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含K类函数和附加控制量的自适应L_2励磁控制

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摘要: 为了简化常规非线性自适应L_2增益控制计算和加快控制系统状态变量的稳定收敛速度, 通过引入附加控制变量和K类函数, 克服了每次虚拟函数设计时都要考虑γ–耗散不等式的不足, 保证了L_2增益控制能力随误差变量的增加而增强, 给出了一种含附加控制变量和K类函数的非线性自适应L_2增益控制的通式, 并以具体军用电站谐波励磁系统为对象, 进行了仿真实验. 仿真结果表明, 相对于传统L_2增益控制, 该方法可提高状态变量的收敛速度, 并可加强军用电站励磁系统的动态稳定性.

关键词: 励磁系统; 自适应L_2增益控制; 军用电站; 改进back-stepping控制; 附加控制变量

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Adaptive L_2 excitation control with K–class functions and additional control variable

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Abstract: In order to simplify the calculation of the nonlinear adaptive L_2–gain control (L_2–NAC) and improve the convergence speed of the state variables, by adopting additional control variable and K–class functions, the γ–dissipation inequality will not be considered in virtual function design and the control ability of L_2–NAC can be improved with the increase of error-variable values, the common formulas of the L_2–NAC with K–class functions and additional control variables (K–L_2–NAC) is deduced. K–L_2–NAC simulation results of the harmonic excitation system for military power station show that the K–L_2–NAC, comparing with the traditional L_2–NAC method, can improve the convergence speed of the control variables and enhance the dynamic stability of the excitation system for military power station.

Key words: excitation system; adaptive L_2–gain control; military power station; improved back-stepping control; additional control variable

1 引言(Introduction)

在雷达探测、导弹发射、牵引高炮、炮兵群(团)指挥系统等场合, 由军用电站、输电线缆、各类型武器装备(雷达、导弹、火炮等)等可构成一类容量有限的独立电力系统. 受武器装备冲击性、瞬时性动作用和战场环境下电磁脉冲等干扰影响, 此独立电力系统具有强的非线性、不确定性[1–3]. 目前, 武器装备性能的不断提升对独立电力系统的稳定控制能力提出了更高的要求, 而军用电站励磁控制是提高独立电力系统能力的重要手段之一. 为此, 许多学者在军用电站励磁系统的特性分析[4–5]、模型建立[6–7]、励磁方式[8]等方面进行了深入的研究.

由于非线性自适应L_2增益控制(nonlinear adaptive L_2–gain control, L_2–NAC)可以适应控制系统的非线性和参数不确定性, 并在保证干扰至控制输出增益小于设定值的同时, 还可以实现系统的鲁棒稳定, 因此, 军用电站励磁系统的L_2–NAC为提高独立电力系统静态、暂态稳定控制能力, 提供了一种直接、有效的方法[9–11].

文献[12–14]分别采用精确反馈线性化非线性H_∞控制、变结构控制、反演设计、无源化设计与变结构控制相结合的方法, 对L_2增益干扰抑制的励磁控制进行了分析, 但在分析时没有考虑参数不确定性; 文献[9]采用精确反馈线性化与最优H_∞控制相结合的方式实现了军用电站的励磁与速度综合控制, 但同样不具备不确定参数自适应的功能; 文献[14–15]介绍

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了基于backstepping设计的L_2–NAC的实现方法, 并详细分析了L_2–NAC在励磁控制中的应用, 但是在各子系统虚拟函数设计时都要考虑γ–耗散不等式, 文献[16–17]同样存在这样的问题. 尽管部分文献给出的L_2–NAC 方法不需要在各子系统虚拟函数设计时考虑γ–耗散不等式, 但外部干扰需要满足确定的不等式关系[18–20].

本文通过引入K类函数和附加控制变量, 提出了一种含K类函数和附加控制变量的L_2–NAC (nonlinear adaptive L_2 control with K–class functions and additional control variable, K–L_2–NAC)新方法. K–L_2–NAC提高了状态变量的稳定收敛速度, 克服了各子系统虚拟函数设计时都要考虑γ–耗散不等式的不足, 简化了计算, 且不需要外部干扰满足特定的不等式, 同时给出了详细的通用公式, 并运用到了军用电站励磁控制中. 军用电站励磁系统的K–L_2–NAC仿真结果表明: 通过引入K类函数和附加控制变量可以提高励磁系统状态变量的稳定收敛速度, 有利于提高军用电站的稳定控制能力.

2 含$\boldsymbol{K}$类函数和附加控制变量的非线性自适应$\boldsymbol{L_2}$增益控制原理 (Principle of K–L_2–NAC)

2.1 非线性系统描述(Description of the nonlinear system)

K–L_2–NAC适应于以下含干扰输入的非线性不确定系统:

$$\dot{x}_1 = f_1(x_1) + g_1(x_1)x_2 + \boldsymbol{\varphi}_1^{\mathrm{T}}(x_1)\boldsymbol{\theta} + \varepsilon_1, \tag{1.1}$$

$$\dot{x}_2 = f_2(x_1,x_2) + g_2(x_1,x_2)x_2 + \boldsymbol{\varphi}_2^{\mathrm{T}}(x_1,x_2)\boldsymbol{\theta} + \varepsilon_2, \tag{1.2}$$

$$\vdots$$

$$\dot{x}_i = f_i(x_1,\cdots,x_i) + g_i(x_1,\cdots,x_i)x_{i+1} + \boldsymbol{\varphi}_i^{\mathrm{T}}(x_1,\cdots,x_i)\boldsymbol{\theta} + \varepsilon_i, \tag{1.i}$$

$$\vdots$$

$$\dot{x}_n = f_n(x_1,\cdots,x_n) + g_n(x_1,\cdots,x_n)u + \boldsymbol{\varphi}_n^{\mathrm{T}}(x_1,\cdots,x_n)\boldsymbol{\theta} + \varepsilon_n, \tag{1.n}$$

$$\boldsymbol{y} = [q_1x_1 \cdots q_nx_n]^{\mathrm{T}}, \tag{2}$$

其中: $\boldsymbol{x}\in\mathbb{R}^n$及$u\in\mathbb{R}$分别为状态和输入变量; $\boldsymbol{\theta}\in\mathbb{R}^p$, $1<p\leqslant n$是未知参数向量; $f_i, g_i, i=1,2,\cdots,n$是光滑函数, 且满足$f_i(0)=0$, $g_i(x_1,\cdots,x_i)\neq 0$; $\varphi_i(x_1,\cdots,x_i)$是光滑向量场, 且满足$\varphi_i(0)=0$; ε_i为随机扰动量, 且满足$\varepsilon\in L_2=\{\varepsilon(t)|\int_0^t \varepsilon^2(t)\,\mathrm{d}t<\infty\}$为有限能量信号集合; $\boldsymbol{y}$为评价信号, $q_j(1\leqslant j\leqslant n)$为加权系数.

定义 1 令$\gamma\geqslant 0$, 对所有$T\geqslant 0$和$\boldsymbol{\varepsilon}\in L_2$, 系统(1)在控制律$u=f(\boldsymbol{x},\hat{\boldsymbol{\theta}})$和参数自适应律$\dot{\hat{\boldsymbol{\theta}}}=g(\boldsymbol{x},\hat{\boldsymbol{\theta}})$作用下满足:

1) 当干扰输入为零时, 闭环系统在$\boldsymbol{x}=0$是渐近稳定的;

2) $V(x_T)-V(x_0)\leqslant\int_0^T(\gamma^2\|\boldsymbol{\varepsilon}\|^2-\|\boldsymbol{y}\|^2)\,\mathrm{d}t$,

则称系统(1)具有小于γ的L_2增益.

其中: $\boldsymbol{\varepsilon}=[\varepsilon_1,\cdots,\varepsilon_n]^{\mathrm{T}}$表示整个系统的干扰变量, $V(\cdot)$为系统(1)的存储函数, $\hat{\boldsymbol{\theta}}$为未知参数向量$\boldsymbol{\theta}$的估计值, x_0为系统初始状态.

2.2 非线性自适应$\boldsymbol{L_2}$增益控制实现(Realization of nonlinear adaptive L_2–gain control)

第1步 取$e_1=x_1$, 由式(1.1)得

$$\dot{e}_1 = f_1(x_1) + g_1(x_1)x_2 + \boldsymbol{\varphi}_1^{\mathrm{T}}(x_1)\boldsymbol{\theta} + \varepsilon_1. \tag{3}$$

取虚拟控制x_2^*:

$$x_2^* = \frac{1}{g_1(x_1)}[-f_1(x_1) - \boldsymbol{\varphi}_1^{\mathrm{T}}(x_1)\hat{\boldsymbol{\theta}} - m_1e_1], \tag{4}$$

其中: 控制系数$m_1=\kappa_1(|e_1|)+c_1$, $\kappa_1(|e_1|)$为关于e_1的K类函数, $c_1>0$; $\hat{\boldsymbol{\theta}}$为$\boldsymbol{\theta}$的估计值.

将式(4)代入式(3)得

$$\dot{e}_1 = -m_1e_1 + \boldsymbol{\varphi}_1^{\mathrm{T}}(x_1)\tilde{\boldsymbol{\theta}} + g_1(x_1)e_2 + \varepsilon_1, \tag{5}$$

其中: $\tilde{\boldsymbol{\theta}}$为估计误差, 满足$\tilde{\boldsymbol{\theta}}=\boldsymbol{\theta}-\hat{\boldsymbol{\theta}}$; e_2为误差变量, 满足$e_2=x_2-x_2^*$.

由式(1.2)(4)得

$$\begin{aligned}
&\dot{e}_2 = \dot{x}_2 - \dot{x}_2^* = \\
&f_2 + g_2x_3 + \boldsymbol{\varphi}_2^{\mathrm{T}}\boldsymbol{\theta} - \frac{\partial x_2^*}{\partial x_1}\dot{x}_1 - \frac{\partial x_2^*}{\partial\hat{\boldsymbol{\theta}}}\dot{\hat{\boldsymbol{\theta}}} + \varepsilon_2 = \\
&f_2 + g_2x_3 + \boldsymbol{\varphi}_2^{\mathrm{T}}\boldsymbol{\theta} - \frac{\partial x_2^*}{\partial x_1}(f_1 + g_1x_2 + \\
&\boldsymbol{\varphi}_1^{\mathrm{T}}\boldsymbol{\theta} + \varepsilon_1) - \frac{\partial x_2^*}{\partial\hat{\boldsymbol{\theta}}}\dot{\hat{\boldsymbol{\theta}}} + \varepsilon_2.
\end{aligned} \tag{6}$$

第2步 取Lyapunov函数

$$V_2 = \frac{e_1^2}{2} + \frac{e_2^2}{2}, \tag{7}$$

式(7)沿式(3)(6)求导得

$$\begin{aligned}
\dot{V}_2 =& e_1\dot{e}_1 + e_2\dot{e}_2 = \\
& -m_1e_1^2 + e_1\boldsymbol{\varphi}_1^{\mathrm{T}}(x_1)\tilde{\boldsymbol{\theta}} + \\
& e_2[g_1e_1 + f_2 + g_2x_3 + \boldsymbol{\varphi}_2^{\mathrm{T}}\boldsymbol{\theta} - \\
& \frac{\partial x_2^*}{\partial x_1}(f_1 + g_1x_2 + \boldsymbol{\varphi}_1^{\mathrm{T}}\boldsymbol{\theta}) - \frac{\partial x_2^*}{\partial\hat{\boldsymbol{\theta}}}\dot{\hat{\boldsymbol{\theta}}}] + \\
& e_1\varepsilon_1 + e_2\varepsilon_2 - e_2\frac{\partial x_2^*}{\partial x_1}\varepsilon_1.
\end{aligned} \tag{8}$$

取虚拟控制x_3^*:

$$\begin{aligned}
x_3^* =& \frac{1}{g_2}[-g_1e_1 - f_2 - \boldsymbol{\varphi}_2^{\mathrm{T}}\hat{\boldsymbol{\theta}} + \frac{\partial x_2^*}{\partial\hat{\boldsymbol{\theta}}}\dot{\hat{\boldsymbol{\theta}}} + \\
& \frac{\partial x_2^*}{\partial x_1}(f_1 + g_1x_2 + \boldsymbol{\varphi}_1^{\mathrm{T}}\hat{\boldsymbol{\theta}}) - m_2e_2],
\end{aligned} \tag{9}$$

其中: 控制系数$m_2=\kappa_2(|e_2|)+c_2$, $\kappa_2(|e_2|)$为关于e_2的K类函数; $c_2>0$.

将式(9)代入式(8)得

$$\dot V_2=-m_1e_1^2-m_2e_2^2+e_1\boldsymbol{\varphi}_1^{\mathrm T}\tilde{\boldsymbol\theta}+e_2\boldsymbol{\varphi}_2^{\mathrm T}\tilde{\boldsymbol\theta}+g_2e_2e_3-e_2\frac{\partial x_2^*}{\partial x_1}\boldsymbol{\varphi}_1^{\mathrm T}\tilde{\boldsymbol\theta}+e_1\varepsilon_1+e_2\varepsilon_2-e_2\frac{\partial x_2^*}{\partial x_1}\varepsilon_1,\tag{10}$$

其中e_3为误差变量, 满足$e_3=x_3-x_3^*$.

将式(9)代入式(6)得

$$\dot e_2=-m_2e_2+\boldsymbol{\varphi}_2^{\mathrm T}\tilde{\boldsymbol\theta}+g_2e_3-g_1e_1-\frac{\partial x_2^*}{\partial x_1}\boldsymbol{\varphi}_1^{\mathrm T}\tilde{\boldsymbol\theta}+\varepsilon_2-\frac{\partial x_2^*}{\partial x_1}\varepsilon_1.\tag{11}$$

第i步　采用上述相同的计算方法得

$$V_i=\sum_{j=1}^{i}\frac{e_j^2}{2},\tag{12}$$

$$\dot V_i=-\sum_{j=1}^{i}m_je_j^2+\sum_{j=1}^{i}e_j\boldsymbol{\varphi}_j^{\mathrm T}\tilde{\boldsymbol\theta}+\sum_{j=1}^{i}e_j\varepsilon_j+g_ie_ie_{i+1}-\sum_{k=2}^{i}\sum_{j=1}^{k-1}e_k\frac{\partial x_k^*}{\partial x_j}\boldsymbol{\varphi}_j^{\mathrm T}\tilde{\boldsymbol\theta}+\sum_{k=2}^{i}\sum_{j=1}^{k-1}e_k\frac{\partial x_k^*}{\partial x_j}\varepsilon_j,\tag{13}$$

$$\dot e_j=-m_ie_i+\boldsymbol{\varphi}_i^{\mathrm T}\tilde{\boldsymbol\theta}+g_ie_{i+1}-g_{i-1}e_{i-1}-\sum_{j=1}^{i-1}\frac{\partial x_i^*}{\partial x_j}\boldsymbol{\varphi}_j^{\mathrm T}\tilde{\boldsymbol\theta}+\varepsilon_i-\sum_{j=1}^{i-1}\frac{\partial x_i^*}{\partial x_j}\varepsilon_j,\tag{14}$$

其中: $m_i=\kappa_i(|e_i|)+c_i$, $\kappa_i(|e_i|)$为关于e_i的K类函数, $c_i>0$.

第n步　取全系统的Lyapunov函数并求导得

$$V_n=V_{n-1}+\frac12\xi^2(e_n)+\frac12\Gamma^{-1}\tilde\theta^2\geqslant0,\tag{15}$$

$$\dot V_n=\dot V_{n-1}+\xi(e_n)\frac{\mathrm d\xi(e_n)}{\mathrm de_n}\dot e_n+\tilde\theta\Gamma^{-1}\dot{\tilde\theta},\tag{16}$$

其中$\xi(e_n)$为满足$\xi(e_n)\dfrac{\mathrm d\xi(e_n)}{\mathrm de_n}|_{e_n=0}\neq0$的任意函数.

按照通式(13)–(14)得

$$\begin{aligned}\dot V_n=&-\sum_{j=1}^{n-1}m_je_j^2+\sum_{j=1}^{n-1}e_j\varepsilon_j+\sum_{j=1}^{n-1}e_j\boldsymbol{\varphi}_j^{\mathrm T}\tilde{\boldsymbol\theta}-\tilde{\boldsymbol\theta}^{\mathrm T}\boldsymbol\Gamma\dot{\hat{\boldsymbol\theta}}-\\&\sum_{k=2}^{n-1}\sum_{j=1}^{k-1}e_k\frac{\partial x_k^*}{\partial x_j}\boldsymbol{\varphi}_j^{\mathrm T}\tilde{\boldsymbol\theta}-\sum_{k=2}^{n-1}\sum_{j=1}^{k-1}e_k\frac{\partial x_k^*}{\partial x_j}\varepsilon_j+\\&b_1g_{n-1}e_{n-1}e_nb_1^{-1}+f_n+g_nu+\boldsymbol{\varphi}_n^{\mathrm T}\boldsymbol\theta+\\&\varepsilon_n-\sum_{j=1}^{n-1}\frac{\partial x_n^*}{\partial x_j}(f_j+g_jx_{j+1}+\boldsymbol{\varphi}_j^{\mathrm T}\boldsymbol\theta+\varepsilon_j)-\\&\frac{\partial x_n^*}{\partial\hat{\boldsymbol\theta}}\dot{\hat{\boldsymbol\theta}}].\end{aligned}\tag{17}$$

取反馈控制律和参数替换律分别为

$$\begin{aligned}u=&\frac{1}{g_n}[-g_{n-1}e_ne_{n-1}b_1^{-1}-f_n-\boldsymbol{\varphi}_n^{\mathrm T}\hat{\boldsymbol\theta}+\\&\frac{\partial x_n^*}{\partial\hat{\boldsymbol\theta}}\dot{\hat{\boldsymbol\theta}}+\sum_{j=1}^{n-1}\frac{\partial x_n^*}{\partial x_j}(f_j+g_jx_{j+1}+\boldsymbol{\varphi}_j^{\mathrm T}\hat{\boldsymbol\theta})+\\&m_nb_1-u_{\mathrm{f1}}],\end{aligned}\tag{18}$$

$$\begin{aligned}\dot{\hat{\boldsymbol\theta}}=&[(\sum_{j=1}^{n-1}e_j\boldsymbol{\varphi}_j^{\mathrm T}-b_1\sum_{j=1}^{n-1}\frac{\partial x_n^*}{\partial x_j}\boldsymbol{\varphi}_j^{\mathrm T}-\\&\sum_{k=2}^{n-1}\sum_{j=1}^{k-1}e_k\frac{\partial x_k^*}{\partial x_j}\boldsymbol{\varphi}_j^{\mathrm T}+b_1\boldsymbol{\varphi}_n^{\mathrm T})\boldsymbol\Gamma]^{\mathrm T},\end{aligned}\tag{19}$$

其中: $b_1=\xi(e_n)\dfrac{\mathrm d\xi(e_n)}{\mathrm de_n}$; 控制系数 $m_n=\kappa_n(|e_n|)+c_n$, $\kappa_n(|e_n|)$为关于e_n的K类函数, $c_n>0$; u_{f1}为附加控制变量.

取误差变量$e_n=x_n-x_n^*$得

$$\begin{aligned}\dot e_n=&\dot x_n-\dot x_n^*=\\&f_n+g_nu+\boldsymbol{\varphi}_n^{\mathrm T}\boldsymbol\theta+\varepsilon_n-\frac{\partial x_n^*}{\partial\hat{\boldsymbol\theta}}\dot{\hat{\boldsymbol\theta}}-\\&\sum_{j=1}^{n-1}\frac{\partial x_n^*}{\partial x_j}(f_j+g_jx_{j+1}+\boldsymbol{\varphi}_j^{\mathrm T}\boldsymbol\theta+\varepsilon_j).\end{aligned}\tag{20}$$

将式(18)代入式(20)得

$$\dot e_n=-g_{n-1}e_{n-1}b_1^{-1}-m_nb_1-u_{\mathrm{f1}}+\boldsymbol{\varphi}_n^{\mathrm T}\tilde{\boldsymbol\theta}-\sum_{j=1}^{n-1}\frac{\partial x_n^*}{\partial x_j}\tilde{\boldsymbol\theta}+\varepsilon_n-\sum_{j=1}^{n-1}\frac{\partial x_n^*}{\partial x_j}\varepsilon_j.\tag{21}$$

将式(18)–(19)代入式(17)得

$$\dot V_n=-\sum_{j=1}^{n-1}m_je_j^2-m_nb_1^2+\sum_{j=1}^{n-1}e_j\varepsilon_j+b_1\varepsilon_n-\sum_{k=2}^{n-1}\sum_{j=1}^{k-1}e_k\frac{\partial x_k^*}{\partial x_j}\varepsilon_j-b_1\sum_{j=1}^{n-1}\frac{\partial x_n^*}{x_j}\varepsilon_j-u_{\mathrm{f1}}b_1,\tag{22}$$

第$n+1$步　定义函数

$$H=\dot V_n+\frac12(\|\boldsymbol y\|^2-\gamma^2\|\boldsymbol\varepsilon\|^2),\tag{23}$$

将式(2)(22)代入式(23)得

$$\begin{aligned}H=&-\sum_{j=1}^{n-1}m_je_j^2-m_nb_1^2+b_1\varepsilon_n+\\&\sum_{j=1}^{n-1}(e_j\varepsilon_j-b_1\frac{\partial x_n^*}{\partial x_j}\varepsilon_j)-\sum_{k=2}^{n-1}\sum_{j=1}^{k-1}e_k\frac{\partial x_k^*}{\partial x_j}\varepsilon_j+\\&\frac12\sum_{j=1}^{n}(q_j^2x_j^2-\gamma^2\varepsilon_j^2)-b_1u_{\mathrm{f1}}.\end{aligned}\tag{24}$$

由式(24)得

$$\begin{aligned}H=&-\sum_{j=1}^{n-1}m_je_j^2-m_nb_1^2-\sum_{j=1}^{n-1}(-e_j\varepsilon_j+\frac{\gamma^2}{2}\varepsilon_j^2)+\\&(b_1\varepsilon_n-\frac{\gamma^2}{2}\varepsilon_n^2)-\sum_{j=1}^{n-1}\sum_{k=j+1}^{n-1}e_k\frac{\partial x_k^*}{\partial x_j}\varepsilon_j-\\&b_1\sum_{j=1}^{n-1}\frac{\partial x_n^*}{\partial x_j}\varepsilon_j+\frac12\sum_{j=1}^{n}(q_jx_j)^2-b_1u_{\mathrm{f1}}.\end{aligned}\tag{25}$$

由式(25)得

$$H = -\sum_{j=1}^{n-1} m_j e_j^2 - \sum_{j=1}^{n-1}(\frac{\gamma\varepsilon_2}{\sqrt{2}} - \frac{b_2}{\sqrt{2}\gamma})^2 + \frac{1}{2}\sum_{j=1}^{n}(q_j x_j)^2 - m_n b_1^2 - (\frac{\gamma\varepsilon_n}{\sqrt{2}} - \frac{b_1}{\sqrt{2}\gamma})^2 + \sum_{j=1}^{n-1}\frac{b_2^2}{2\gamma^2} + \frac{b_1^2}{2\gamma^2} - b_1 u_{\mathrm{f1}}, \tag{26}$$

其中$b_2 = e_j + \sum_{k=j+1}^{n-1} e_k(\frac{\partial x_k^*}{\partial x_j}) + b_1(\frac{\partial x_n^*}{\partial x_j})$.

取附加控制变量u_{f1}为

$$u_{\mathrm{f1}} = b_1^{-1}[\sum_{j=1}^{n-1}\frac{b_2^2}{2\gamma^2} + \frac{b_1^2}{2\gamma^2} + \frac{1}{2}\sum_{j=1}^{n}(q_j x_j)^2]. \tag{27}$$

将式(27)代入式(26)得

$$H = -\sum_{j=1}^{n-1} m_j e_j^2 - m_n b_1^2 - \sum_{j=1}^{n-1}(\frac{\gamma\varepsilon_j}{\sqrt{2}} - \frac{b_2}{\sqrt{2}\gamma})^2 - (\frac{\gamma\varepsilon_n}{\sqrt{2}} - \frac{b_1}{\sqrt{2}\gamma})^2 \leqslant 0. \tag{28}$$

由式(23)(28)得

$$2\dot{V}_n + \|\boldsymbol{y}\|^2 \leqslant \gamma^2\|\boldsymbol{\varepsilon}\|^2. \tag{29}$$

取系统(1)的存储函数为$V(\boldsymbol{x}) = 2V_n \geqslant 0$, 由式(15)(29)得

$$V(T) - V(0) \leqslant \int_0^T (\gamma^2\|\boldsymbol{\varepsilon}\|^2 - \|\boldsymbol{y}\|^2)\,\mathrm{d}t. \tag{30}$$

当不考虑系统干扰时, 由式(22)和式(27)得

$$\dot{V}_n = -\sum_{j=1}^{n-1} m_j e_j^2 - m_n b_1^2 - \frac{b_1^2}{2\gamma^2} - \sum_{j=1}^{n-1}\frac{b_2^2}{2\gamma^2} - \frac{1}{2}\sum_{j=1}^{n}(q_j x_j)^2 < 0. \tag{31}$$

因此, $\boldsymbol{x} = 0$是系统的渐近稳定平衡点.

由式(30)和式(31)可知: 系统(1)的L_1增益系数小于γ.

以上L_2增益干扰抑制方法即是本文提出的含K类函数和附加控制变量的非线性自适应L_2增益控制(nonlinear adaptive L_2–gain control with K–class functions, K–L_2–NAC).

评价 1 当K–L_2–NAC中的$\kappa_i(|e_i|)$等于零时, 控制系数$m_i = c_i$为大于零的常数, 此时的K–L_2–NAC退化为常规非线性 L_2 增益干扰抑制控制(nonlinear adaptive L_2–gain control, L_2–NAC).

评价 2 在常规基于Lyapunov稳定理论的L_2–NAC方法中, m_j为常数, 不随误差变量e_j的增加而变化, 而在K–L_2–NAC中, $\kappa_i(|e_i|)$是关于e_i的K类函数, 当e_j增加时, $\kappa_j(|e_j|)$和m_j值增加, 因此, K–L_2–NAC具有更快的干扰抑制速度.

评价 3 在常规基于Lyapunov稳定理论的L_2–NAC方法中, 每个子系统虚拟函数选取时都需要考虑不等式$2\dot{V}_i \leqslant (\gamma^2\|\varepsilon_i\|^2 + \|\boldsymbol{y}\|)$, 而在$K$–$L_2$–NAC中, 通过引入附加控制变量$u_{\mathrm{f1}}$, 简化了$L_2$增益控制计算, 并给出了规律性计算公式(18)(27)和式(19), 简化了L_2增益干扰抑制计算.

评价 4 由式(22)知, 当不考虑系统干扰输入时, 采用控制律式(18)(27)和参数自适应律式(19)可以保证

$$\dot{V}_n = -\sum_{j=1}^{n-1} m_j e_j^2 - m_n b_1^2 - \sum_{j=1}^{n-1}\frac{b_2^2}{2\gamma^2} - \frac{b_1^2}{2\gamma^2} - \frac{1}{2}\sum_{j=1}^{n}(q_j x_j)^2 \leqslant 0,$$

因此, 式(18)(27)表示的控制律和式(19)表示的参数自适应律可保证系统渐进稳定, 并使 $x_i \to 0, (i = 1, \cdots, n)$.

3 谐波励磁系统的$\boldsymbol{K}$–$\boldsymbol{L_2}$–NAC (K–L_2–NAC of harmonic excitation system)

带有不确定参数的谐波励磁系统数学模型可表示为[6]

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \omega - \omega_0, \tag{32.1}$$

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \frac{\omega_0}{M}P_{\mathrm{m}} + \frac{\omega_0}{M}\frac{E_{\mathrm{q}}'u_{\mathrm{s}}}{x_{\mathrm{d}}'}\sin\delta - \frac{D}{M}(\omega - \omega_0) + \varepsilon_1, \tag{32.2}$$

$$\frac{\mathrm{d}E_{\mathrm{q}}'}{\mathrm{d}t} = -\frac{1}{T_{\mathrm{d}}'}E_{\mathrm{q}}' + \frac{1}{T_{\mathrm{d0}}}\frac{x_{\mathrm{d}} - x_{\mathrm{d}}'}{x_{\mathrm{d}}'}u_{\mathrm{S}}\cos\delta + \frac{K_{\mathrm{A}}}{T_{\mathrm{d0}}}A_{30} + \frac{K_{\mathrm{u}}}{T_{\mathrm{d0}}}u + \frac{K_{\mathrm{A}}}{T_{\mathrm{d0}}}A_3' + \varepsilon_2', \tag{32.3}$$

其中: ε_1综合考虑了力矩干扰输入(谐波励磁功率可以看作干扰的一部分)和模型不确定性; ε_2'综合考虑了励磁绕组电磁干扰输入和模型不确定性; 阻尼系数D通常难以确定, 可看作不确定系数;

$$A_3 = M_{\mathrm{h}}E_3 = M_{\mathrm{h}}\sqrt{(KE_0 + K'I_\phi\sin\psi)^2 + (K''I_\phi\cos\psi)^2},$$

M_{h}为整流系数, $\psi = \delta + \varphi$为内功率因数角, δ为发电机功角, φ为负载功率因数角.

当定义$\boldsymbol{x} = [x_1, x_2, x_3]^{\mathrm{T}} = [\delta - \delta_0, \omega - \omega_0, E_{\mathrm{q}}' - E_{\mathrm{q0}}']^{\mathrm{T}}$时, 由模型式(32)得

$$\dot{x}_1 = x_2, \tag{33.1}$$

$$\dot{x}_2 = -\frac{D}{M}x_2 - \beta_1 u_{\mathrm{s}}\sin(\delta_0 + x_1)x_3 - \beta_1 u_{\mathrm{s}}x_{30}[\sin(\delta_0 + x_1) - \sin\delta_0] + \varepsilon_1, \tag{33.2}$$

$$\dot{x}_3 = -\beta_2 x_3 + \beta_3 u_{\mathrm{s}}[\cos(\delta_0 + x_1) - \cos\delta_0] - \frac{1}{T_{\mathrm{d0}}}E_{\mathrm{f0}} + \frac{K_{\mathrm{A}}}{T_{\mathrm{d0}}}A_{30} + \frac{K_{\mathrm{u}}}{T_{\mathrm{d0}}} + \varepsilon_2, \tag{33.3}$$

其中$(\delta_0, \omega_0, E_{\mathrm{q0}}')$为起始稳定工作点;

$$\beta_1 = \omega_0/x_{\mathrm{d}}'M;\ \beta_2 = 1/T_{\mathrm{d}}';$$

$$\beta_3=(1/T'_{\mathrm{d0}})((x_{\mathrm{d}}-x'_{\mathrm{d}})/x'_{\mathrm{d}});$$

在稳定工作点, 满足

$$P_{\mathrm{m}}\approx P_{\mathrm{e0}}=(E'_{\mathrm{q0}}u_{\mathrm{s}}/x'_{\mathrm{d}})\sin\delta_0;$$
$$\varepsilon_2=(K_{\mathrm{A}}/T_{\mathrm{d0}})A'_3+\varepsilon'_2.$$

在谐波励磁系统稳定工作状态下, 假定A_3的值为A_{30}, 则当谐波励磁系统受到外部扰动后, A_3的值则可表示为$A_{30}+A'_3$, 其中A'_3为受扰变化量.

当引入预反馈u时, 由式(33)可得

$$\dot x_1=x_2, \tag{34.1}$$
$$\dot x_2=-\theta x_2-\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)x_3-\beta_1u_{\mathrm{s}}x_{30}[\sin(\delta_0+x_1)-\sin\delta_0]+\varepsilon_1, \tag{34.2}$$
$$\dot x_3=\upsilon+\varepsilon_2, \tag{34.3}$$
$$\boldsymbol{y}=[q_1x_1\quad q_2x_2]^{\mathrm{T}}, \tag{34.4}$$

其中: $\theta=\dfrac{D}{M}$为不确定系数; $u=K_{\mathrm{u}}^{-1}\{T_{\mathrm{d0}}\upsilon+T_{\mathrm{d0}}\beta_2x_3+E_{\mathrm{f0}}-K_{\mathrm{A}}A_{30}-T_{\mathrm{d0}}\beta_3u_{\mathrm{S}}[\cos(\delta_0+x_1)-\cos\delta_0]\}$.

取$e_1=x_1$, $x_2^*=-m_1e_1$, $e_2=x_2-x_2^*$, $V_2=\dfrac{e_1^2}{2}+\dfrac{e_2^2}{2}$, 采用第2 节计算方法, 得

$$\dot e_1=-m_1e_1+e_2, \tag{35}$$
$$\dot V_2=-m_1e_1^2+e_2\varepsilon_1+e_2\{e_1-x_2\theta-\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)x_3-\beta_1u_{\mathrm{s}}x_{30}\cdot[\sin(\delta_0+x_1)-\sin\delta_0]+m_1x_2\}, \tag{36}$$
$$\dot e_2=-x_2\theta-\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)x_3+\varepsilon_1+m_1x_2-\beta_1u_{\mathrm{s}}x_{30}[\sin(\delta_0+x_1)-\sin\delta_0], \tag{37}$$

其中: $m_1=\kappa_1(|e_1|)+c_1$, $\kappa_1(|e_1|)$为关于e_1的K类函数, $c_1>0$.

取虚拟控制x_3^*为

$$x_3^*=(e_1-x_2\hat\theta+m_1x_2+m_2e_2-\beta_1u_{\mathrm{s}}x_{30}[\sin(\delta_0+x_1)-\sin\delta_0])/(\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)), \tag{38}$$

其中: $\hat\theta$为θ的估计值; $m_2=\kappa_2(|e_2|)+c_2$, $\kappa_2(|e_2|)$为关于e_2的K类函数, $c_2>0$.

将式(38)代入式(36)–(37)得

$$\dot V_2=-m_1e_1^2-m_2e_2^2-x_2\tilde\theta e_2-\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)e_2e_3+e_2\varepsilon_1, \tag{39}$$
$$\dot e_2=-m_2e_2-e_1-x_2\tilde\theta-\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)e_3+\varepsilon_1, \tag{40}$$

其中: $e_3=x_3-x_3^*$, $\tilde\theta=\theta-\hat\theta$.

由式(38)得

$$\dot x_3^*=(x_2-x_2\dot{\hat\theta}-\beta_1u_{\mathrm{s}}x_{30}\cos(\delta_0+x_1)x_2+m_1m_2x_2+(-\hat\theta+m_1+m_2)\{-\theta x_2-\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)x_3+\varepsilon_1-\beta_1u_{\mathrm{s}}x_{30}\cdot[\sin(\delta_0+x_1)-\sin\delta_0]\})/(\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1))-\cos(\delta_0+x_1)x_2(e_1-x_2\hat\theta+m_1x_2+m_2e_2-\beta_1x_{30}[\sin(\delta_0+x_1)-\sin\delta_0])/(\beta_1u_{\mathrm{s}}\sin^2(\delta_0+x_1)). \tag{41}$$

取$V_3=V_2+(\xi^2(e_3)/2)+(1/2\rho)\tilde\theta^2$, 则有

$$\dot V_3=-\sum_{i=1}^2m_ie_i^2-x_2\tilde\theta e_2-\beta_1\sin(\delta_0+x_1)e_2e_3+e_2\varepsilon_1+b_1(\upsilon+\varepsilon_2-\dot x_3^*)+\frac{1}{\rho}\tilde\theta\dot{\tilde\theta}, \tag{42}$$

其中$b_1=\xi(e_3)\dfrac{\mathrm{d}\xi(e_3)}{\mathrm{d}e_3}$.

将式(41)代入式(42), 并分别取以下控制律(43)和参数自适应律(44)为

$$\upsilon=\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)e_2e_3b_1^{-1}-m_3b_1-u_{\mathrm{f1}}+(x_2-\beta_1u_{\mathrm{s}}x_{30}\cos(\delta_0+x_1)x_2+m_1m_2x_2-\dot{\hat\theta}x_2+(-\hat\theta+m_1+m_2)\{-\hat\theta x_2-\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)x_3-\beta_1u_{\mathrm{s}}x_{30}[\sin(\delta_0+x_1)-\sin\delta_0]\})/(\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1))-x_2\cos(\delta_0+x_1)(-\hat\theta x_2+e_1+m_1x_2+m_2e_2-\beta_1u_{\mathrm{s}}x_{30}[\sin(\delta_0+x_1)-\sin\delta_0])/(\beta_1u_{\mathrm{s}}\sin^2(\delta_0+x_1)), \tag{43}$$
$$\dot{\hat\theta}=\rho[-e_2x_2+\frac{(-\hat\theta+m_1+m_2)b_1x_2}{\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)}], \tag{44}$$

其中: $m_3=\kappa_3(|e_3|)+c_3$, $\kappa_3(|e_3|)$为关于e_3的K类函数, $c_3>0$; u_{f1}为附加控制变量.

将式(43)–(44)代入式(42)得

$$\dot V_3=-\sum_{i=1}^2m_ie_i^2-m_3b_1^2+e_2\varepsilon_1-\frac{(-\hat\theta+m_1+m_2)\varepsilon_1}{\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1)}+b_1\varepsilon_2-b_1u_{\mathrm{f1}}. \tag{45}$$

取$H=\dot V_3+(\|\boldsymbol{y}\|^2-\gamma^2\|\boldsymbol{\varepsilon}\|^2)/2$, 由式(45)得

$$H=-\sum_{i=1}^2m_ie_i^2-m_3b_1^2-(\frac{\gamma\varepsilon_1}{\sqrt2}-\frac{b_2}{\sqrt2\gamma})^2+\frac{b_2^2}{2\gamma^2}-(\frac{\gamma\varepsilon_2}{\sqrt2}-\frac{b_1}{\sqrt2\gamma})^2+\frac{b_1^2}{2\gamma^2}+\frac{q_1^2x_1^2+q_2^2x_2^2}{2}-b_1u_{\mathrm{f1}}, \tag{46}$$

其中$b_2=e_2-(-\hat\theta+m_1+m_2)/(\beta_1u_{\mathrm{s}}\sin(\delta_0+x_1))$.

取附加控制变量u_{f1}为

$$u_{f1} = b_1^{-1}\left(\frac{b_1^2+b_2^2}{2\gamma^2} + \frac{4x_1^2+9x_2^2}{2}\right). \tag{47}$$

将式(47)代入式(46)得

$$H = \hat{V}_3 + \frac{1}{2}(\|\boldsymbol{y}\|^2 - \gamma^2\|\boldsymbol{\varepsilon}\|^2) = -\sum_{i=1}^{2} m_i e_i^2 - m_3 b_1^2 - \left(\frac{\gamma\varepsilon_1}{\sqrt{2}} - \frac{b_2}{\sqrt{2}\gamma}\right)^2 - \left(\frac{\gamma\varepsilon_2}{\sqrt{2}} - \frac{b_1}{\sqrt{2}\gamma}\right)^2 \leqslant 0. \tag{48}$$

取谐波励磁系统的能量存储函数为

$$V(\boldsymbol{x}) = 2V_3 = \sum_{i=1}^{2} e_i^2 + f^2(e_3) + \frac{1}{\rho}\tilde{\theta}^2 \geqslant 0. \tag{49}$$

由式(49)可知, 式(48)求积分可得

$$\int_0^T \|\boldsymbol{y}\|^2\,\mathrm{d}t \leqslant \gamma^2 \int_0^T \|\boldsymbol{\varepsilon}\|^2\,\mathrm{d}t + V(\boldsymbol{x}_0). \tag{50}$$

由上述计算可知, K–L_2–NAC的控制律为式(43)(47), 参数自适应律为式(44).

4 仿真结果与分析(Simulation results and analysis)

分别对常规PID、常规L_2–NAC和K–L_2–NAC的控制效果进行对比. 谐波励磁系统稳定工作点为

$E'_{q0} = 1.029\,\text{p.u.},\ 3.5\delta_0 = 0.904\,\text{rad},\ \omega_0 = 1.0\,\text{p.u.},$

$A_{30} = 2.01\,\text{p.u.},\ E_{f0} = -0.7833\,\text{p.u.}.$

仿真过程中, 谐波励磁系统在2.8 s时突增25%的额定负载, 然后在2.9 s时突减25%负载.

当采用PID控制时,仿真结果分别如图1所示.

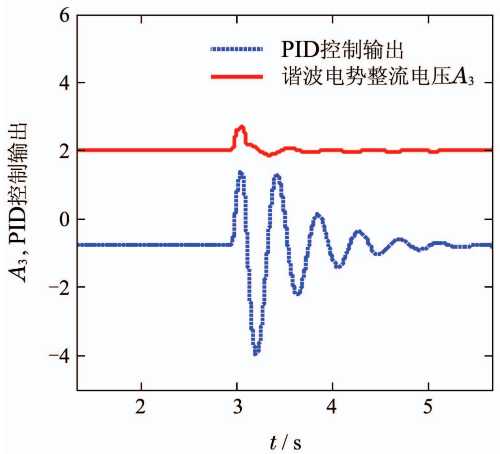
采用常规L_2–NAEC时, 仿真参数为

$\kappa_1(|e_1|) = \kappa_2(|e_2|) = 0; \kappa_3(|e_3|) = 0;$

$c_1 = 5; c_2 = 2; c_3 = 9; M_h = 1.4; q_1 = 0.4;$

$q_2 = 0.6; \gamma = 0.5; \rho = 1;$

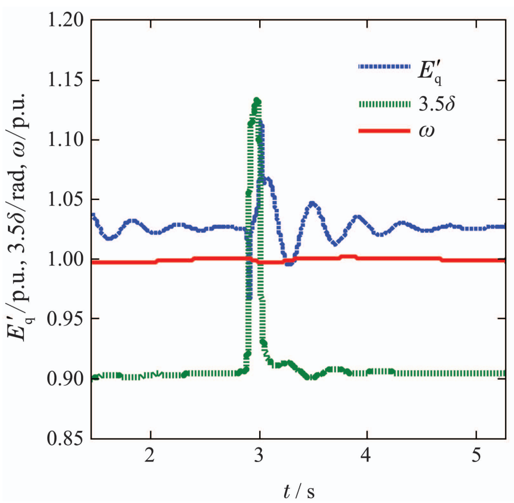
ε_1和ε_2均为白噪声(噪声功率分别为0.2和0.3). 状态变量和与反馈控制变量的动态变化曲线如图2所示.



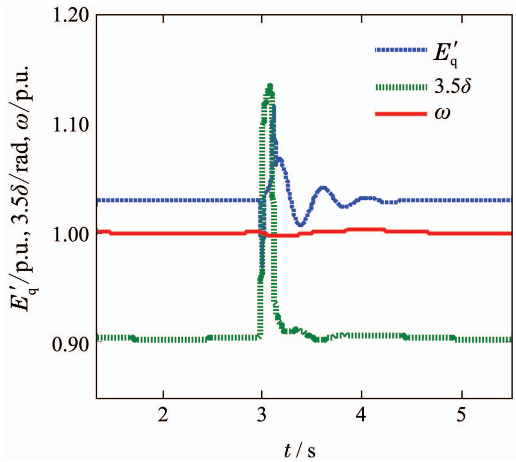
(b) 励磁控制输入变化曲线

图 1 采用PID控制时的状态及控制变化曲线

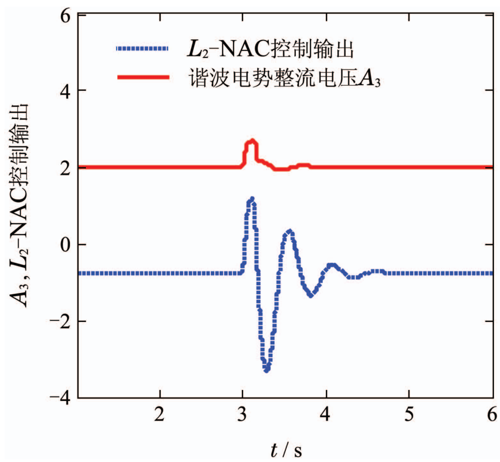
Fig. 1 Curves of state parameters and control input by PID control



(a) 状态变量变化曲线



(a) 暂态电势、功角、转速变化曲线



(b) A_3变化增量、预反馈控制v变化曲线

图 2 采用L_2–NAC控制时的状态及控制变化曲线

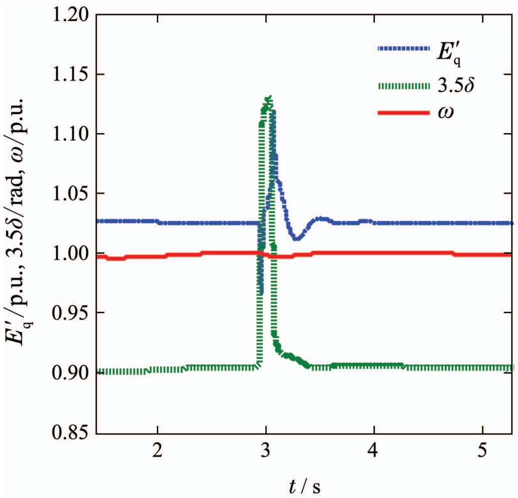
Fig. 2 Curves of state parameters and control input by L_2–NAC control

采用K–L_2–NAC时, 仿真参数为

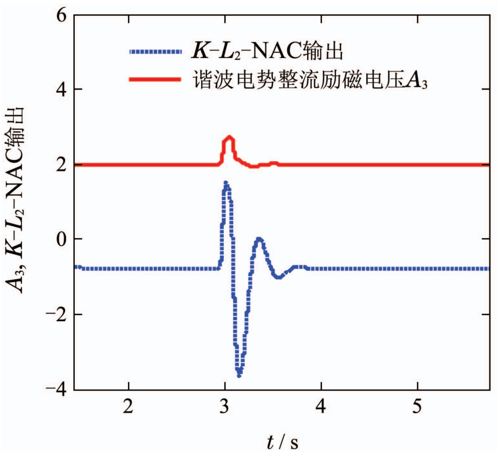
$\kappa_1(|e_1|) = e_1^2;\ \kappa_2(|e_2|) = 2e_2^2;$

$$\kappa_3(|e_3|) = |e_3|;\ f(e_3) = 2|e_3| + \cos e_3;$$
$$c_1 = 5; c_2 = 2;\ c_3 = 9;\ M_\mathrm{h} = 1.4;$$
$$q_1 = 0.4; q_2 = 0.6;\ \gamma = 0.5;\ \rho = 1;$$

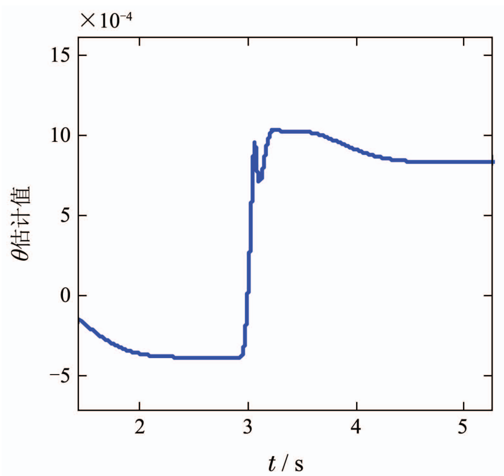
ε_1和ε_2均为白噪声(噪声功率分别为0.2和0.3). 状态变量和与反馈控制变量的动态变化曲线如图3所示.



(a) 状态变量变化曲线



(b) 励磁控制输入变化曲线



(c) 不确定参数估计值变化曲线

图 3 采用K–L_2–NAC时的状态及控制变化曲线

Fig. 3 Curves of state parameters and control input by K–L_2–NAC

比较图1、图2可知: 相对于传统PID控制, 采用常规L_2–NAC时, E'_q和δ的波动次数由5次减小为3次, 稳定时间由接近2.0 s减小为1.2 s. 由于常规L_2–NAC能够有效适应军用电站励磁系统的非线性和单数不确定性, 所以控制效果较好.

比较图2、图3可知: 相对于常规L_2–NAC时, 采用K–L_2–NAC时, E'_q和δ的波动次数由3次减小为1次, 稳定时间由接近1.2 s减小为0.7 s, 说明通过引入K类函数, K–L_2–NAC可以明显提高励磁系统状态变量的收敛速度, 有利于增强军用电站的稳定供电能力.

5 总结(Conclusions)

本文针对一类含干扰输入的严参数反馈非线性不确定系统, 提出了一种K–L_2–NAC的L_2增益干扰抑制的新方法, 并给出了计算通式. K–L_2–NAC通过在back-stepping鲁棒自适应控制中引入附加控制变量, 使得L_2增益干扰抑制控制只需在反演设计最后一步统一考虑γ–耗散不等式即可实现, 克服了常规L_2–NAC中各子系统虚拟函数设计时都要考虑γ–耗散不等式的不足, 简化了计算, 并通过引入K类函数, 使得非线性系统的状态变量能够快速恢复稳定, 提高了非线性不确定系统的稳定控制能力. 在军用电站谐波励磁系统的K–L_2–NAC仿真结果证明了该方法的有效性和优点, 为提高军用电站励磁系统的稳定控制能力提供了一种新的方法.

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