\mathrm T} + \boldsymbol{W}_i, \boldsymbol{\Phi}_{i13} = \boldsymbol{P}_{i34}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i14} = \boldsymbol{P}_{i44} + \boldsymbol{D}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{A}_{il}^{\mathrm T} + \boldsymbol{Y}_{im}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i15} = \boldsymbol{M}_i\boldsymbol{A}_{il}^{\mathrm T} + \boldsymbol{Y}_{im}^{\mathrm T} + \boldsymbol{B}_{ijl}\boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i16} = \boldsymbol{T}_{ij5}$,

$\boldsymbol{\Phi}_{i18} = \boldsymbol{M}_i\boldsymbol{A}_{il}^{\mathrm T} + \boldsymbol{Y}_{im}^{\mathrm T} + \boldsymbol{P}_{i12} + \boldsymbol{C}_{il}\boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i19} = \boldsymbol{P}_{i13}$,

$\boldsymbol{\Phi}_{i10} = \boldsymbol{M}_i\boldsymbol{A}_{il}^{T} + \boldsymbol{Y}_{im}^{\mathrm T} + \boldsymbol{D}_{il}\boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i1,11} = (1-\alpha_i\bar{\eta}_i)\boldsymbol{R}_{i3} + \dfrac{1}{\alpha_i}\boldsymbol{R}_{i4} - \boldsymbol{P}_{i14}, \boldsymbol{\Phi}_{i1,13} = \boldsymbol{M}_i\boldsymbol{A}_{il}^{\mathrm T} + \boldsymbol{Y}_{im}^{\mathrm T} + \boldsymbol{P}_{i11} + \boldsymbol{S}_{i12} - \boldsymbol{M}_i^{\mathrm T}$,

$\boldsymbol{\Phi}_{i1,14} = \boldsymbol{T}_{ij5}, \boldsymbol{\Phi}_{i1,15} = \boldsymbol{F}_{il}\boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i29} = \boldsymbol{P}_{i23}$,

$\boldsymbol{\Phi}_{i2,11} = -\boldsymbol{P}_{i24}, \boldsymbol{\Phi}_{i12,12} = -\boldsymbol{R}_{i4}$,

$\boldsymbol{\Phi}_{i22} = \bar{\tau}_i\boldsymbol{Q}_{i2} + \bar{\eta}_i\bar{\boldsymbol{Q}}_{i2} - (1-\bar{\tau}_i)\boldsymbol{S}_{i11} + (1-\underline{\tau}_i)\boldsymbol{S}_{i21} - 2\boldsymbol{W}_i$,

$\boldsymbol{\Phi}_{i23} = \boldsymbol{W}_i, \boldsymbol{\Phi}_{i28} = \boldsymbol{P}_{i22} + (1-\underline{\tau}_i)\boldsymbol{S}_{i22} - (1-\bar{\tau}_i)\boldsymbol{S}_{i12}$,

$\boldsymbol{\Phi}_{i33} = \bar{\tau}_i\boldsymbol{Q}_{i3} + \bar{\eta}_i\bar{\boldsymbol{Q}}_{i3} - \boldsymbol{W}_i - \boldsymbol{S}_{i21}, \boldsymbol{\Phi}_{i38} = \boldsymbol{P}_{i23}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i39} = \boldsymbol{P}_{i33} - \boldsymbol{S}_{i22}, \boldsymbol{\Phi}_{i3,11} = -\boldsymbol{P}_{i34}$,

$\boldsymbol{\Phi}_{i44} = \bar{\tau}_i\boldsymbol{Q}_{i4} + \bar{\eta}_i\bar{\boldsymbol{Q}}_{i4} - \dfrac{1}{\alpha_i}\boldsymbol{R}_{i2} - (1-\alpha_i\bar{\eta}_i)\boldsymbol{R}_{i1} + \boldsymbol{D}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{D}_{il}^{\mathrm T}, \boldsymbol{\Phi}_{i45} = \boldsymbol{B}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{D}_{il}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i48} = \boldsymbol{P}_{i24}^{\mathrm T} + \boldsymbol{C}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{D}_{il}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i49} = \boldsymbol{P}_{i34}^{\mathrm T}, \boldsymbol{\Phi}_{i40} = \boldsymbol{D}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{D}_{il}^{\mathrm T}, \boldsymbol{\Phi}_{i4,11} = -\boldsymbol{P}_{i44}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i4,13} = \boldsymbol{M}_i\boldsymbol{D}_{il}^{\mathrm T} + \boldsymbol{P}_{i14}^{\mathrm T} - \boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i4,15} = \boldsymbol{F}_{il}\boldsymbol{M}_i^{\mathrm T}$,

$\boldsymbol{\Phi}_{i55} = \boldsymbol{B}_{ijl}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{B}_{ijl}^{\mathrm T} - (1-\bar{d}_{ij})\boldsymbol{T}_{ij1} - 2\boldsymbol{T}_{ij4}$,

$\boldsymbol{\Phi}_{i56} = \boldsymbol{T}_{ij4}$,

$\boldsymbol{\Phi}_{i57} = \boldsymbol{T}_{ij4}, \boldsymbol{\Phi}_{i58} = \boldsymbol{C}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{B}_{ijl}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i50} = \boldsymbol{D}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{B}_{ijl}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i5,13} = \boldsymbol{M}_i\boldsymbol{B}_{ijl}^{\mathrm T} - \boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i5,15} = \boldsymbol{F}_{il}\boldsymbol{M}_i^{\mathrm T}$,

$\boldsymbol{\Phi}_{i66} = -\boldsymbol{T}_{ij3} - \boldsymbol{T}_{ij4} - \boldsymbol{T}_{ij5}, \boldsymbol{\Phi}_{i77} = -\hat{\boldsymbol{T}}_{ij2} - \hat{\boldsymbol{T}}_{ij4}$,

$\boldsymbol{\Phi}_{i88} = \boldsymbol{C}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{C}_{il}^{\mathrm T} + (1-\underline{\tau}_i)\boldsymbol{S}_{i23} - (1-\bar{\tau}_i)\boldsymbol{S}_{i13}$,

$\boldsymbol{\Phi}_{i80} = \boldsymbol{D}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{C}_{il}^{\mathrm T}, \boldsymbol{\Phi}_{i8,13} = \boldsymbol{M}_i\boldsymbol{C}_{il}^{\mathrm T} - \boldsymbol{M}_i^{\mathrm T}$,

$\boldsymbol{\Phi}_{i8,15} = \boldsymbol{F}_{il}\boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i99} = -\boldsymbol{S}_{i23}$,

$\boldsymbol{\Phi}_{i00} = -\boldsymbol{R}_{i2} + \boldsymbol{D}_{il}\boldsymbol{M}_i^{\mathrm T} + \boldsymbol{M}_i\boldsymbol{D}_{il}^{\mathrm T}$,

$\boldsymbol{\Phi}_{i0,13} = \boldsymbol{M}_i\boldsymbol{D}_{il}^{\mathrm T} - \boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i0,15} = \boldsymbol{F}_{il}\boldsymbol{M}_i^{\mathrm T}$,

$\boldsymbol{\Phi}_{i11,11} = -(1-\alpha_i\bar{\eta}_i)\boldsymbol{R}_{i3} - \boldsymbol{R}_{i4} - \dfrac{1}{\alpha_i}\boldsymbol{R}_{i4}$,

$\boldsymbol{\Phi}_{i13,15} = \boldsymbol{F}_{il}\boldsymbol{M}_i^{\mathrm T}$,

$\boldsymbol{\Phi}_{i13,13} = \boldsymbol{S}_{i13} + \tau_{iM}^2\boldsymbol{W}_i + \alpha_i^2\eta_{iM}^2\boldsymbol{R}_{i3} + \eta_{iM}^2\boldsymbol{R}_{i4} + (d_{iM} - d_{im})^2\boldsymbol{T}_{ij4} + d_{im}^2\boldsymbol{T}_{ij5} - \boldsymbol{M}_i - \boldsymbol{M}_i^{\mathrm T}, \boldsymbol{\Phi}_{i,18} = \boldsymbol{M}_i\boldsymbol{H}_i + \boldsymbol{Y}_i^{\mathrm T}\boldsymbol{L}_i^{\mathrm T}$,

$\boldsymbol{\Phi}_{i14,14} = \boldsymbol{T}_{ij1} + \boldsymbol{T}_{ij2} + \boldsymbol{T}_{ij3} - \boldsymbol{T}_{ij5}, \boldsymbol{\Phi}_{i15,15} = -\gamma_i^2\boldsymbol{I}$.

证明省略.

注 1 这里只给出了在 $\underline{\tau}_i \leqslant \dot{\tau}_i(t) \leqslant \bar{\tau}_i < 1, 0 \leqslant \tau_i(t) \leqslant \tau_{iM}$ 时的控制器设计方法，与此方法相似，可得 $1 < \underline{\tau}_i \leqslant \dot{\tau}_i(t) \leqslant \bar{\tau}_i$ 和 $\underline{\tau}_i \leqslant \dot{\tau}_i(t) \leqslant \bar{\tau}_i, \underline{\tau}_i < 1, \bar{\tau}_i \geqslant 1, 0 \leqslant \tau_i(t) \leqslant \tau_{iM}$ 等情况的 H_∞ 条件. 在 $\bar{\eta}_i < 1$ 的情况下，只需令 $\alpha_i = 1$，即可得到相应结论.

注 2 式(3)可简化成带有混合时滞的线性中立型系统 $\dot{x}(t) = \boldsymbol{A}x(t) + \boldsymbol{B}x(t-d(t)) + \boldsymbol{C}\dot{x}(t-\tau(t)) + \boldsymbol{D}\int_{t-\eta(t)}^{t} x(s)\,\mathrm{d}s$，定理 1 同样适用，取

$$\boldsymbol{A} = \begin{bmatrix} -0.9 & 0.2 \\ 0.1 & -0.9 \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} -1.1 & -0.2 \\ -0.1 & -1.1 \end{bmatrix},$$

$\boldsymbol{C} = \begin{bmatrix} -0.2 & 0 \\ 0.2 & -0.1 \end{bmatrix}, \boldsymbol{D} = \mathrm{diag}[0\quad 0]$，当 $\tau_M = 0.1, \underline{\tau} = 0, \bar{\tau} = 0.5$，得表 1 所示结果，可见本文方法降低了保守性.

表 1　取不同 $\bar{d}$ 的时滞上限 d_M

Table 1　Maximum upper bound d_M for different $\bar{d}$

方法	$\bar{d} = 0.1$	$\bar{d} = 0.5$	$\bar{d} = 0.7$
文献[8]	$d_M = 1.236$	$d_M = 1.113$	$d_M = 0.994$
文献[9]	$d_M = 1.506$	$d_M = 1.160$	$d_M = 1.046$
定理 1	$d_M = 1.532$	$d_M = 1.173$	$d_M = 1.052$

3　仿　　真

将沈阳某电厂用一个三机无穷大互联系统表示，系统结构见图 1. 发电机 4# 为无穷大母线，即

有 $E'_{q4}=1\angle 0°$,以该发电机为参考节点,1#,2#和3#为发电机节点,系统基准容量为 100 MVA. 令 $\Delta\delta_{12}(t)=\delta_1(t)-\delta_2(t)$,$\Delta\delta_{23}(t)=\delta_2(t)-\delta_3(t)$,为减少计算负担,建立如下 9 条模糊规则:

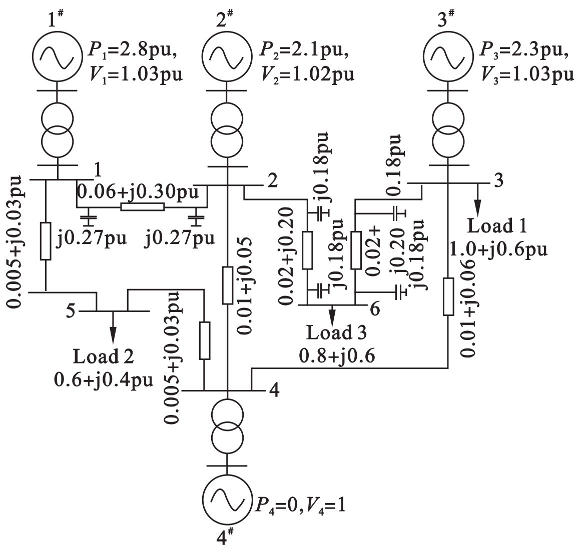

图 1 三机无穷大母线系统示意图

Fig. 1 Schematic diagram of three-machine infinite bus system

Rule $l(l=1,\cdots,9)$:

If $\Delta\delta_{12}(t)$ is M_m,$\Delta\delta_{23}(t)$ is $M_n(m,n=1,2,3)$,

then $\dot{\boldsymbol{x}}_i(t)=\boldsymbol{A}_i^l\boldsymbol{x}_i(t)+\sum_{j=1,j\neq i}^{J}\boldsymbol{B}_{ijl}\boldsymbol{x}_j(t-d_{ij}(t))+\boldsymbol{C}_{il}\dot{\boldsymbol{x}}_i(t-\tau_i(t))+\boldsymbol{D}_{il}\int_{t-\eta_i(t)}^{t}\boldsymbol{x}_i(s)\mathrm{d}s+\boldsymbol{B}_i\boldsymbol{u}_i(t)+\boldsymbol{\omega}_i(t)$,

$z_i(t)=\boldsymbol{H}_{il}\boldsymbol{x}_i(t)+\boldsymbol{L}_{il}\boldsymbol{\omega}_i(t)$.

其中:M_1,M_2,M_3 分别表示 NB(负大),ZR(零),PB(正大),取三角形隶属度函数,即可得 $\boldsymbol{A}_i^l$,$\boldsymbol{B}_{ijl}$.

取 $\boldsymbol{H}_{il}=[1\quad 0\quad 1\quad 0]$,

$$\boldsymbol{C}_{il}=\begin{bmatrix}0&0&0&0\\0&0&0&-5\\-0.6&0&-0.6&-0.6\\0&1&-1&0\end{bmatrix},$$

$$\boldsymbol{D}_{il}=\begin{bmatrix}-1&0&1&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix},$$

$d_{ij}(t)=(\sin(t)-0.6)^2$,$\tau_i(t)=2\sin^2(t)$,$\eta_i(t)=\sin^2(t)$,$\boldsymbol{L}_{il}=1$,$i,j=1,2,3$,$i\neq j$;$l=1,\cdots,9$. 利用定理 1 求得

$\boldsymbol{K}'_{1l}\approx[-42.6\quad -14.4\quad -12.6\quad -18.5]$,

$\boldsymbol{K}'_{2l}\approx[-21.5\quad -6.6\quad -9.8\quad -11.1]$,

$\boldsymbol{K}'_{3l}\approx[-13.1\quad -9.6\quad -12.7\quad -15.7]$,

$l=1,\cdots,9$.

取初值 $\boldsymbol{x}_i(t)=[1\quad 0\quad 1\quad 0]^{\mathrm{T}}$,扰动 $\boldsymbol{w}_1(t)=0.5\sin(8\pi t)\mathrm{e}^{-5t}$,$\boldsymbol{w}_2(t)=\boldsymbol{w}_3(t)=0.5\cos(8\pi t)\mathrm{e}^{-5t}$. 发电机输出曲线见图 2.

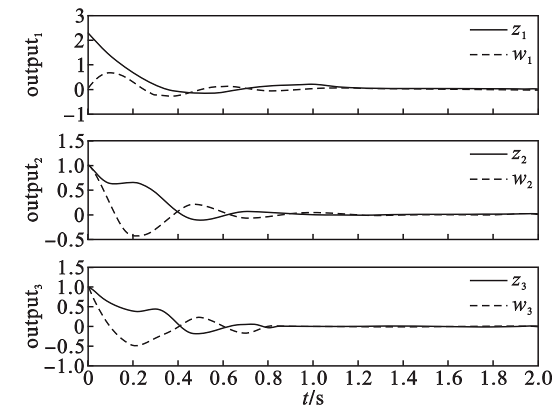

图 2 1#,2#,3#发电机的输出曲线

Fig. 2 Output signals of the 1#,2#,3# generators

4 结 语

本文在 LMI 的框架下研究了混合时变时滞的多机电力系统的 H_∞ 稳定条件,并将结论推广到时滞的不同情况,首次给出了包括带有快时变分布时滞的互联系统的 H_∞ 稳定条件. 对多机电力系统的仿真结果证明了所提出方法的有效性.

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