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Robust adaptive speed regulator with self-tuning law for surfaced-mounted permanent magnet synchronous motor

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ABSTRACT

This study exhibits a self-tuning speed control scheme for the surface-mounted permanent magnet synchronous motor (SPMSM) against the parameter variations through the multivariable approach. The proposed method has two novelties. The first one is to combine the adaptive controller with the self-tuning algorithm so as to make the decay ratio of the tracking errors higher in the transient period. The second one is to provide a systematical way to find a robust stabilizing control gain corresponding the speed and current tracking errors by solving an optimization problem. The efficacy of the proposed method was experimentally investigated using a 3-*kW* SPMSM.

1. Introduction

Due to the high efficiency, power factor, and density, the permanent magnet synchronous motors (PMSMs) have been considered as an alternative to the classical DC and induction motors in many industrial applications (Khanchoul, Hilairet, & Normand-Cyrot, 2014; Zhong, Rahman, Hu, & Lim, 1997).

The cascade control strategy has been preferred to use to control the speed of the permanent magnet synchronous motors (PMSMs), which is composed of the inner-loop current (torque) controller and outer-loop speed controller in the cascade manner. In particular, the feedback linearizing technique based proportional-integral (PI) controller was mainly utilized to control the inner and outer-loops owing to its simplicity (Kwon, Choi, Kwak, & Sul, 2008; Kwon, Kim, & Sul, 2014, 2012). The PI gains were determined to meet the desired closed-loop performance in the frequency domain, and the additional feed-forward compensation terms were introduced to make the transient closed-loop performance better by cancelling the nonlinearities caused from the back EMF. In order to improve the closed-loop performance in the time-domain, there have been various novel controllers such as the deadbeat (Lee, Choi, Seok, & Lorenz, 2011) and feedback linearizing method (Boldea & Blaabjerg, 2012; Fazeli, Zarchi, Soltani, & Ping, 2008) for the inner-loop. A robust control scheme (Errouissi, Ouhrouche, Chen, & Trzynadlowski, 2012) has been developed for the inner-loop to improve the closed-loop robustness, employing the convergent state estimates of the disturbance observer (DOB). It is, however, questionable that these control schemes could still keep the closed-loop performance satisfactory in the parameter variations. In order to maintain the closed-loop performance to be satisfactory regardless the disturbance caused by the parameter variations and the external noises, the sliding mode control (SMC) schemes (Corradini, Ippoliti, Longhi, & Orlando, 2012; Jezernik, Korelic, & Horvat, 2013) have been devised for replacing the inner-loop PI controller. The optimal time-domain performance of the closed-loop system should be found by tuning the control gain through the trial-error method since there has been no systematic way to assign the optimal control gain. It has been reported that the recent model predictive control (MPC) methods (Chai, Wang, & Rogers, 2013a; Zhang & Zhu, 2011) for the inner-loop provide a faster transient performance than the existing methods with the closed-loop optimality in some sense. These optimal control schemes, however, optimize the cost function through performing either the exhaustive search method or the online membership test for each control step, which would make the computational burden heavy. It should be noticed that, although both inner-loop and outer-loop controllers are designed to keep their closed-loop systems stable, respectively, it is ambiguous that the whole closed-loop system combining the inner-loop and outer-loop is also stable, which is a fundamental limitation of the cascade control scheme.

There have been the multivariable approach based speed control strategies such as back-stepping controls (Morawiec, 2013), adaptive controls (Choi, Vu, & Jung, 2011; Karabacak & Eskikurt, 2011; Kim, Lee, & Lee, 2016; Zhoua & Wang, 2005), sliding mode control (Zhang, Sun, Zhao, & Sun, 2013), fuzzy logic controls (Vu, Yu, Choi, & Jung, 2013), and MPCs (Chai, Wang, & Rogers, 2013b; Preindl & Bolognani, 2013). The both back-stepping methods in Morawiec

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(2013) require the true values of inductance, viscous damping, and inertia, in order to ensure the closed-loop stability and desired closed-loop performance. However, there is no guarantee that the closed-loop stability and the desired closed-loop performance would be preserved in the presence of parameter uncertainties. The adaptive speed control scheme in Zhoua and Wang (2005) guarantees that the PMSM speed follows its reference, estimating the resistance, mechanical friction, and load torque, in the online, but this controller needs to know the true values of inductance and flux. Although another type adaptive speed control law suggest in Choi et al. (2011) considers all parametric uncertainties of the PMSM, it requires to feedback the accelerated speed, which is hard to access in practice. The proposed adaptive method in Karabacak and Eskikurt (2011), Kim et al. (2016) did not provide a systematic way to determine the optimal closed-loop performance. In particular, the recent adaptive control scheme in Kim et al. (2016) presented a method to avoid the singularity problem while estimating the all electrical and mechanical parameters, and it tried to enhance the closed-loop robustness against the load torque using the sigma-modification terms for the both integrator and the adaptation law, but there was no guarantee to remove the offset errors in the tracking errors. The sliding mode control (Zhang et al., 2013) and MPCs (Chai et al., 2013b; Preindl & Bolognani, 2013) have the same drawbacks as their inner-loop cases (Corradini et al., 2012; Jezernik et al., 2013) and (Chai et al., 2013a; Zhang & Zhu, 2011). The fuzzy logic control schemes (Vu et al., 2013) consider all parameter uncertainties; but the closed-loop stability has been proved under the assumption that the control input is assumed to be bounded all the time, and these schemes might require a heavy online computational effort.

This article presents a speed controller design method embedding the self-tuning algorithm for the surface-mounted permanent magnet synchronous motor (SPMSM) via the multivariable approach in the presence of the parametric uncertainties, relaxing the inadequacies of aforementioned literatures. The novelties of the proposed method are divided into two parts: (a) the inner and outer-loop controllers are designed simultaneously by combining the adaptive method with self-tuning algorithm in order to improve the closed-loop performance in the transient period, (b) an optimal stabilizing control gain corresponding to the speed and current tracking errors can be found by solving an optimization problem under the bilinear matrix inequality constraints (BMIs) presenting the parameter variations. The experimental results using the 3-*kW* SPMSM show that the proposed method provides a satisfactory speed tracking performance with a desirable current behavior thanks to the introduced self-tuning algorithm.

2. SPMSM model in synchronous rotating *d*-*q* axis

In the synchronous rotating *d*-*q* axis, the dynamics of the SPMSM is described as follows (Zhoua & Wang, 2005):

$$\frac{di_d(t)}{dt} = -\frac{R_s}{L}i_d(t) + P\omega(t)i_q(t) + \frac{1}{L}u_d(t), \tag{1}$$

$$\frac{di_q(t)}{dt} = -P\omega(t)i_d(t) - \frac{R_s}{L}i_q(t) - \frac{P\lambda_m}{L}\omega(t) + \frac{1}{L}u_q(t), \tag{2}$$

$$\frac{d\omega(t)}{dt} = -\frac{B}{J}\omega(t) + \frac{1}{J}(T_e(i_q(t)) - T_L), \quad \forall\, t \ge 0, \tag{3}$$

where $i_d(t)$, $i_q(t)$, and $\omega(t)$ denote the *d*-axis current, *q*-axis current, and the rotor speed, respectively. The *d*-*q* axis input voltages are denoted as $u_d(t)$ and $u_q(t)$, which are treated as the control inputs. The electrical torque $T_e(i_q(t))$ is given by

$$T_e(i_q(t)) := \frac{3}{2}P\lambda_m i_q(t), \quad \forall\, t. \tag{4}$$

The electrical coefficients R_s, L, and λ_m represent the stator resistance, inductance, and magnet flux, respectively. The mechanical coefficients B, J, and P denote the viscous friction, rotor moment of inertia, and the number of pole pairs, respectively. $T_L(t)$ refers to the load torque, R_s and L are the stator resistance and inductance, respectively, and λ_m is the permanent magnet flux.

Note that it is difficult to always know the exact values of the electrical and mechanical parameters, except for the number of pole pairs P, because these values would vary as the operating conditions are changed (e.g., the reference speed and the temperature). Moreover, the load torque T_L can also be abruptly changed by an unexpected load failure, and it is considerably slower than the electrical variables. Thus, for the rest of the paper, it is assumed that:

1. All the electrical and mechanical coefficients, except for the number of pole pairs P, are unknown but the upper and lower bounds of these parameters are known. i.e., there exist known positive constants $R_{s,min}$, $R_{s,max}$, L_{min}, L_{max}, $\lambda_{m,min}$, $\lambda_{m,max}$, B_{min}, B_{max}, J_{min}, and J_{max}, such that
$$\begin{aligned} &0 < R_{s,min} \le R_s \le R_{s,max}, \\ &0 < L_{min} \le L \le L_{max},\ 0 < \lambda_{m,min} \le \lambda_m \le \lambda_{m,max}, \\ &0 < B_{min} \le B \le B_{max},\ 0 < J_{min} \le J \le J_{max}. \end{aligned} \tag{5}$$
2. The load torque T_L is unknown constant so that $\dot{T}_L = 0,\ \forall\, t \ge 0$ (Morawiec, 2013; Zhoua & Wang, 2005).
3. The *a*-*b*-*c* (stationary) axis current and the SPMSM speed are accessible for measurement, and so is the corresponding *d*-*q* axis current.

Under these assumptions, a robust speed tracking control scheme is designed in the following section using the state equation comprised of (1), (2), and (3).

Remark 1. It is known that the two parameters R_s and B_m are less sensitively varied than the rest of parameters. However, it is desirable to estimate these two parameters on the online in order to improve the control accuracy for all time.□.

3. Speed controller design

In this section, a robust speed tracking control law is built for attaining the control objective

$$\lim_{t\to\infty}\omega(t) = \omega_{ref} \quad \text{and} \quad \lim_{t\to\infty}i_d(t) = i_{d,ref} \tag{6}$$

for given constant speed and *d*-axis current references, ω_{ref} and $i_{d,ref}$, under the parametric uncertainties. Note that the current reference $i_{d,ref}$ is given for maximizing the torque per ampere within the rating speed operations; it is set to be zero in the case of SPMSM (Kadjoudj, Benbouzid, Ghennai, & Diallo, 2004; Ke & Lin, 2005). On the other hand, in the high speed operations, $i_{d,ref}$ is given so that the steady state value of the control input is feasible, which is called the field-weakening control.

First, since the load torque $T_L(t)$ acts as a mismatched unknown disturbance in the speed dynamics (3), define the coordinate transformation as

$$e_{iq}(t) := i_q(t) - i_{q,ref}(t), \quad \forall\, t \ge 0, \tag{7}$$

with $i_{q,ref}(t)$ being the virtual control input acting as the *q*-axis current reference to be designed later. Defining the speed tracking error as