Speed Estimation and Fault Detection for PMSM via Quasi Sliding Modes

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Abstract: The paper presents a cascade control scheme for Permanent Magnet Synchronous Motors (PMSMs) based on a novel reduced order state observer which provides accurate speed tracking performance. The asymptotic vanishing of both the observation error and the speed tracking error is proven. The observer design allows a residual signal to be defined, able to detect faults using Park's vector currents. The performance of the proposed solution is evaluated by simulation using the model of a commercial PMSM drive.

Keywords: Fault detection, Variable structure control, Observers, Permanent magnet synchronous motors, Nonlinear control.

1. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) are widely used in industry, particularly in motion control applications in the low and medium power range (e.g. robotics and machine tool drives) due to their fast dynamical response, high torque to weigh ratio, linear dependence of the torque on one component of the current in a suitable reference frame, simple construction and easy maintenance (Rossi and Tonielli, 1994; Xu and Rahma, 2007; Shyu et al., 2002; Ebrahimi et al., 2009).

With advances in digital technology over the last several years, adequate data processing capability is now available on cost-effective DSP-based platforms, enabling the integration of control and fault diagnosis procedure able to increase PMSMs performance, raise their lifetime and lower their high costs. Nevertheless, the cost-effectiveness of any proposed approach for control and fault detection has to be addressed. Indeed, the cost associated with mechanical sensors and expensive hardware required by computational complexity is significant in particular for mass-produced motors in the kW range. Therefore, control and fault diagnosis of motors based on readily available sensors and on algorithms simple enough to be executed using low-cost industrial DSP in real-time appears susceptible of industrial interest due to its cost-effective nature and wide applicability to a large class of motors (Kliman et al., 1997; Aller et al., 2002; Han and Song, 2003).

Considering control issues requiring specific attention in electric drive systems, it is well known that electromechanical parameters are subject to significant variations. A nonlinear control strategy widely recognized and successfully applied in recent years is Variable Structure Control (VSC) (Pisano et al., 2008; Utkin et al., 1999; Sabanovic et al., 2002; Chern and Wong, 1995; Hung et al., 1993; Young et al., 1999.; Utkin, 1993; Yan et al., 2000). Indeed, VSC methods provide robustness to matched uncertainties (Utkin, 1992) (Zinober, 1994), and are computational simpler with respect to other robust control approaches, thus well suited for low-cost DSP implementation. VSC schemes are typically affected by chattering of the control signal but, as discussed in (Bartolini et al., 2006; Utkin et al., 1999), this well-known implementation drawback of VSC does not cause difficulties for electric drives since the on-off operation mode is the only admissible one for power converters. For PMSM, the cascade control structure of the Field Oriented Control (FOC) is often usefully applied to achieve fast four quadrant operation, smooth starting and acceleration (Lin, 1997; Lin et al., 1997; Lin and Chiu, 1997; Lin and Lin, 1999; Ghribi and Le-Huy, 1994). FOC is implemented with two current controllers in inner control loops and a speed controller in an outer control loop. The speed controller provides the reference current for one of the two inner current control loops; this reference current corresponds to the required motor torque. As argued in (Utkin et al., 1999), VSC techniques cannot be applied for the outer speed control loop, since the reference input of the inner current control loop should have bounded time derivatives.

To overcome this problem, different approaches have been followed, such as, for instance, the 'direct speed control' (Utkin et al., 1999) and the 'second-order sliding-mode technique' (Pisano et al., 2008). Both techniques, however, share a formulation in the continuous time framework, while the practical implementation on a low-cost DSP of a real motor drive claims for a more appropriate formulation of the problem in a sampled-data systems context. A possible solution is presented in this paper, where a control system based on Discrete-Time VSC (DTVSC) (Chan, 1997; Chen et al., 2001; Corradini and Orlando, 1997; Furuta, 1993; Kaynak and Denker, 1993; Lee and Oh, 1998) is designed. The introduction of DTVSC, in fact, allows to take directly into account the issue of control law digitalization and to ensure robustness with respect to disturbances and model uncertainties. Moreover, decoupling and linearization of the nonlinear PMSM model is not required before the application of the VSC technique.

High performance control of PMSM drives also requires the knowledge of the shaft speed (Vas, 1990; Bartolini et al., 2003). The standard backward-difference method to speed estimation, using sampled position measurements provided by a digital incremental encoder, gives high errors in particular at low speed (Khadim et al., 1993; Fujita and Sado, 1992). To overcome the problem of ineffective speed measurement, different results have been given considering the use of nonlinear observers (Misawa and Hedrick, 1989; Rajamani, 1998), in particular based on high-gain, adaptive or sliding mode control (Utkin, 1992; Tornambè, 1992; Slotine et al., 1987; Drakunov, 1992).

In this paper, a novel observer of the speed variable is presented, and a coupled controller based on quasi sliding modes is proposed. The asymptotic vanishing of both the observation error and the speed tracking error is proved. Summing up, the features of the DTVSC technique combined with the state observer are exploited in this work to design the cascade-based architecture shown in Fig. 1, where it can be identified the external observer-speed control loop and the two internal current control loops (the meaning of the signals and blocks shown in Fig. 1 will be explained throughout this paper).

A further feature of the proposed scheme of Fig. 1 is that the observer designed for speed estimation also allows a residual signal to be defined, able to detect fault using Park's vector currents. Early detection of faults is desirable for online condition assessment, product quality assurance and improved operational efficiency of PMSMs. Indeed, fault detection issues are receiving increasing attention in recent years. Various model-based approaches have been developed (Chen and Patton, 1999), and in particular observer-based techniques constitute a very active research thrust. The comprehensive survey paper (Frank, 1987) provides an overview of observer-based approaches, and a number of results have been established (see e.g. (Shields, 2005; Xu and Zhang, 2004) and the references therein). In particular, sliding mode well-established method for handling disturbances and modeling uncertainties has been employed to develop robust observer for fault detection (Tan and Edwards, 2002; Yan and Edwards, 2007). A noticeable feature of the control approach presented in this paper is that it offers a simple fault diagnosis method that can be implemented at no cost using the readily available electric motor inverter sensor and the DSP control unit.

The paper is organized as follows. The motor dynamics is presented in Section 2. In Section 3 some preliminaries are given and details on the considered observer based sliding mode control and fault detection are discussed. Results on numerical tests are reported in Section 4. The paper ends with comments on the performance of the proposed controller.

2. MOTOR DYNAMICS

In the $(d,\, q)$ reference frame, synchronously rotating with the motor rotor, the electrical equations of motion of a permanent magnet synchronous motor can be written as (Shi and Lu, 1996; Utkin et al., 1999):

$$\frac{di_d}{dt} = -\frac{R}{L} i_d + \omega_e i_q + \frac{1}{L} u_d \tag{1}$$

$$\frac{di_q}{dt} = -\frac{R}{L} i_q - \omega_e i_d - \frac{1}{L}\lambda_0 \omega_e + \frac{1}{L} u_q \tag{2}$$

where i_d and i_q are the $d-axis$ and $q-axis$ stator currents, respectively; u_d and u_q are the $d-axis$ and $q-axis$ stator voltages, respectively; R is the winding resistance and $L = L_d = L_q$ is the winding inductance on axis d and q ; λ_0 is the flux linkage of the permanent magnet and ω_e is the electrical angular speed.

The electrical torque τ_e and the mechanical power P of the motor are given by $\tau_e = K_t i_q$ and $P = \tau_e \omega_r$, respectively, in which $K_t = \frac{3}{2}\lambda_0 N_r$ is the torque constant with N_r the number of pole pairs and ω_r is the mechanical angular speed of the motor rotor. The developed torque of the motor is proportional to the i_q current because of the assumption that there is no reluctance torque in the considered PMSM Vas (1990).

The mechanical motion equation of the motor is described by:

$$J\frac{d\omega_r}{dt} + B\omega_r = \tau_e \tag{3}$$

$$\frac{d\theta_r}{dt} = \omega_r \tag{4}$$

where J is the mechanical inertia of the motor, B is the coefficient of viscous friction and θ_r denotes the mechanical angular position of the motor rotor.

For the electrical angular position/speed and the mechanical angular position/speed, the following relationships hold: $\omega_e = N_r \omega_r$ and $\theta_e = N_r \theta_r$.

3. CONTROL DESIGN AND FAULT DETECTION

Technical aspects of the proposed solution are described in the following where same preliminaries are first considered. Details on the design of the control strategy are given in Subsection 3.2 and the faulty case is considered in Subsection 3.3.

3.1 Preliminaries

Control design methods performed in the $(d,\, q)$ coordinates are called field-oriented control which consists of controlling the stator currents represented by a vector (vector control) Vas (1990). The field-oriented control scheme of Fig. 1 is based on the measure of two phase currents (i_a and i_b) and of the motor rotor position (θ_r) given by encoder measurements. The DTVSC technique is exploited to design the external observer-speed control loop and the two internal current control loops. The Park coordinate transformation and its inverse are used to transform the dynamic motor model from the phase frame, i.e. the $(a,\, b,\, c)$ coordinate frame to the rotor frame, i.e. the (d, q) coordinate frame and vice versa.

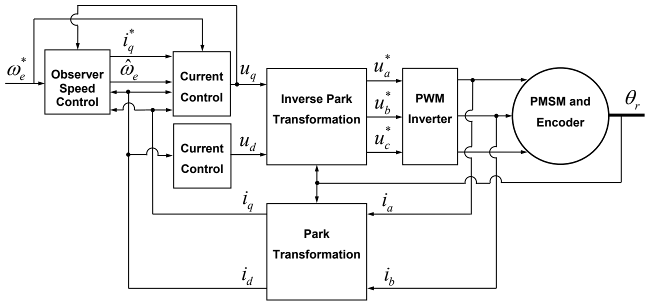

Fig. 1. Block scheme of the control system.

3.2 Observer-based Control Design

The discretization of the model equations with a sampling time T_c according to standard techniques gives:

$$\begin{aligned} \omega_e(k+1) &= A_\omega \omega_e(k) + B_\omega K_t i_q(k) \\ i_d(k+1) &= A_i i_d(k) + B_i u_d(k) + g_1(\omega_e, i_q, k) \\ i_q(k+1) &= A_i i_q(k) + B_i u_q(k) - g_2(\omega_e, i_d, k) \end{aligned} \tag{5}$$

with

$$A_\omega = e^{-\frac{B}{J}T_c},\ B_\omega = -\frac{1}{J}\int_0^{T_c} e^{-\frac{B}{J}\tau} d\tau$$

$$A_i = e^{-\frac{R}{L}T_c},\ B_i = -\frac{1}{L}\int_0^{T_c} e^{-\frac{R}{L}\tau} d\tau$$

$$g_1(\omega_e, i_q, k) = \omega_e(k) i_q(k) T_c; \tag{6}$$

$$g_2(\omega_e, i_d, k) = \omega_e(k)(i_d(k) + \frac{\lambda_0}{L})T_c. \tag{7}$$

Since currents are directly measured, while speed ω_e is not available for direct measurement, the output variable $y(k)$ of the plant (5) is:

$$y(k) = \left[\, i_d(k)\ \ i_q(k)\, \right]^T .$$

Define the following error variables:

$$e_\omega(k) = \omega_e(k) - \omega_e^*(k) \tag{8}$$

$$e_q(k) = i_q(k) - i_q^*(k) \tag{9}$$

where $\omega_e^*(k)$ is the given reference value for the angular velocity, and $i_q^*(k)$ will be defined in the following. Moreover define:

$$\gamma = \frac{\lambda_0}{L}; \quad B = B_\omega K_t. \tag{10}$$

Assumption 3.1. As a consequence of physical limits of devices, a bound is available for the maximal currents supplied. Therefore it exists a bound i_{dM} such that

$$|i_d(k)| \le i_{dM}.$$

Define the following observer of the speed variable:

$$\begin{cases} z(k+1) &= A_\omega \hat{\omega}_e(k) + u(k) \\ \hat{\omega}_e(k+1) &= H\left[A_i i_q(k) + B_i u_q(k) - g_2(\hat{\omega}_e, i_d, k)\right] + \\ & \quad + A_\omega \hat{\omega}_e(k) + u(k) + v(k) \end{cases} \tag{11}$$

where $\hat{\omega}_e(k)$ is the estimate of the angular velocity $\omega_e(k)$. Define the following discrete-time sliding surfaces:

$$s_\omega(k) = \hat{e}_\omega(k) + \lambda_\omega \hat{e}_\omega(k-1) = 0 \tag{12}$$

$$s_{iq}(k) = e_q(k) = 0 \tag{13}$$

$$s_{id}(k) = i_d(k) = 0 \tag{14}$$

where $\lambda_\omega \in (-1, 1)$, $\hat{e}_\omega(k) = \hat{\omega}_e(k) - \omega_e^*(k)$.

The following result can be given.

Theorem 1. For the plant (5) in the fault free case, the observer (11) guarantees the asymptotic vanishing of the observation error $\epsilon_\omega(k)$:

$$\epsilon_\omega(k) = e_\omega(k) - \hat{e}_\omega(k) \tag{15}$$

and of the tracking error $e_\omega(k)$ with respect to the reference variable $\omega_e^*(k)$ if:

- $v(k)$ is designed as:

$$v(k) \;=\; H\hat{\omega}_e(k)\left[i_d(k) + \gamma\right] T_c \tag{16}$$

$$H = -\theta \frac{1}{(i_{dM} + \gamma)T_c}; \quad 0 < \theta < 1 \tag{17}$$

- $u(k)$ is designed as:

$$u(k) \;=\; \left[B - HA_i\right] i_q(k) - HB_i u_q(k) \tag{18}$$

- $i_q^*(k)$ has the expression:

$$Bi_q^*(k) \;=\; \omega_e^*(k+1) - A_\omega \hat{\omega}_e(k) - \lambda_\omega(\hat{\omega}_e(k) - \omega_e^*(k)) \tag{19}$$

- $u_q(k)$ has the expression:

$$\begin{aligned} B_i u_q(k) =& i_q^*(k+1) - A_i i_q(k) + \hat{\omega}_e\left(i_d(k) + \gamma\right) T_c \\ &+ \lambda_\omega(i_q(k) - i_q^*(k)) \end{aligned} \tag{20}$$

- $u_d(k)$ is designed as:

$$B_i u_d(k) = -A_i i_d(k). \tag{21}$$

Proof. The dynamics of the observation error $\epsilon_\omega(k)$ is given by:

$$\epsilon_\omega(k+1) = A_\omega \epsilon_\omega(k) + Bi_q(k) - Hi_q(k+1) - v(k) - u(k).$$

Inserting the plant model and the expressions (16),(18) one gets:

$$\epsilon_\omega(k+1) = \left[A_\omega + H(i_d(k) + \gamma)T_c\right] \epsilon_\omega(k)$$

Since $\gamma \gg i_{dM}$ $\forall k \ge 0$, it is straightforward to verify that

$$0 < \lambda(k) = A_\omega - \theta \frac{i_d(k) + \gamma}{i_{dM} + \gamma} < 1 \quad \forall k \ge 0$$

i.e.

$$\epsilon_\omega(k+1) = \lambda(k)\epsilon_\omega(k)$$

which proves that the observation error asymptotically vanishes.

Consider now the sliding surface (12). It holds:

$$\begin{aligned} s_\omega(k+1) =& A_\omega \hat{\omega}_e(k) + Bi_q(k) - HT_c \epsilon_\omega(k)\left[i_d(k) + \gamma\right] \\ &- \omega_e^*(k+1) + \lambda_\omega\left[\hat{\omega}_e(k) - \omega_e^*(k)\right]. \end{aligned} \tag{22}$$

After the vanishing of the observation error (just proved), setting $i_q(k) = i_q^*(k)$ according to the expression (19) produces $s_\omega(k+1) = 0$. Finally, the tracking of $i_q^*(k)$ by the current $i_q(k)$ can be ensured setting $s_q(k+1) = 0$, i.e. designing $u_q(k)$ according to (20). This ensures that $i_q(k) = i_q^*(k)$ after the vanishing of the observation error, i.e. that $\hat{\omega}_e(k)$ tends to $\omega_e^*(k)$ asymptotically. This in turn guarantees that the tracking of the reference variable, i.e. that $\omega_e(k)$ tends to $\omega_e^*(k)$ asymptotically. Finally, the control law (21) ensures the finite time vanishing of $s_{id}(k)$.

3.3 The faulty case

In the case when an eventual constant abrupt fault of the form

$$f(k) = F step(k - k_f); \quad F \in R; \quad t_f > 0 \tag{23}$$

affects measurements of the current i_q, k_f being the occurrence time of the fault, F its intensity, and $step(k)$ the unitary step function, the last component of the output variable which can be measured is:

$$\tilde{i}_q(k) = i_q(k) + f(k) \tag{24}$$

and the discrete-time model assumes the form

$$\begin{aligned}\omega_e(k+1) &= A_\omega \omega_e(k) + B_\omega (K_t \tilde{i}_q(k) - \tau_\ell) - B_\omega K_t f(k) \\ i_d(k+1) &= A_i i_d(k) + B_i u_d(k) + g_1(\omega_e, \tilde{i}_q, k) + \omega_e(k) T_c f(k) \\ \tilde{i}_q(k+1) &= A_i \tilde{i}_q(k) + B_i u_q(k) - g_2(\omega_e, i_d, k) \\ &\quad - A_i f(k) + f(k+1).\end{aligned} \tag{25}$$

It can be easily verified that the proposed observer does behave as a residual generator, according to the following result.

Corollary 2. For the plant (25) in the eventual presence of faults (23) affecting measurements of the current $i_q(k)$, the observer (11) guarantees that if a fault has occurred at a time instant $\bar{k}$, then the residual signal

$$r(k+1) = \hat{e}_\omega(k+1) = \hat{\omega}_e(k+1) - \omega_e^*(k+1) \neq 0 \quad k > \bar{k} \tag{26}$$

provided that $\bar{k}$ is large enough such that the initial transient is extinguished.

Proof. According to the plant model (25), in the presence of faults one has

$$\begin{aligned} r(k+1) &= \hat{\omega}_e(k+1) - \omega_e^*(k+1) \\ &= -H A_i f(k) + B \tilde{i}_q(k) - B f(k) - \omega_e^*(k+1) \\ &\quad + A_\omega \hat{\omega}_e(k). \end{aligned} \tag{27}$$

In the fault free case, whenever $i_q(k) = i_q^*(k)$ the previous expression gives:

$$r(k+1) = -\lambda_\omega r(k)$$

which proves that the residual signal vanishes with dynamics assigned by λ_ω. On the contrary, after the occurrence of a fault one gets:

$$r(k+1) = \lambda_\omega r(k) - H A_i f(k) - B f(k)$$

which proves the assert.

4. SIMULATION TESTS

The proposed controller has been tested by intensive simulations using the model of the Technosoft MBE.300.E500 PMSM shown in Fig. 2, as a preliminary step before experimental validation on the Technosoft MCK2812-Pro DSP motion control kit (Technosoft, 2009). The experimental setup is shown in Fig. 2. It is a combination of hardware and software and includes a DSP-based controller board, a power module, a PMSM equipped with a 500-line encoder and a software platform for development of motion control applications. All communication between PC and DSP board is done through the RS-232 interface using a real-time serial communication monitor resident in the DSP flash. The motor catalog electric and mechanical parameters are presented in Table 1. The performed speed-tracking tests are shown in Figs. 3 through 6. In these figures, the performance produced by the proposed control scheme are illustrated for the motor following a reference trajectory given by a sinusoidal velocity profile. A fault of amplitude $F = 0.1$ has been considered to occur at $k = 0.1\ s$.

Table 1. Technosoft MBE.300.E500 PMSM parameters (Technosoft, 2009).

Coil dependent parameters		
Phase-phase resistance	ohm	8.61
Phase-phase inductance	mH	07.13
Back-EMF constant	V/1000 rpm	3.86
Torque constant	mNm/A	36.8
Pole pairs	–	1
Dynamic parameters		
Rated voltage	V	36
Max. voltage	V	58
No-load current	mA	73.2
No-load speed	rpm	9170
Max. cont. current (at 5000 rpm)	mA	913
Max. cont. torque (at 5000 rpm)	mNm	30
Max. permissible speed	rpm	15000
Peak torque (stall)	mNm	154
Mechanical parameters		
Rotor inertia	$Kgm^2 \cdot 10^{-7}$	11
Mechanical time constant	ms	7

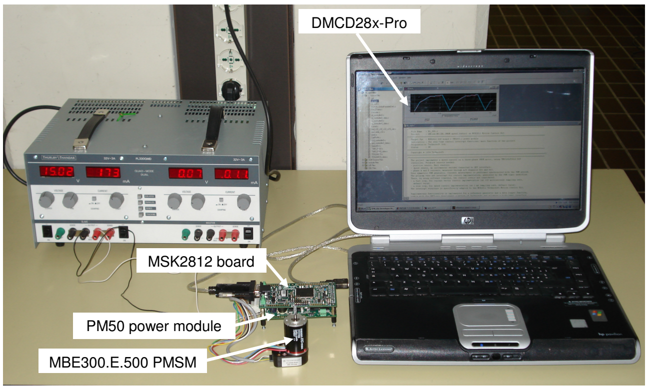

Fig. 2. Experimental setup

The tracking error is reported in Fig. 3 and the observation error is shown in Fig. 4.

The Fig. 5 shows the residual signal, while Fig. 6 reports the sliding surface $s_q(k)$ (8).

In all the above simulations, the sampling frequency has been selected as 10 kHz according to the real device specifications.

5. CONCLUDING REMARKS

In this paper problems of speed control and fault detection for PMSMs have been addressed. The considered nonlinear control scheme is based on the cascade implementation of discrete-time VS controllers and makes use of an observer estimating the angular speed unavailable to direct measurement. The proposed observer based sliding control ensures the asymptotic vanishing of both the observation error and the speed tracking error. The observer design also allows a residual signal to be defined, able to detect fault using Park's vector currents. Conditioning monitoring and fault detection of electric motors are quite vital for

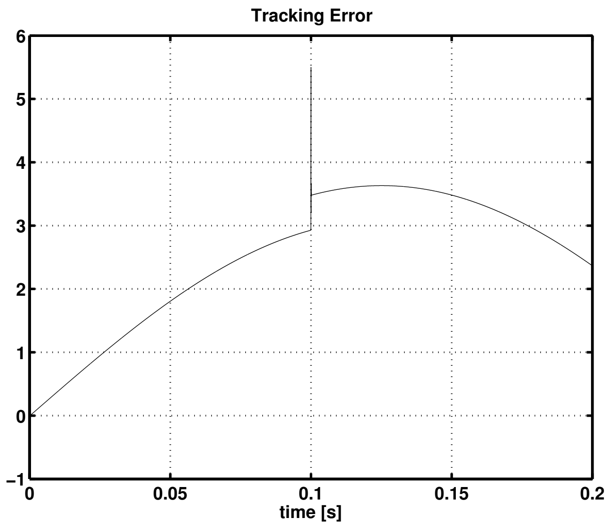

Fig. 3. Tracking error $e_\omega(k)$

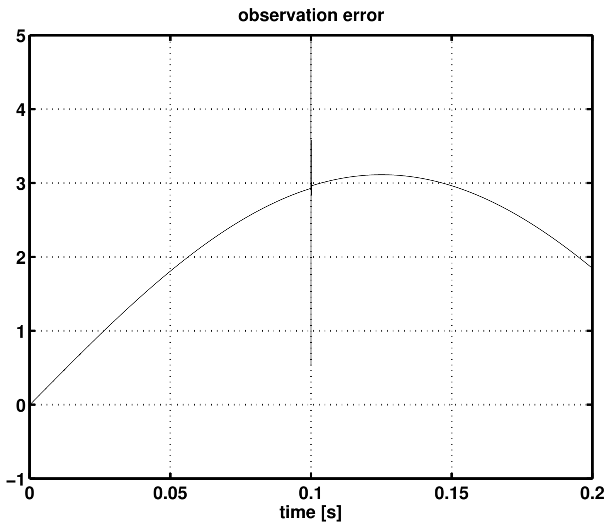

Fig. 4. Observation error $\epsilon_\omega(k)$

safety and cost-effective maintenance. A noticeable feature of the proposed fault detection method is that it is based on readily available drive hardware and no additional cost is necessary. The presented solution has been validated by simulations on the model of a commercial PMSM drive. Simulations show good speed trajectory tracking performance as well as fault detection capability.

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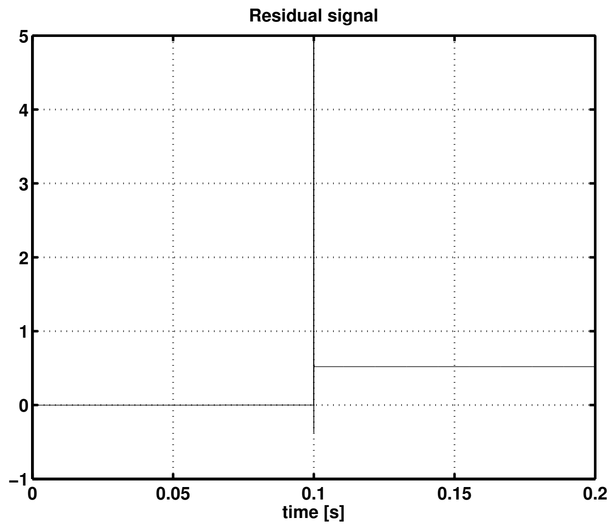

Fig. 5. Residual signal for a fault occurring at $k = 0.1$ s

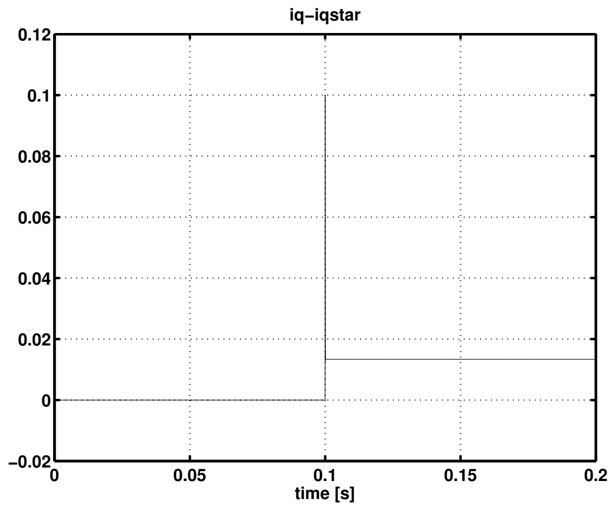

Fig. 6. Sliding surface $s_q(k)$ (8)

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