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New variable gain super-twisting sliding mode observer for sensorless vector control of nonsinusoidal back-EMF PMSM☆

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ABSTRACT

This paper presents a new discrete-time super-twisting sliding mode observer with variable gains for sensorless nonsinusoidal vector control of permanent magnet synchronous motors. This observer is adopted to estimate the back electromotive forces (back-EMF) that are required for the rotor speed estimation and for the nonsinusoidal vector control. In addition, their gains are time-varying to minimize the chattering. So, they are adjusted based on internal states of the super-twisting algorithm. The stability analysis is investigated from the Lyapunov theory for discrete-time systems. Finally, simulation and experimental results are presented to demonstrate the good performance and the effectiveness of the proposed observer.

1. Introduction

Sensorless control of permanent magnet synchronous motors (PMSMs) has been a focus of intensive research during the last decades (Betin et al., 2014). The main reason for this interest is the elimination of rotor position or/and speed sensors that results in cost reduction, increased robustness and compactness (Briz and Degner, 2011). Other motivations result from advances in power electronic devices and in digital signal processors that have allowed product developers to apply high-performance sensorless methods to low-cost PMSM drives (Bose, 2009; Pacas, 2011). As a result, these motor drives have been widely adopted in manufacturing processes as well as in large-scale applications such as compressors, pumps and fans (Rahman, 2013).

Nowadays, the sensorless control methods for PMSM can be summarized in two categories (Betin et al., 2014; Acarnley and Watson, 2006): fundamental excitation signal (FES) and high-frequency signal injection (HFSI). In the first category, the methods are based on the motor model, and they can use either reduced-order or full-order observers for the closed-loop operation. On the other hand, in the second category, the rotor position detection is achieved by exploiting the motor saliences (i.e. magnetic rotor anisotropy and/or magnetic saturation). In this method, the motor control signals are synthesized superposing high-frequency signals with the fundamental excitation allowing to estimate the rotor position even at standstill (Briz and Degner, 2011). Although FES methods have limitations to operate close to zero speed, they have been expansively used in several applications that do not require very low-speed operation or when the rotor saliences are inappropriate for HFSI methods (Pacas, 2011).

In this regard, sliding mode (SM) observers have become a promising alternative for FES methods applied to PMSMs due to the observation accuracy and the robustness with respect to bounded disturbances and parameter uncertainties (Bernardes, Foletto Montagner, Grundling, and Pinheiro, 2014; Hamida, Glumineau, and De Leon, 2013; Salgado, Chairez, Bandyopadhyay, Fridman, and Camacho, 2014; Slotine, Hedrick, and Misawa, 1986; Yan and Utkin, 2002). However, it is well known that the major drawback in SM approach is the chattering phenomenon (Levant, 2010). Thus, filters and continuous switching functions are often used to mitigate the chattering (Hung, Gao, and Hung, 1993; Kim, Son, and Lee, 2011; Yuan et al., 2013). On the other hand, a solution to overcome this challenge, without compromising the observation performance, is to use high-order sliding mode (HOSM) observers (Levant, 1993, 2003). HOSM can considerably reduce the chattering keeping the first order SM properties. However, this approach requires to determine the switching function derivative

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(s) which makes the implementation more complex when compared to the first-order SM. The exception is the second order SM approach which is known as super-twisting algorithm (STA).

STA was proposed by Levant (1993). Since then, this approach and similar ones have been widely applied to state estimation and control (Alwi and Edwards, 2014; Basin and Rodriguez Ramirez, 2014; Di Gennaro, Rivera, and Castillo-Toledo, 2010, 2014; Ezzat, de Leon, Gonzalez, and Glumineau, 2010; Kuntanapreeda, 2015; Kunusch, Puleston, Mayosky, and Fridman, 2013; Lascu, Boldea, and Blaabjerg, 2013; Liu, Laghrouche, Harmouche, and Wack, 2014; Moreno, 2009; Utkin, 2013; Utkin and Poznyak, 2013). In addition, this algorithm has been enhanced by using variable gains (Davila, Moreno, and Fridman, 2010; Gonzalez, Moreno, and Fridman, 2010). It is important to point out that variable gains allow to attenuate the chattering, compensating perturbations whose bounds are time-variant. Recently, variable gains STA has been found in several applications (Davila et al., 2010; Evangelista, Puleston, Valenciaga, and Fridman, 2013, 2014; Gonzalez et al., 2010, Gonzalez, Moreno, and Fridman, 2012; Mishra and Kurode, 2014; Zhan, Guo, and Zhu, 2013). Even though these methods present successfully the use of STA with variable gains in different applications, they are developed in continuous-time domain. However, the control and state estimation strategies for industrial applications, especially for electrical motor drives, are implemented using microcontrollers and digital signal processors (DSP) which demand discrete-time algorithms. As a consequence, SM approaches in discrete-time domain have gained more attention from researchers in the last few decades (Salgado et al., 2014). Since the discrete-time approach differs from continuous-time one with respect to the sliding motion in the vicinity of sliding surface (i.e the motion is often called quasi-sliding mode) (Bartoszewicz, 1998). In regard to STA, Dominguez, Navarrete, Meza, Loukianov, and Canedo (2014) present an algorithm based on (Salgado et al., 2014). The proposed approach is used to estimate sinusoidal back electromotive forces (EMFs) for classical PMSMs. Although, the sinusoidal back-EMF is properly obtained, the gains are tuned just for the fundamental harmonic component, which in turn requires low constant gains (limited rotor speed range). This method with constant gains is inadequate for estimating nonsinusoidal back-EMFs in variable rotor speed applications due to the chattering increase.

Thus, differently from the above-mentioned methods that have been proposed in continuous-time domain or have been presented for sinusoidal back-EMF estimation, a new discrete-time STA (DTSTA) sliding mode observer with variable gains for PMSM drives is proposed in this paper. This observer allows to estimate the nonsinusoidal back-EMFs which are required for the nonsinusoidal sensorless vector control in a wide rotor speed range. In other words, the estimated back-EMFs are used to derive the rotor speed, the synchronous reference frame and the decoupling terms.

Fig. 1 shows the digital implementation overview of the observer and the sensorless vector control. In this observer, the back-EMFs are assumed as bounded and unmatched disturbances. Hence, the STA gains are adjusted online according to the rotor speed. As a result, the chattering that is caused by the digital implementation and the parameter uncertainties is significantly reduced in all operational speed range. Moreover, the stability analysis of the observer is investigated by means of Lyapunov theory for discrete-time systems. This analysis provides numerical tools to evaluate the finite-time convergence and the observer design. Finally, simulation and experimental results reveal the excellent performance and effectiveness of the proposed observer as well as the sensorless vector control.

The rest of the paper is organized as follows. In Section 2, the proposed observer is described in details. In the following, the sensorless vector control with hybrid orientation is presented in Section 3. In Section 4, simulation and experimental results are shown to demonstrate the effectiveness and the estimation accuracy of the proposed method. Then, conclusions are summarized in Section 5. Finally, the stability analysis of the proposed observer is investigated in Appendix A.

2. DTSTA SM observer with variable gains

The discrete-time linear time-invariant model of the PMSM that is shown in Fig. 1 can be expressed in stationary reference frame by

$$\mathbf{i}_{\alpha\beta}(k+1) = \left(1 - \frac{T_s R_s}{L_s}\right)\mathbf{i}_{\alpha\beta}(k) + \frac{T_s}{L_s}\left(\mathbf{v}_{\alpha\beta}(k) - \mathbf{e}_{\alpha\beta}(k)\right) \tag{1}$$

where $\mathbf{i}_{\alpha\beta} = [i_\alpha\ i_\beta]^T$ are the stator currents, R_s is the stator resistance, L_s is the stator inductance, T_s is the sampling time period, $\mathbf{v}_{\alpha\beta} = [v_\alpha\ v_\beta]^T$ are the stator phase voltages, and $\mathbf{e}_{\alpha\beta} = [e_\alpha\ e_\beta]^T$ are the phase back-EMFs. Here, it is assumed that the motor has surface-mounted permanent magnets (PMs).

Now, assuming that the phase back-EMFs in (1) are bounded and unmodelled disturbances, a stator current state observer derived from (1) can be written as

$$\hat{\mathbf{i}}_{\alpha\beta}(k+1) = \left(1 - \frac{T_s R_s}{L_s}\right)\hat{\mathbf{i}}_{\alpha\beta}(k) + \frac{T_s}{L_s}\mathbf{v}_{\alpha\beta}(k) - \mathbf{u}_{\alpha\beta}(k) \tag{2}$$

where $\hat{\mathbf{i}}_{\alpha\beta} = [\hat{i}_\alpha\ \hat{i}_\beta]^T$ are the estimated stator currents, and $\mathbf{u}_{\alpha\beta} = [u_\alpha\ u_\beta]^T$ are the forcing terms. Here, the observer aims to obtain the forcing terms that minimize the observation error. As a result, a back-EMF estimation can be achieved.

In this paper, the forcing terms are determined from a novel DTSTA with variable gains that can be expressed as

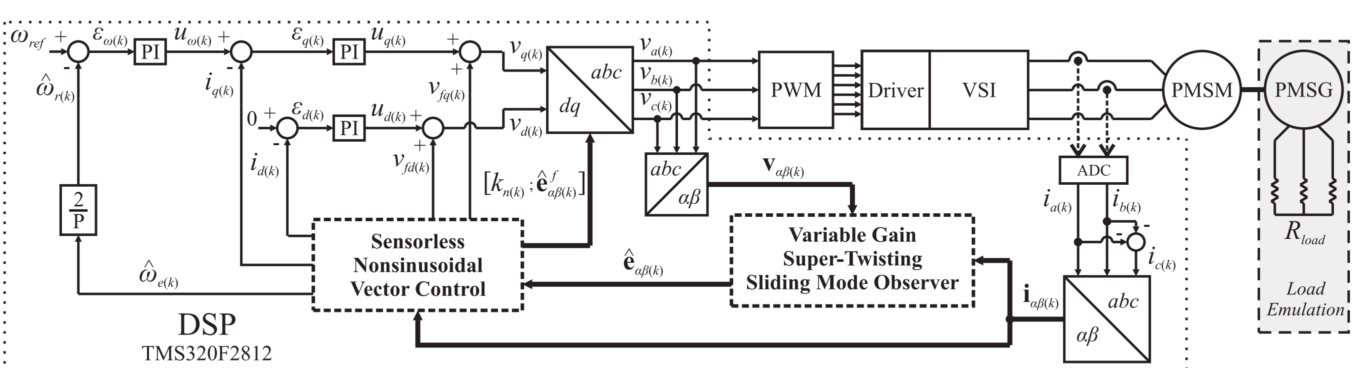

Fig. 1. Block diagram of the sensorless nonsinusoidal vector control using the proposed observer.