

基于非线性观测器的永磁同步电机位置 估计算法研究

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Research on Position Estimation Algorithm of Permanent Magnet Synchronous Motor Based on Nonlinear Observer

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Abstract: In order to improve the estimation accuracy of rotor position and speed for sensorless control of the surface-mounted permanent magnet synchronous motor, an improved nonlinear observer is proposed. By reconstructing the mathematical model of the nonlinear observer, the error equation is constructed, and the stability of the error equation is analyzed by using Lyapunov theory. Based on the stability condition, an error step-size optimization method is proposed to realize the self-regulation of the step gain of the nonlinear observer. The simulation and experiment results show that the improved nonlinear observer has good dynamic performance, and the feasibility is verified.

Key words: permanent magnet synchronous motor; sensorless; nonlinear observer; step-size optimization

摘要: 为提高表贴式永磁同步电机无位置传感器控制中转子位置和速度的估计精度,提出了一种改进型非线性观测器。通过重构非线性观测器的数学模型,构建了误差方程,利用 Lyapunov 理论对误差方程进行了稳定性分析。并基于稳定性条件提出了一种误差项步长优化方法,实现了非线性观测器的步长增益自调节。仿真与试验结果表明,改进型非线性观测器具有良好的动态性能,验证了其可行性。

关键词: 永磁同步电机; 无位置传感器; 非线性观测器; 步长优化

0 引言

永磁同步电机 (Permanent Magnet Synchronous

Motor, PMSM) 在电动汽车和风力发电领域受到越来越多的关注^[1-2]。PMSM 控制系统需要通过机械式传感器获取准确的速度和位置信息^[3-4]以获得良好的动、静态性能,而机械式传感器具有体积大、易受干扰等缺点。因此,越来越多的学者对电机无位置传感器控制技术进行了研究^[5-6]。

目前永磁同步电机无位置控制策略一般分为脉振高频电压注入法、旋转高频电压注入法、模型参考自适应法、扩展卡尔曼滤波法、滑模观测法以及磁链估计法^[7-9]。刘兵等人基于脉振高频电压注入法理论,分析了由电机参数不对称等非理想因素导致的位置估计精度的问题,分别利用二阶广义积分器 (Second-Order General Integrator, SOGI)、初相角的双重滤波补偿方法以及自适应滤波模块消除了谐波误差^[10-12]。Romeo Ortega 等人设计了一种永磁同步电机非线性观测器,并详细分析了观测器的全局渐近稳定性^[13-14]。严浩等人基于非线性观测器提出了一种仅使用一个电流传感器的无位置传感器控制方法^[15]。毛永乐等人基于内置式永磁同步电机,依据扰动理论建立了负载转矩估算方程,在线估算负载转矩以消除由机械模型误差引起的转子位置和转速的估算误差^[16]。文献[10-14]通过大量的试验验证得出步长,但产生了针对不同电机、不同工况需要提前调试的问题,且在电机运行过程中需要根据不同的工况实时调节参数来减小误差。

为了解决上述问题,本文提出了一种步长增益自调节方法对非线性观测器进行改进。首先,重新构造非线性观测器的数学模型,利用

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Lyapunov 理论对误差函数进行稳定性分析。其次,由稳定性的约束条件提出一种步长优化方法,根据电机的实时电压、电流以及转速来确定步长,实现参数的自调节,同时通过对状态误差的预测来确定步长最优解。最后,通过仿真与试验,验证改进型非线性观测器位置估计算法的可行性。

1 改进型非线性观测器

1.1 非线性观测器基本原理

在两相静止坐标系中,表贴式永磁同步电机 (Surface-Mounted Permanent Magnet Synchronous Motor, SPMSM) 的数学模型为

$$L \dot{i}_{\alpha\beta} = -R_s i_{\alpha\beta} + \omega_e \varphi_f \begin{bmatrix} \sin\theta_e \\ -\cos\theta_e \end{bmatrix} + u_{\alpha\beta} \quad (1)$$

式中: R_s 为定子电阻; $i_{\alpha\beta} = [i_\alpha \ i_\beta]^T$ 为定子电流; $u_{\alpha\beta} = [u_\alpha \ u_\beta]^T$ 为电机端电压; $L = L_d = L_q$ 为定子电感; φ_f 为电机永磁体磁链; ω_e 为电机角速度; θ_e 为电机电角度。这里假设 ω_e 和 θ_e 未知。

建立位置观测器的关键是选择状态变量和基于代数约束的修正项,该约束可以迫使观察变量收敛到实际变量。考虑到这一特性,采用基于梯度的算法。

首先,将状态变量 x 定义为

$$x = L i_{\alpha\beta} + \varphi_f \begin{bmatrix} \cos\theta_e \\ \sin\theta_e \end{bmatrix} \quad (2)$$

由式(1)和式(2)可得:

$$\dot{x} = L \dot{i}_{\alpha\beta} - \omega_e \varphi_f \begin{bmatrix} \sin\theta_e \\ -\cos\theta_e \end{bmatrix} = -R_s i_{\alpha\beta} + u_{\alpha\beta} \quad (3)$$

可以看出,式(3)右边的所有项都是可测量的,为了简化,设 $y = -R_s i_{\alpha\beta} + u_{\alpha\beta}$, 式(3)最终可以改写为

$$\dot{x} = y \quad (4)$$

为了构造非线性观测器,应向式(4)增加一个能够反映观测误差程度的修正项。一个向量函数被定义为 $\eta: \mathbb{R}^2 \rightarrow \mathbb{R}^2$, 其表达式为

$$\eta = x - L i_{\alpha\beta} \quad (5)$$

根据欧几里得范数,可得 η 与 φ_f 之间的关系为

$$\|\eta(x)\|^2 = \varphi_f^2 \quad (6)$$

根据式(4)和式(6),可以构建一个非线性观测器,如式(7)所示:

$$\dot{\hat{x}} = y + \gamma [\eta(\hat{x})] (\varphi_f^2 - \|\eta(\hat{x})\|^2) \quad (7)$$

式中: $\hat{x}$ 为 x 的估计值; γ 为迭代步骤; $\varphi_{err} = \varphi_f^2 - \|\eta(\hat{x})\|^2$ 为磁链估计误差。

根据观测的变量和式(2)可得:

$$\begin{bmatrix} \cos\hat{\theta}_e \\ \sin\hat{\theta}_e \end{bmatrix} = \frac{1}{\varphi_f} \begin{bmatrix} \hat{x}_1 - L i_{\alpha} \\ \hat{x}_2 - L i_{\beta} \end{bmatrix} \quad (8)$$

式中: $\hat{\theta}_e$ 为 θ_e 的估计值; $\hat{x}_1, \hat{x}_2$ 分别为 $\hat{x}$ 在 α, β 轴的分量。

引用锁相环 (Phase Locked Loop, PLL), 通过比例积分 (Proportional Integra, PI) 调节器和积分器分别获取转速和转子位置, 锁相环结构框图如图 1 所示。

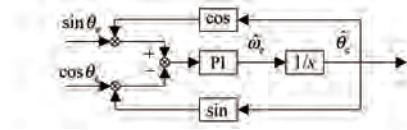


图 1 PLL 结构框图

Fig. 1 Block diagram of PLL structure

1.2 步长优化方法

定义状态变量的估计误差为 $\tilde{x} = \hat{x} - x$, 根据式(3)和式(7)可推导出误差动力学方程, 即:

$$\begin{aligned} \dot{\tilde{x}} = & -\gamma \left(\tilde{x} + \varphi_f \begin{bmatrix} \cos\theta_e \\ \sin\theta_e \end{bmatrix} \right) \left(\|\tilde{x}\|^2 + 2\varphi_f \tilde{x}^T \begin{bmatrix} \cos\theta_e \\ \sin\theta_e \end{bmatrix} \right) \end{aligned} \quad (9)$$

根据 Lyapunov 理论对式(9)进行稳定性分析, 可得出以下结论^[10]:

1) 任意速度

当电机以任意速度运行时, 式(9)满足:

$$\{\tilde{x} \in \mathbb{R}^2 \mid \|\tilde{x}\| \leq 2\varphi_f\} \quad (10)$$

这意味着式(9)的所有轨迹都将收敛到这个范围。

2) 恒定速度

$$|\omega_e| > \frac{1}{2} \gamma \varphi_f^2 \quad (11)$$

电机速度是一个常数且满足式(11)时, 误差方程式(9)满足全局渐近稳定性。

基于式(10)和式(11), 提出了一种步长优化方法。具体过程如下:

在 PMSM 的实际控制程序中, 需要将式(7)离散化。这里采用欧拉公式离散化式(7), 离散

后的表达式为

$$\hat{\mathbf{x}}(k+1) - \hat{\mathbf{x}}(k) =$$
$$\mathbf{y}(k)T_s + \gamma[\boldsymbol{\eta}(\hat{\mathbf{x}})](\varphi_i^2 - \|\boldsymbol{\eta}(\hat{\mathbf{x}})\|^2)T_s$$

(12)

式中: $\hat{\mathbf{x}}(k)$ 和 $\hat{\mathbf{x}}(k+1)$ 分别为第 k 和 $k+1$ 个周期内状态变量的估计值; $\mathbf{y}(k)$ 为第 k 个周期内 $\mathbf{y}$ 矢量的实际值; T_s 为采样时间。

迭代步骤 γ 是影响位置估计结果的一个关键因素。如果 γ 太大,会导致在极值附近的振荡,如果 γ 过小将大大降低该函数收敛到极值的速度,并且 γ 的取值应满足式(10)和式(11)。根据式(11)确定 γ 的取值范围为 $\gamma < 2|\omega_e|/\varphi_i^2$,引入一个常数 n ,其中 n 为根据数字信号处理器(Digital Signal Processor,DSP)的处理能力选择的正整数。将 $\gamma = 2|\omega_e|/\varphi_i^2$ 均分成 n 份,除去0和 $2|\omega_e|/\varphi_i^2$,取其中的 $(n-1)$ 个数分别代入到式(7)和磁链的估计误差中进行计算,进而选取一个合适的 γ 。步长优化的流程图如图2所示。

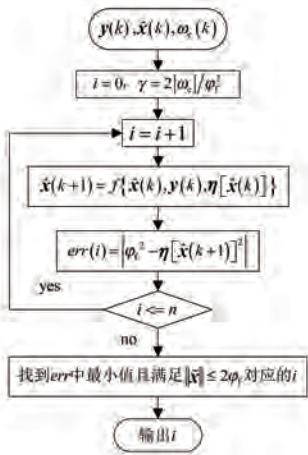


图 2 步长优化流程图

Fig. 2 Step size optimization flowchart

2 仿真结果与分析

使用 Matlab/Simulink 对算法进行建模仿真,并对结果进行比较和分析。仿真中 SPMSM 的主要参数如表 1 所示。

2.1 电机空载启动性能

图 3 和图 4 为传统非线性观测器和改进型非线性观测器,电机空载启动,在 0.3 s 内升至 1 500 rpm 工况下的转速与转子位置的仿真图。其中传统非线性观测器的步长增益为 $\gamma = 10\,000$ 。

由图 3 和图 4 可知,改进型非线性观测器空载启动性能良好,估计精度较高。

表 1 SPMSM 主要参数表

Tab. 1 SPMSM main parameter table

参数名称	参数值
额定功率/kW	1
额定电压/V	380
定子电阻/ Ω	0.65
转动惯量/($\text{kg}\cdot\text{m}^2$)	0.002 7
阻尼系数/($\text{N}\cdot\text{m}\cdot\text{s}$)	0.000 5
d,q 轴电感/mH	4.7
永磁体磁链/Wb	0.202
极对数	5

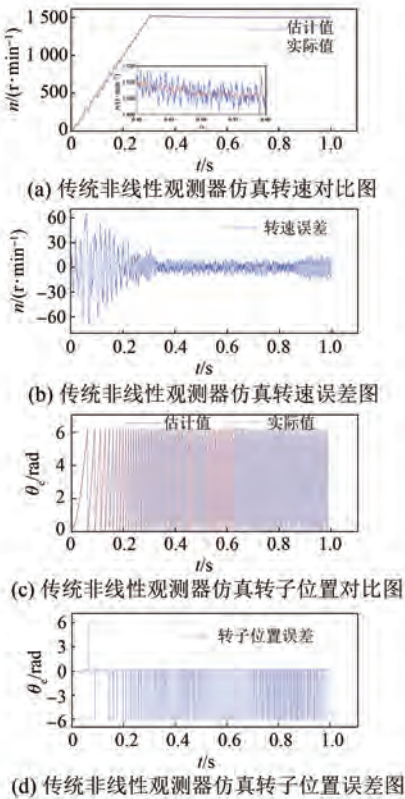


图 3 传统非线性观测器仿真空载启动图

Fig. 3 Simulated no-load starting diagram of traditional nonlinear observer

2.2 电机恒速加载性能

电机转速在 0.3 s 时稳定在 1 500 rpm,0.6 s 时给电机增加 5 N·m 的负载转矩,传统非线性观测器和改进型非线性观测器下转速波形图分别如图 5 和图 6 所示。其中传统非线性观测器的步长增益为 $\gamma = 10\,000$ 。从图 5 和图 6 中可以看出两种观测器都有良好的动态响应,改进型非线性观测器相比更平滑。

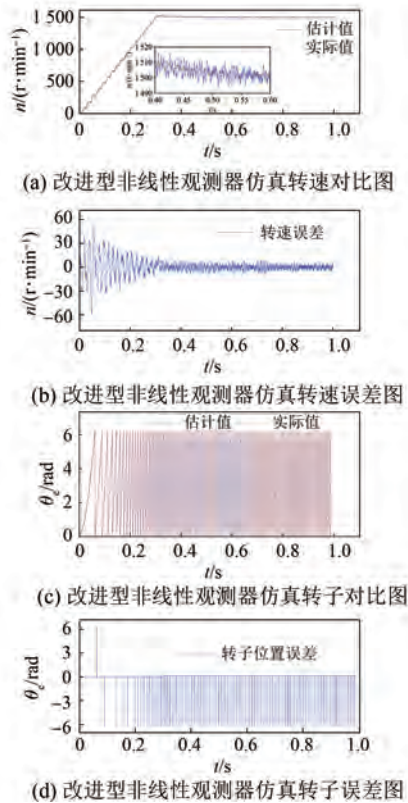


图4 改进型非线性观测器仿真空载启动图
Fig.4 Simulated no-load starting diagram of improved nonlinear observer

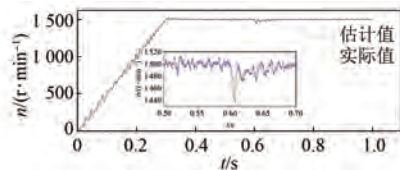


图5 传统非线性观测器仿真加载过程图
Fig.5 Simulation loading process diagram of conventional nonlinear observer

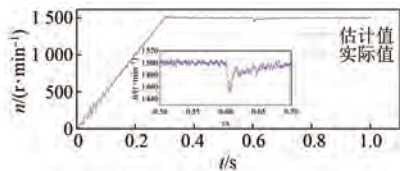


图6 改进型非线性观测器仿真加载过程图
Fig.6 Simulation loading process diagram of improved nonlinear observer

3 试验结果与分析

采用半实物仿真平台进行基于非线性观测器的位置估计算法的验证,试验平台如图7所示,试

验电机参数与仿真电机参数一致,见表1。试验数据通过上位机软件获得,在试验结束后,上位机软件自动上传试验数据到 Matlab 工作区,最后将试验数据导入 Origin 软件中进行图形绘制。



图7 半实物仿真平台

Fig.7 Semi-physical simulation platform

3.1 电机空载启动性能

图8和图9为电机空载启动,在0.8 s内升至1 000 rpm 工况下转速对比图和转子位置对比图,其中传统非线性观测器的步长增益为 $\gamma = 2\ 000$ 。由图9可知,改进型非线性观测器仍具有可行性,

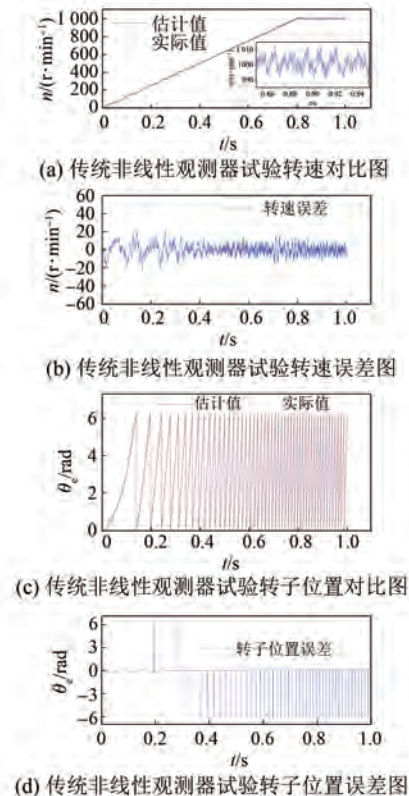


图8 传统非线性观测器试验空载启动图
Fig.8 Experimental no-load starting diagram of traditional nonlinear observer

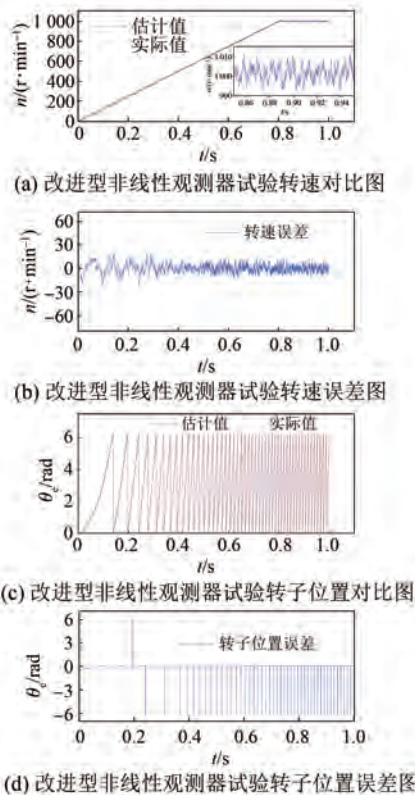


图 9 改进型非线性观测器试验空载启动图

Fig. 9 Experimental no-load starting diagram of improved nonlinear observer

能良好地跟踪电机的实际转子位置,空载启动效果良好。

3.2 电机带载启动且恒速加载性能

图 10 和图 11 分别为传统非线性观测器和改进型非线性观测器试验加载过程图。电机带载启动,负载转矩为 $1 \text{ N} \cdot \text{m}$,转速在 0.8 s 时稳定在 1000 rpm ,在 1 s 时负载转矩变为 $3 \text{ N} \cdot \text{m}$,加载后电机转速下降到 960 rpm 左右,并且在 0.1 s 后恢复到 1000 rpm 。传统非线性观测器的步长增益为 $\gamma = 10000$ 。由图 11 可知,改进型非线性观测器具有良好的带载启动能力和动态响应性能。

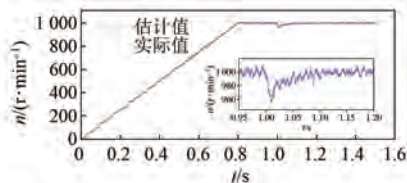


图 10 传统非线性观测器试验加载过程图

Fig. 10 Experimental loading process diagram of traditional nonlinear observer

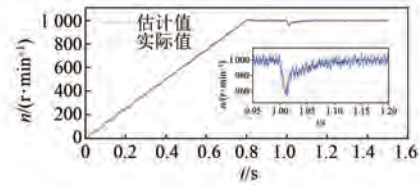


图 11 改进型非线性观测器试验加载过程图

Fig. 11 Experimental loading process diagram of improved nonlinear observer

4 结语

本文通过步长增益自调节优化方法对非线性观测器进行了改进。重新构造了非线性观测器的数学模型,利用 Lyapunov 理论对误差函数进行稳定性分析,基于稳定性的约束条件提出了一种步长优化方法。改进型非线性观测器不需要通过提前做大量的测试来选取合适的参数,也不需要再试验的过程中更改参数,减少了工作量。最后,通过仿真与试验,验证了改进型非线性观测器位置估计算法的可行性与良好的跟踪性能。

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Research on Position Estimation Algorithm of Permanent Magnet Synchronous Motor Based on Nonlinear Observer

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Key words: permanent magnet synchronous motor; sensorless; nonlinear observer; step-size optimization; phase-locked loop

Sensorless control technology of permanent magnet synchronous motor can improve system robustness and reduce system cost, and has broad application prospects in the field of modern industrial transmission. Through the continuous efforts of academia and industry, sensorless control technology has made great progress and has been applied in many industrial drive sites. However, the performance of sensorless drive systems needs to be further improved in some cases where control accuracy and dynamic response are required. In this paper, the performance improvement of nonlinear observer is studied to meet the needs of more industrial transmission applications.

At present, the position-free control strategies of permanent magnet synchronous motors are generally divided into pulse vibration high frequency voltage injection method, rotating high frequency voltage injection method, model reference adaptive method, extended Kalman filter method, sliding mode observation method and flux linkage estimation method. Romeo Ortega and the others designed a nonlinear observer for permanent magnet synchronous motors, and detailed analysis revealed the global asymptotic stability

properties. Yan Hao and the others proposed a sensorless control method using only one current sensor based on nonlinear observer. At present, most scholars select the step length through a large number of experiments in advance, which leads to a problem. For different motors and different working conditions, it is necessary to debug in advance. During the operation of the motor, parameters need to be adjusted in real time according to different working conditions to reduce errors, which increases a lot of workload.

In this paper, a step gain self-adjusting optimization method is proposed to improve the nonlinear observer. Firstly, the mathematical model of nonlinear observer is reconstructed, and the stability of error function is analyzed by Lyapunov theory. Secondly, a step size optimization method is proposed based on the stability constraint conditions. The step size is determined according to the voltage, current and speed of the motor at that time to realize the self-regulation of parameters. At the same time, the optimal step size solution is determined by predicting the state error. Finally, the feasibility of the improved nonlinear observer position estimation algorithm is verified by simulation and experiment.

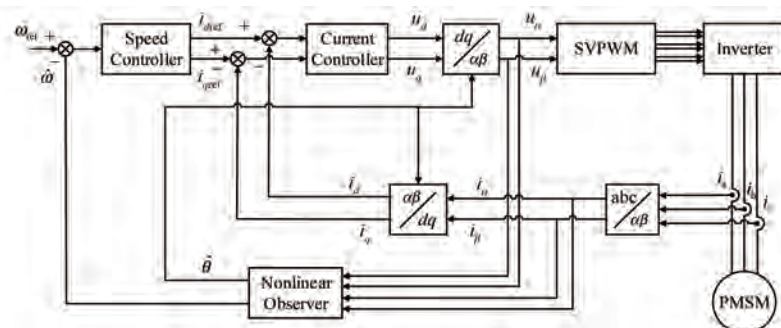


Fig. 1 Nonlinear observer control block diagram