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Speed control of Five-Phase IPMSM through PI, SMC and FITSMC approaches under normal and open phase faulty conditions

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ABSTRACT

This paper focuses on speed control of Five-Phase interior permanent magnet synchronous motor (IPMSM) through proportional-integral (PI) controller, sliding mode control (SMC) and novel fractional integral terminal sliding mode control (FITSMC) approaches under normal and open one-phase and two-phase faulty conditions. The SMC and FITSMC design processes have been deeply illustrated, while the stability of the aforementioned controllers has been guaranteed via Lyapunov theory. These ones are all designed based on rotor speed error which is generated from its measured and referenced values. Simulation results confirm the effectiveness and feasibility of the proposed control approaches in the fault tolerant control strategy and normal drive for Five-Phase IPMSM.

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Five-Phase IPMSM; SMC; FITSMC; open phase faulty conditions

1. Introduction

Because of multi-phase permanent magnet synchronous motors (PMSMs) high-power density, less current per phases, less torque ripples and fault tolerance capability, speed-drives based on these motors are receiving more attention in the last decade in some sensitive applications such as: aerospace, electric vehicles, marine and ships [1–5]. These motors control and supply techniques have blossomed from the huge development of power electronics. Nowadays, various real-time complex controllers can be implemented using FPGAs (Field Programmable Gate Arrays) and DSPs (Digital Signal Processors) [6,7].

The PMSM can be classified in two main types: interior PMSM (IPMSM) and surface mounted PMSM (SPMSM). The IPMSM usually has a higher torque density due to its extra reluctance torque. Another advantage of the IPMSM is better flux-weakening capability. Despite of these advantages, IPMSM drive and control processes are more complicated than the SPMSM's due to its rotor saliency [8].

Vector control is a common strategy for the multi-phase IPMSMs. This strategy can be classified in two types, Direct Torque Control (DTC) [9,10] and Field Oriented Control (FOC) [11,12]. The DTC aims to control the torque producing flux vector and FOC aims to control the current vector. The FOC has a very good performance in both transient and steady-state conditions [3]. The Five-Phase IPMSM drive with the FOC technique is core of this study. The FOC strategy allows handling the Five-Phase IPMSM like a DC motor by decoupling the Five-Phase IPMSM model

equations from stationary reference frame $abcde$ to rotary reference frame $d_1q_1d_2q_2$ with a zero-sequence variable [1].

PMSM motors faults can be divided in to the four main groups as [13]:

- mechanical faults such as bearing damages and rotor eccentricities;
- magnetic faults such as demagnetization;
- electrical faults like open phase fault or short circuits;
- other drive equipment's faults such as sensors faults.

This study is focused on developing a controller to drive and compensate the open phase fault in a Five-Phase IPMSM. The open phase fault phenomenon is the most common fault [14] which occurs in supply disconnection or in the winding connection failure.

Sliding mode control (SMC) is one of most powerful control technique for linear and nonlinear systems which show high accuracy and robust behaviour against system uncertainties, disturbances and noises. Due to these advantages, the SMC is used in many linear, nonlinear, uncertain, stochastic and faulty systems etc. [15–17]. The SMC can be designed in linear (conventional) and nonlinear (terminal) classes based on the sliding surface types. The terminal sliding mode controller (TSMC) has relatively fast transient response and small tracking error in comparison with the conventional SMC [18].

The SM and TSM controllers have been developed for the Three-Phase PMSM in various literatures [19–21]. Recently, some FTC strategies based on the

SMC have been proposed for Five-Phase PMSM in normal and faulty conditions under single [22] and two open phase faults [23]. To the author's best knowledge, up to present time there is no research about using the TSM controller for Five-Phase IPMSM under open phase faults.

In this paper, we propose a novel TSM controller for Five-Phase IPMSM in normal and open phased conditions for the first time. The main idea of this method is to keep same magnetomotive force (MMF) in normal and open phase fault conditions. For this purpose, a novel fractional integral terminal sliding mode controller (FITSMC) is proposed. The controller utilizes a fractional integral terminal sliding surface for extra convergence. Moreover, the common SMC and proportional-integral (PI) controllers are designed to compare the results. Inspired by the above discussions, this study contains the following efforts and novelties:

- a novel FITSMC technique is developed for the Five-Phase IPMSM which has small tracking error in comparison with the SMC and PI controllers;
- both single and double open phase faults oscillations has been restrained with negligible steady-state error.

This research is organized in nine sections including the introduction as follows. Section 2, introduces model of the Five-Phase IPMSM. A fault tolerant strategy for one open phase for the Five-Phase IPMSM is presented in Section 3. In Section 4, a fault tolerant strategy is developed for two open phases fault. Sections 5 and 6 deal with the SMC and a novel FITSMC designing. The closed-loop system configuration is presented in Section 7. Section 8, devoted to simulations and results of the proposed methods and in the final section conclusion is presented.

2. Model of Five-Phase IPMSM

The mechanical model of the Five-Phase IPMSM in the $d_1q_1d_2q_2$ reference frame is given by [1]:

$$\begin{aligned}
 V_{d1} &= R_s i_{d1} + \frac{d\psi_{d1}}{dt} - \omega_e \psi_{q1}, \\
 V_{q1} &= R_s i_{q1} + \frac{d\psi_{q1}}{dt} + \omega_e \psi_{d1}, \\
 V_{d2} &= R_s i_{d2} + \frac{d\psi_{d2}}{dt}, \\
 V_{q2} &= R_s i_{q2} + \frac{d\psi_{q2}}{dt}, \\
 T_e &= \frac{5P}{2} (\psi_r i_{q1} + (L_d - L_q) i_{d1} i_{q1}), \\
 T_e &= J \frac{d\omega_m}{dt} + F\omega_m + T_m,
 \end{aligned} \tag{1}$$

where $i_{q1}, i_{d1}, i_{q2}, i_{d2}$ are the $d_1q_1d_2q_2$ -axis stator currents, $V_{d1}, V_{q1}, V_{d2}, V_{q2}$ are the stator voltages, R_s is

the stator resistance, $\psi_{q1}, \psi_{d1}, \psi_{q2}, \psi_{d2}$ are the stator flux-linkage components, L_d and L_q are the d_1q_1 -axis inductances, ω_e is the electrical angular velocity, T_e is the electrical torque, P is the number of poles, J is the rotational inertia, F is the friction factor and T_m is the motor load respectively.

Dynamics of the stator flux-linkage in the $d_1q_1d_2q_2$ reference frame is given by:

$$\begin{aligned}
 \psi_{d1} &= L_d i_{d1} + \psi_r, \\
 \psi_{q1} &= L_q i_{q1}, \\
 \psi_{d2} &= L i_{d2}, \\
 \psi_{q2} &= L i_{q2}, \\
 L_q &= L + L_{mq}, \\
 L_d &= L + L_{md},
 \end{aligned} \tag{2}$$

where L is the d_2, q_2 -axis inductance, L_{mq}, L_{md} are the d_1q_1 -axis mutual inductances and ψ_r is the rotor permanent magnet flux-linkage.

Using (1) and (2), the Five-Phase IPMSM dynamics will be as:

$$\begin{aligned}
 \frac{d}{dt} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} &= \begin{bmatrix} -\frac{R_s}{L_d} & \omega_e \frac{L_d}{L_q} & 0 & 0 \\ -\omega_e \frac{L_d}{L_q} & -\frac{R_s}{L_d} & 0 & 0 \\ 0 & 0 & -\frac{R_s}{L_d} & 0 \\ 0 & 0 & 0 & -\frac{R_s}{L_d} \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} \\
 &+ \begin{bmatrix} \frac{1}{L_d} & 0 & 0 & 0 \\ 0 & \frac{1}{L_d} & 0 & 0 \\ 0 & 0 & \frac{1}{L_d} & 0 \\ 0 & 0 & 0 & \frac{1}{L_d} \end{bmatrix} \begin{bmatrix} v_{d1} \\ v_{q1} \\ v_{d2} \\ v_{q2} \end{bmatrix} \\
 &+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{\omega_e}{L_q} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ \psi_r \\ 0 \\ 0 \end{bmatrix}. \tag{3}
 \end{aligned}$$

The pseudo orthogonal transformation matrix that transfers the variables of the Five-Phase IPMSM into a reference rotating frame $d_1 - q_1 - d_2 - q_2$ is defined as equation (4) [1]. Equation (4) has been showed in note¹ section.

3. Open one-phase fault for Five-Phase IPMSM

Multi-phase machines are potentially fault tolerant to the open phase fault in closed-loop control. In other words, it is possible to keep the same MMFs without one or two phases. The stator MMFs in sinusoidal

distributions for stator windings are given as follows:

$$\begin{aligned} \text{MMF}_a &= 1/2NI_m \cos(\theta) \cos(\varphi), \\ \text{MMF}_b &= 1/2NI_m \cos\left(\theta - \frac{2\pi}{5}\right) \cos\left(\varphi - \frac{2\pi}{5}\right), \\ \text{MMF}_c &= 1/2NI_m \cos\left(\theta - \frac{4\pi}{5}\right) \cos\left(\varphi - \frac{4\pi}{5}\right), \\ \text{MMF}_d &= 1/2NI_m \cos\left(\theta + \frac{4\pi}{5}\right) \cos\left(\varphi + \frac{4\pi}{5}\right), \\ \text{MMF}_e &= 1/2NI_m \cos\left(\theta + \frac{2\pi}{5}\right) \cos\left(\varphi + \frac{2\pi}{5}\right). \end{aligned} \quad (5)$$

Here, N is the total number of turns for each phase, φ is the spatial angle, $\theta = \omega t$ and I_m is the amplitude of the phase currents.

The stator total MMF is sum of MMFs of all phases

$$\begin{aligned} \text{MMF}(\theta, \varphi) &= \text{MMF}_a + \text{MMF}_b + \text{MMF}_c + \text{MMF}_d \\ &+ \text{MMF}_e = \frac{5}{4}NI_m \cos(\theta - \varphi). \end{aligned} \quad (6)$$

Now, if phase “a” is opened as result of winding fault or disconnection in the power line, it is possible in infinite ways to keep same MMFs with remained four phases. One of the most popular ways is that assume $i_b^* = -i_d^*$, $i_c^* = -i_e^*$, therefore the currents can be obtained as follows

$$\begin{aligned} i_b^* &= -i_d^* = \frac{5I_m}{4(\sin(\frac{2\pi}{5}))^2} \cos\left(\theta - \frac{\pi}{5}\right), \\ i_c^* &= -i_e^* = \frac{5I_m}{4(\sin(\frac{2\pi}{5}))^2} \cos\left(\theta - \frac{4\pi}{5}\right). \end{aligned} \quad (7)$$

And the stator currents can be expressed as follow in $d_1 - q_1$ reference frame [1]:

$$\begin{aligned} i_b^* &= 1.382 \left(i_{q1} \cos\left(\theta - \frac{\pi}{5}\right) + i_{d1} \sin\left(\theta - \frac{\pi}{5}\right) \right), \\ i_c^* &= 1.382 \left(i_{q1} \cos\left(\theta - \frac{4\pi}{5}\right) + i_{d1} \sin\left(\theta - \frac{4\pi}{5}\right) \right), \\ i_d^* &= 1.382 \left(i_{q1} \cos\left(\theta + \frac{4\pi}{5}\right) + i_{d1} \sin\left(\theta + \frac{4\pi}{5}\right) \right), \\ i_e^* &= 1.382 \left(i_{q1} \cos\left(\theta + \frac{\pi}{5}\right) + i_{d1} \sin\left(\theta + \frac{\pi}{5}\right) \right). \end{aligned} \quad (8)$$

It can be rewritten in transfer matrix form as Equation (9)

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \\ i_d^* \\ i_e^* \end{bmatrix} = 1.382 \begin{bmatrix} 0 & 0 \\ \cos\left(\theta - \frac{\pi}{5}\right) & \sin\left(\theta - \frac{\pi}{5}\right) \\ \cos\left(\theta - \frac{4\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) \\ \cos\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{4\pi}{5}\right) \\ \cos\left(\theta + \frac{\pi}{5}\right) & \sin\left(\theta + \frac{\pi}{5}\right) \end{bmatrix} \times \begin{bmatrix} i_{q1} \\ i_{d1} \end{bmatrix}. \quad (9)$$

4. Open two-phase fault

Now if phase “a” and “b” are opened at the same time and considering $\ddot{i}_c + \ddot{i}_d + \ddot{i}_e = 0$, the remaining three phases can produce the same MMFs and the currents in this situation are shown in Equation (10) [1]:

$$\begin{aligned} \ddot{i}_c &= \frac{5I_m \cos\left(\frac{\pi}{5}\right)}{2(\sin(\frac{2\pi}{5}))^2} \cos\left(\theta - \frac{2\pi}{5}\right), \\ \ddot{i}_d &= \frac{5I_m \cos\left(\frac{\pi}{5}\right)^2}{2(\sin(\frac{2\pi}{5}))^2} \cos\left(\theta + \frac{4\pi}{5}\right), \\ \ddot{i}_e &= \frac{5I_m \cos\left(\frac{\pi}{5}\right)}{2(\sin(\frac{2\pi}{5}))^2} \cos(\theta). \end{aligned} \quad (10)$$

The stator currents can be expressed in $d_1 - q_1$ reference frame as follow:

$$\begin{aligned} \ddot{i}_c &= 2.2361 \left(i_{q1} \cos\left(\theta - \frac{2\pi}{5}\right) + i_{d1} \sin\left(\theta - \frac{2\pi}{5}\right) \right), \\ \ddot{i}_d &= 3.618 \left(i_{q1} \cos\left(\theta + \frac{4\pi}{5}\right) + i_{d1} \sin\left(\theta + \frac{4\pi}{5}\right) \right), \\ \ddot{i}_e &= 2.2361(i_{q1} \cos(\theta) + i_{d1} \sin(\theta)). \end{aligned} \quad (11)$$

It can be shown in transfer matrix form as Equation (12)

$$\begin{bmatrix} \ddot{i}_a \\ \ddot{i}_b \\ \ddot{i}_c \\ \ddot{i}_d \\ \ddot{i}_e \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 2.2361 \cos\left(\theta - \frac{2\pi}{5}\right) & 2.2361 \sin\left(\theta - \frac{2\pi}{5}\right) \\ 3.618 \cos\left(\theta + \frac{4\pi}{5}\right) & 3.618 \sin\left(\theta + \frac{4\pi}{5}\right) \\ 2.2361 \cos(\theta) & 2.2361 \sin(\theta) \end{bmatrix} \times \begin{bmatrix} i_{q1} \\ i_{d1} \end{bmatrix}. \quad (12)$$

To determine which phases are opened, a Fault Detection and Diagnose (FDD) unit is need to imply correspondent transform matrix to the closed-loop drive system.

5. SMC for Five-Phase IPMSM

In this section, a sliding mode speed controller is proposed for Five-Phase IPMSM.

According to Equation (1), by setting $i_{d1} = 0$ and assuming $k = (5/2)(P/2)(\psi_r)$, the torque equation of Five-Phase IPMSM can be shown as below:

$$\begin{aligned} T_e &= \frac{5P}{2} (\psi_r i_{q1} + (L_d - L_q) i_{d1} i_{q1}) \\ &= \frac{5P}{2} (\psi_r i_{q1}) = k i_{q1}. \end{aligned} \quad (13)$$

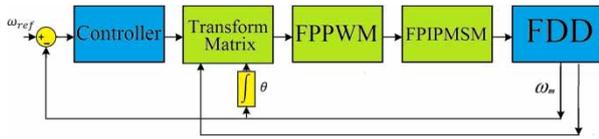


Figure 1. Schematic diagram of the speed control for Five-Phase IPMSM.

By assuming the parameters a, b, c as follow Equation (14) can be obtained

$$a = \frac{F}{J}, b = \frac{1}{J}, c = \frac{k}{J},$$

$$\dot{\omega}_m = -a\omega_m - bT_m + ci_{q1}. \quad (14)$$

Now, consider the following sliding surface

$$s_{c1} = e_c = \omega_{ref} - \omega_m. \quad (15)$$

Taking time derivative from s_{c1} and substituting

Table 1. Parameters of IPMSM.

Parameters	Unit	Values
Stator resistance (R_s)	Ω	2.875
q_1 -axis inductance (L_q)	H	0.0075
d_1 -axis inductance (L_d)	H	0.0025
$d_2 - q_2$ -axis inductance (L)	H	0.0007
Rotational Inertia (J)	Kg m	0.089
Friction Factor	F	0.005
Rotor PM flux (ψ_r)	Wb	0.175
Number of poles (np)	-	6
a	-	0.0562
b	-	11.2360
c	-	29.4944
ρ	-	1

Table 2. Parameters of PI.

Parameters	Values
k_p	100
k_i	2

Table 3. Parameters of SMC.

Parameters	Values
k_{swc1}	50
k_{c1}	1
ρ	1

Table 4. Parameters of FITSMC.

Parameters	Values
k_{swc2}	15
k_{c2}	0.5
μ	$\frac{1}{3}$
λ	1

(14), yields

$$\dot{s}_{c1} = \dot{\omega}_{ref} + a\omega_m + bT_m - ci_{q1}. \quad (16)$$

Now control law is proposed as

$$i_{q1} = \frac{1}{c}[a\omega_m + bT_m + \dot{\omega}_{ref} + k_{c1}s + k_{swc1}\text{sign}(s_{c1})]. \quad (17)$$

In order to reduce chattering problems sign function can be replaced by tanh function

$$\text{sign}(s_{c1}) = \tanh\left(\frac{s_{c1}}{\rho}\right),$$

where ρ is positive number.

Theorem 1: Consider the sliding surface (15) with the sliding surface dynamic (16), then the control law (17) guarantees the rotor speed error e_c convergence.

Proof: Let's consider the following Lyapunov candidate function:

$$V(t) = \frac{1}{2}s_{c1}^2. \quad (18)$$

Now, by taking time derivative and inserting (18) in it, we have

$$\begin{aligned} \dot{V} &= s_{c1}\dot{s}_{c1} = s_{c1}[\dot{\omega}_{ref} + a\omega_m(t) + bT_m(t) - ci_{sq}(t)] \\ &= s_{c1}\left[\dot{\omega}_{ref} + a\omega_m(t) + bT_m(t) - c\left[\frac{1}{c}(a\omega_m(t) \right. \right. \\ &\quad \left. \left. + bT_m(t) + \dot{\omega}_{ref} + k_{c1}s(t) + k_{swc1}\text{sign}(s(t)))\right]\right] \\ &= s_{c1}[-k_{c1}s_{c1} - k_{swc1}\text{sign}(s_{c1})]. \end{aligned} \quad (19)$$

Replacing $\text{sign}(s_{c1}) = (|s_{c1}|/s_{c1})$, Equation (20) will be obtained

$$\dot{V}(t) = -k_{c1}s_{c1}^2 - k_{swc1}|s_{c1}|. \quad (20)$$

Then for $k_{c1}, k_{swc1} > 0$, the sliding surface s_{c1} zero convergence will be satisfied. ■

6. FITSMC for Five-Phase IPMSM

In this section, for the speed control of Five-Phase IPMSM, a fractional integral terminal sliding mode speed controller has been proposed. For this purpose, the sliding surface is defined as follows

$$s_{c2} = e_c + \lambda \int_0^t e_c^\mu d\tau, \quad (21)$$

where $\lambda > 0$, $\mu = \frac{p}{q}$, $0 < \mu < 1$, $p, q > 0$ and p and q are odd numbers.

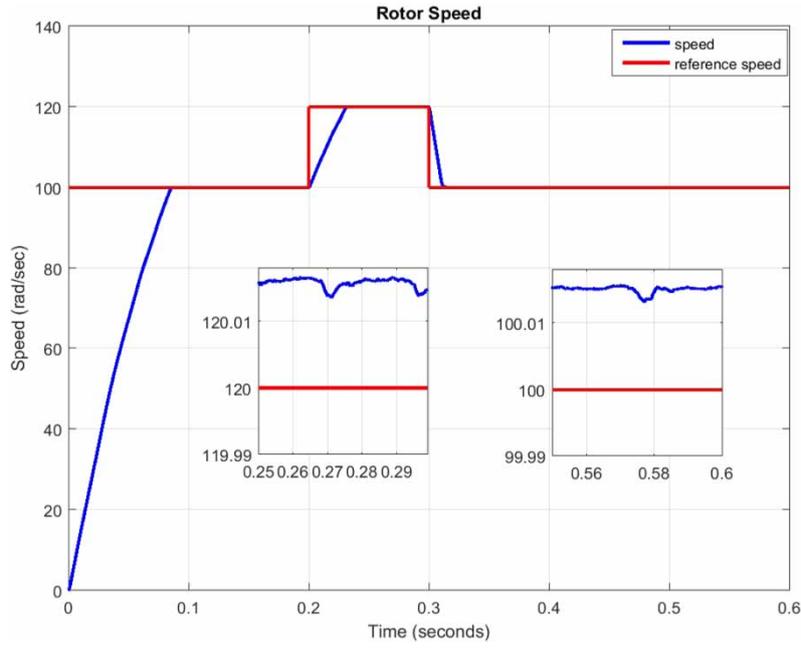


Figure 2. Rotor speed.

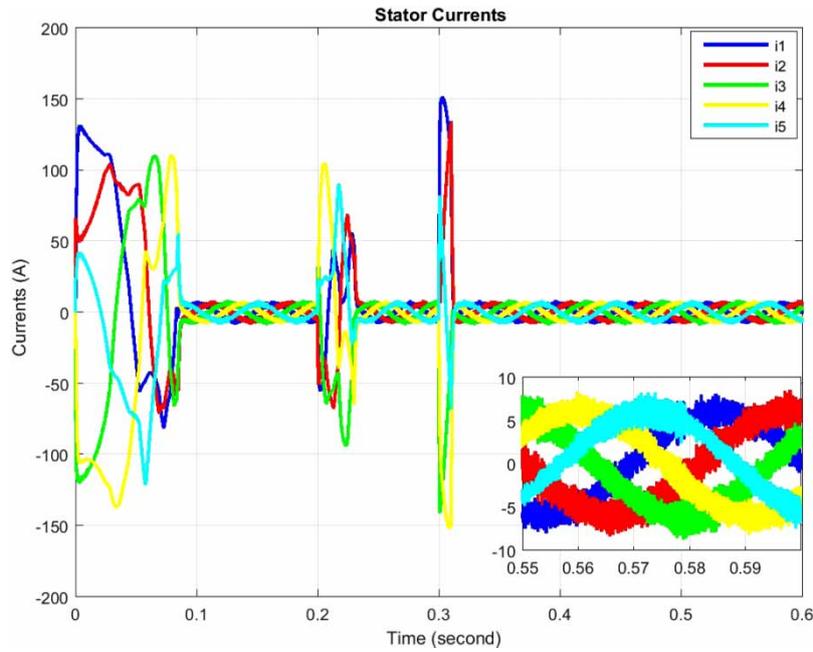


Figure 3. Stator currents.

Taking time derivative of (21), and substituting (14) in it results in

$$\begin{aligned} \dot{s}_{c2} = \dot{e}_c + \lambda e_c^\mu &= \dot{\omega}_{ref} - \dot{\omega}_m + \lambda e_c^\mu = \dot{\omega}_{ref} + a\omega_m \\ &+ b\mathcal{T}_m - ci_{q1} + \lambda e_c^\mu. \end{aligned} \quad (22)$$

Control law for FITSMS is proposed as Equation (23)

$$\begin{aligned} i_{q1} = \frac{1}{c} [a\omega_m + b\mathcal{T}_m + \dot{\omega}_{ref} + k_{c2}s_{c2} \\ + k_{swc2}\text{sign}(s_{c2}) + \lambda e_c^\mu]. \end{aligned} \quad (23)$$

Theorem 2: The control law (23) with the sliding surface (21) and the sliding surface dynamic (22) guarantees the rotor speed error e_c convergence.

Proof: Let's consider the following Lyapunov candidate function as (24)

$$V(t) = \frac{1}{2}s_{c2}^2. \quad (24)$$

Now, by taking time derivative from (24) and inserting (22) in it, we have

$$\begin{aligned} \dot{V} &= s_{c2}\dot{s}_{c2} = s_{c2}[\dot{\omega}_{ref} + a\omega_m + b\mathcal{T}_m - ci_{q1} + \lambda e_c^\mu] \\ &= s_{c2} \left[\dot{\omega}_{ref} + a\omega_m(t) + b\mathcal{T}_m - c \left[\frac{1}{c}(a\omega_m + b\mathcal{T}_m \right. \right. \\ &\quad \left. \left. + \dot{\omega}_{ref} + k_{c2}s_{c2} + k_{swc2}\text{sign}(s_{c2}) + \lambda e_c^\mu \right) \right] \\ &= s_{c2}[-k_{c2}s_{c2} - k_{swc2}\text{sign}(s_{c2})]. \end{aligned} \quad (25)$$

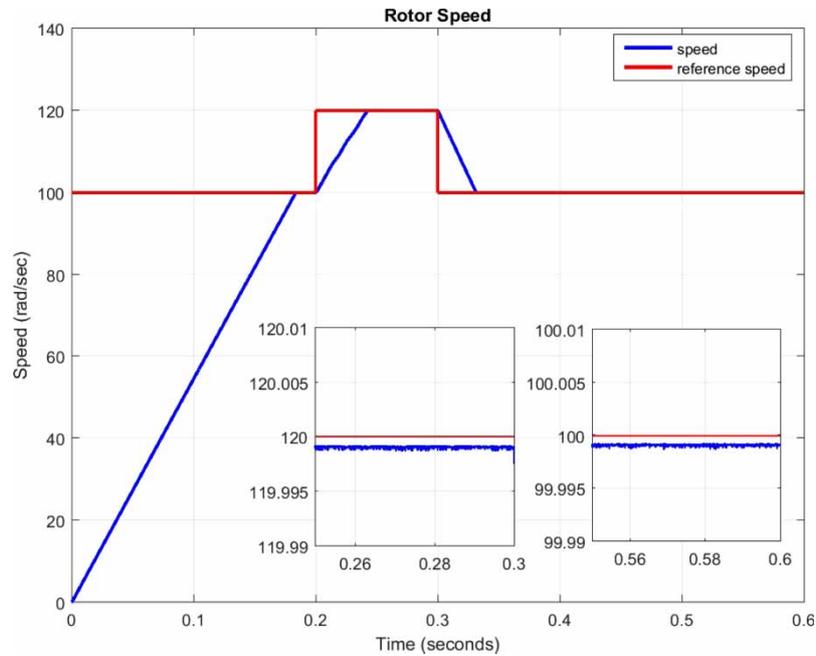


Figure 4. Rotor speed.

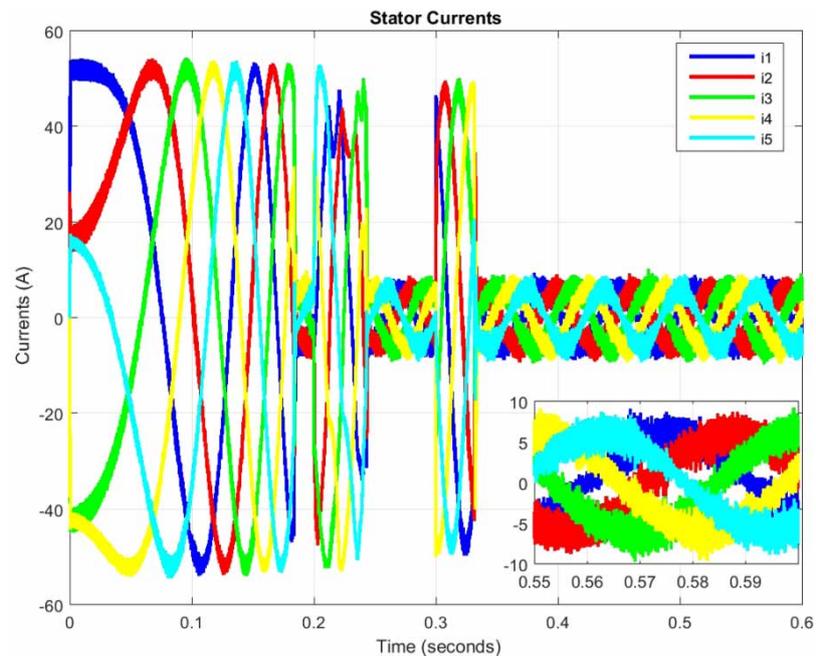


Figure 5. Stator currents.

Replacing $\text{sign}(s_{c2}) = (|s_{c2}|/s_{c2})$ Equation (26) will be obtained

$$\dot{V}(t) = -k_{c2}s^2(t) - k_{swc2}|s(t)|. \quad (26)$$

Then, $k_{c2}, k_{swc2} > 0$ satisfy the sliding surface s_{c1} zero convergence. ■

7. Five-Phase IPMSM control configuration

The schematic diagram of Five-Phase IPMSM control loop is shown in Figure 1. It contains the following blocks:

- Five-Phase IPMSM (FPIPMSM),
- controller (PI/SMC/FITSMC),
- Five-Phase pulse-width modulation (FPPWM),
- transformation matrixes, and
- FDD block.

8. Simulation

In this section, some simulations have been carried out in MATLAB/Simulink environment to validate the effectiveness of the proposed controllers for Five-Phase IPMSM. Simulation studies are performed with a 100-kHz control frequency.

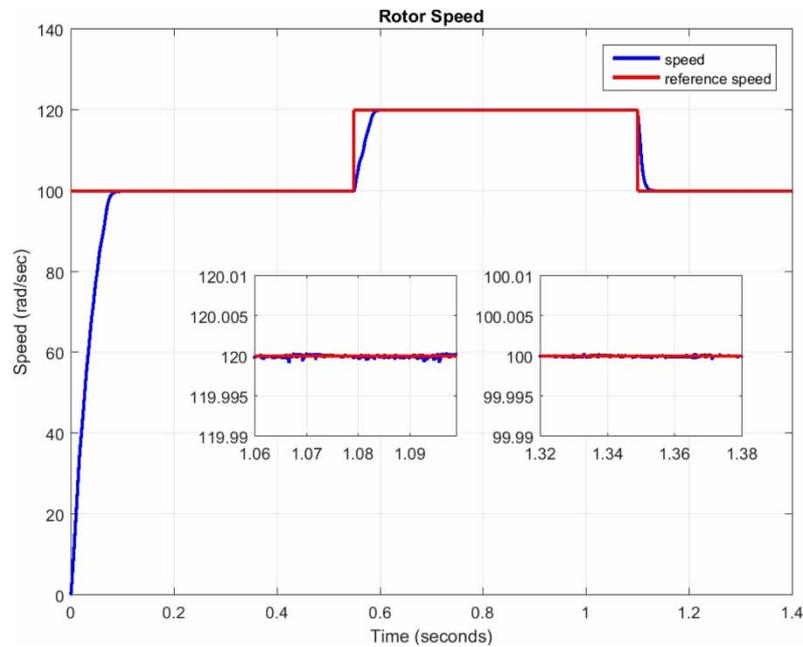


Figure 6. Rotor speed.

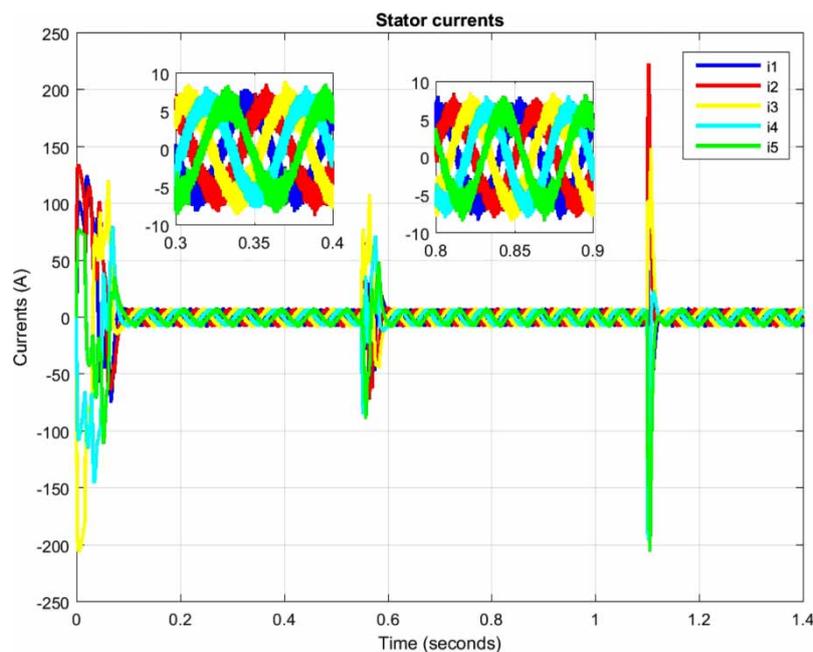


Figure 7. Stator currents.

The Five-Phase IPMSM parameters are listed in Table 1. The PI, SMC and proposed FITSMC speed controller parameters are listed in Tables 2, 3 and 4, respectively.

(A) Normal drive

To demonstrate the performance of the proposed schemes in a normal drive process, the following changes are applied.

In PI and SMC controllers, the initial reference speed is set to 100 rad/sec at $t = 0.0 - 0.4, 0.5 - 0.6$ sec and increases to 120 rad/sec at $t = 0.4 - 0.5$ sec.

In FITSMC controller, the initial reference speed is set to 100 rad/sec at $t = 0.0 - 0.55, 1.1 - 1.4$ sec and increases to 120 rad/sec at $t = 0.55 - 1.1$ sec.

Figures 2 and 3 give the simulation results of PI controller in the presence of the above changes. All of these figures contain extra zoom to provide more information. Figure 2 shows the reference and actual rotor

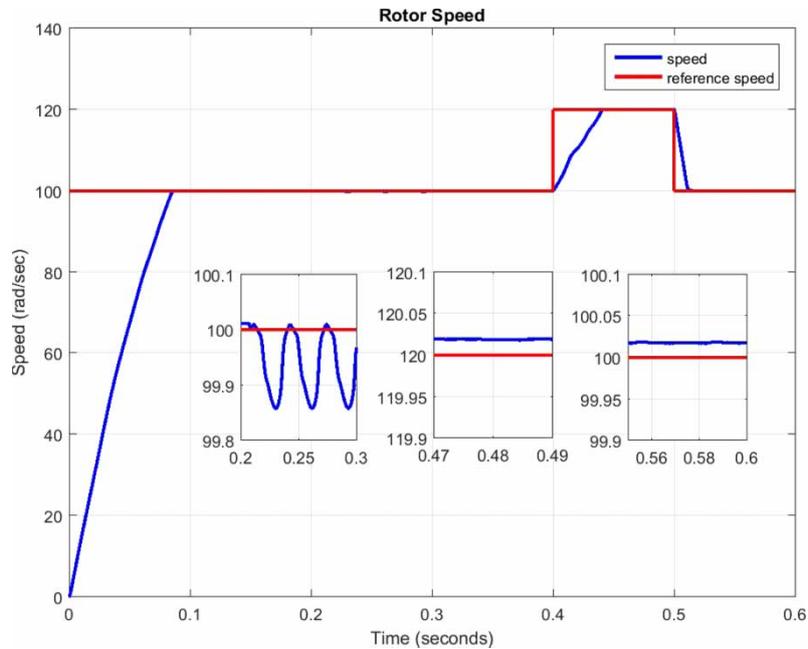


Figure 8. Rotor speed.

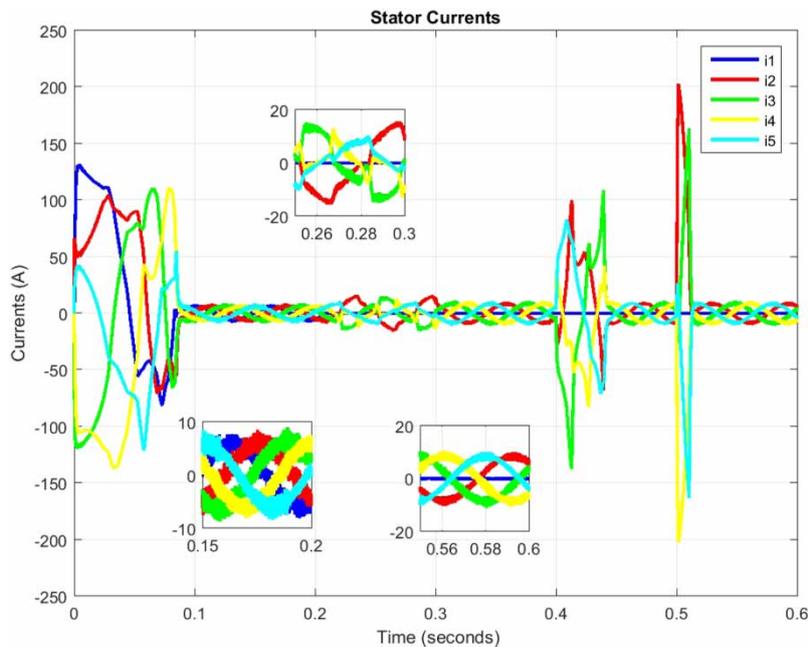


Figure 9. Stator currents.

speed, and in Figure 3 the stator currents have been presented.

Figures 4 and 5 give the simulation results of SMC in the presence of the mentioned changes. Figure 4 shows the reference and actual rotor speed, and in Figure 5 the stator currents have been presented.

Figures 6 and 7 give the simulation results of FITSMC in the presence of the mentioned changes. Figure 6 shows the reference and actual rotor speed, and the stator currents have been presented in Figure 7.

In a normal drive condition, as shown in the above figures, the FITSMC has a better performance in the

speed steady-state error as compared with the SMC and PI. Also the converging time of the FITSMC is lower than the PI and SMC.

(B) *Open one-phase fault*

To demonstrate performance of the proposed schemes, in drive with open one-phase fault, the following changes are applied.

In PI and SMC controllers, the initial reference speed is set to 100 rad/sec at $t = 0.0 - 0.4, 0.5 - 0.6$ sec and increases to 120 rad/sec at $t = 0.4 - 0.5$ sec. The open phase fault has been set to $t = 0.2$ and the

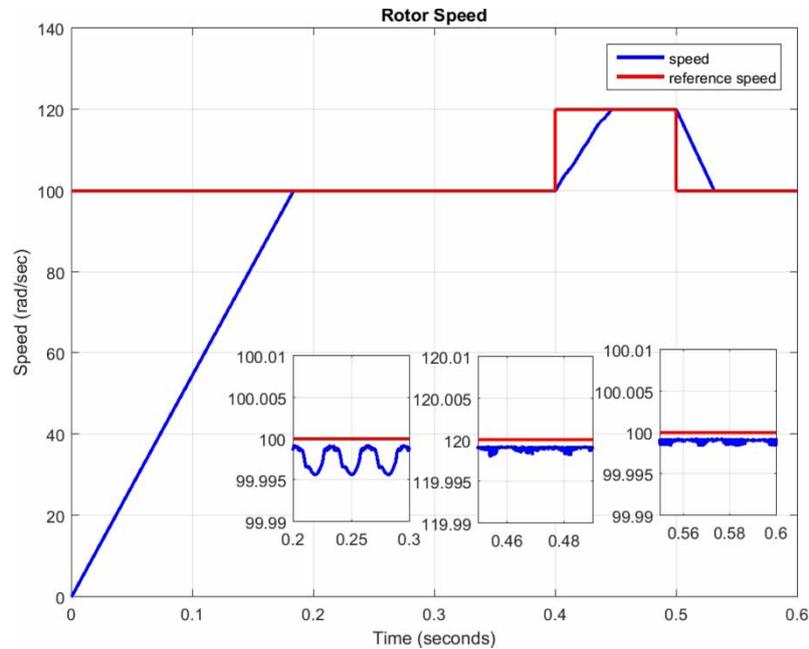


Figure 10. Rotor speed.

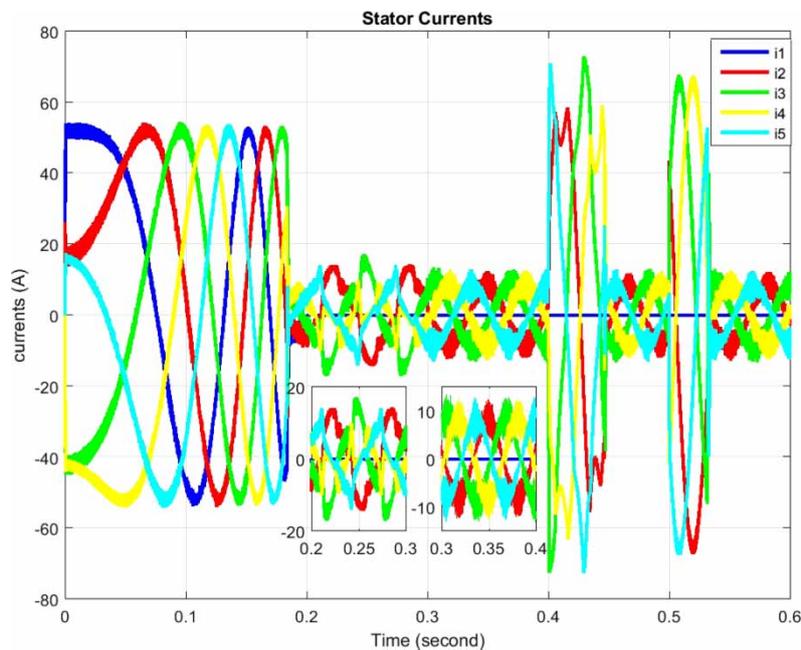


Figure 11. Stator currents.

inverter matrix replacement has been performed at $t = 0.3$.

In FITSMC controller, the initial reference speed is set to 100 rad/sec at $t = 0.0 - 1, 1.5 - 2$ sec and increase to 120 rad/sec at $t = 1 - 1.5$ sec. Open phase fault has been set to $t = 0.6$ and the inverter matrix replacement has been performed at $t = 0.7$.

Figures 8 and 9 give the simulation results of PI in the presence of the above changes. Figure 8 shows the reference and actual rotor speed, and in Figure 9 the stator currents have been presented.

Figures 10 and 11 show the simulation results of SMC in the presence of the mentioned changes.

Figure 10 shows the reference and actual rotor speed, and Figure 11 presents the IPMSM stator currents.

Figures 12 and 13 give the simulation results of FITSMC in the presence of the mentioned changes. Figures contain extra zoom to provide more information. Figure 12 shows the reference and actual rotor speed, and finally stator currents have been presented in Figure 13.

In an open one-phase drive condition, on the occurrence of a fault, 0.1 second is considered to cover FDD block delay, which causes the current increase and distortion. However, it is both restrained and reformed well following the matrix change. Moreover,

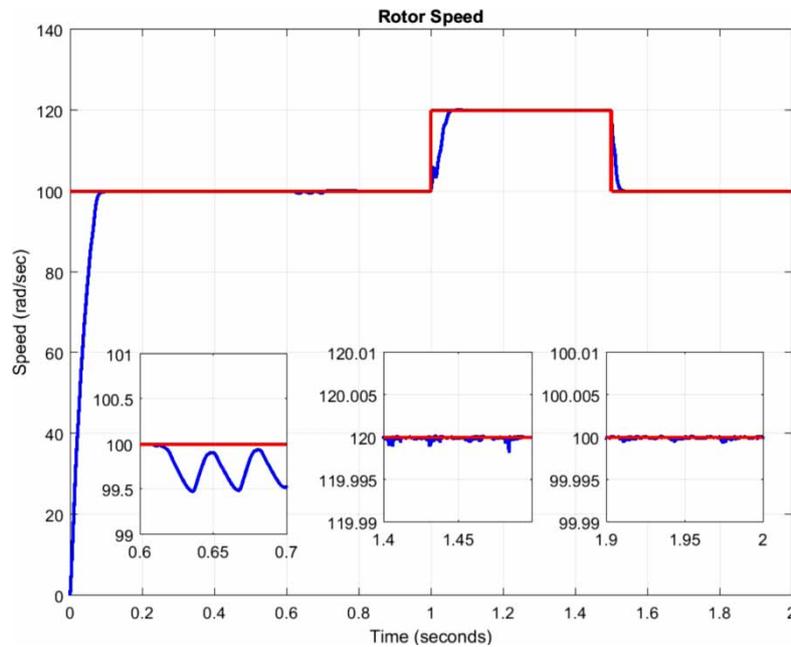


Figure 12. Rotor speed.

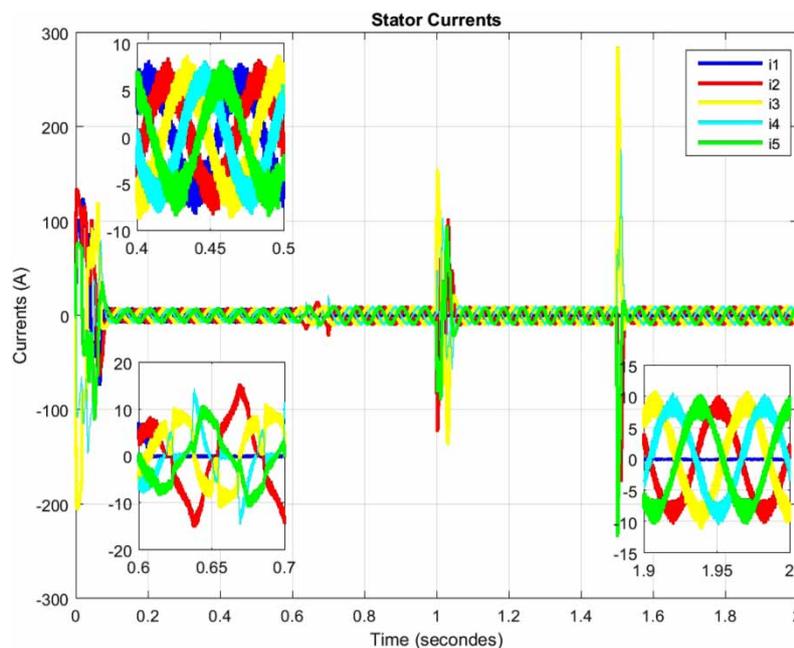


Figure 13. Stator currents.

the FITSMC performance is much better than PI and SMC.

(C) Open two-phase fault

To demonstrate performance of the proposed schemes, in drive with two opened phase fault, the following changes are applied.

In PI and SMC controllers the initial reference speed has been set to 100 rad/sec at $t = 0.0 - 0.5$ sec and increases to 120 rad/sec at $t = 0.4 -$

0.5 sec. Open phase fault has been set to $t = 0.2$ and the inverter matrix replacement has been performed at $t = 0.3$.

In FITSMC controller, the initial reference speed is set to 100 rad/sec at $t = 0.0 - 1.5$ sec and increase to 120 rad/sec at $t = 1 - 1.5$ sec. Open two-phase fault has been set to $t = 0.6$ and the inverter matrix replacement has been performed at $t = 0.7$.

Figures 14 and 15 give the simulation results of PI in the presence of the above changes. Figure 14

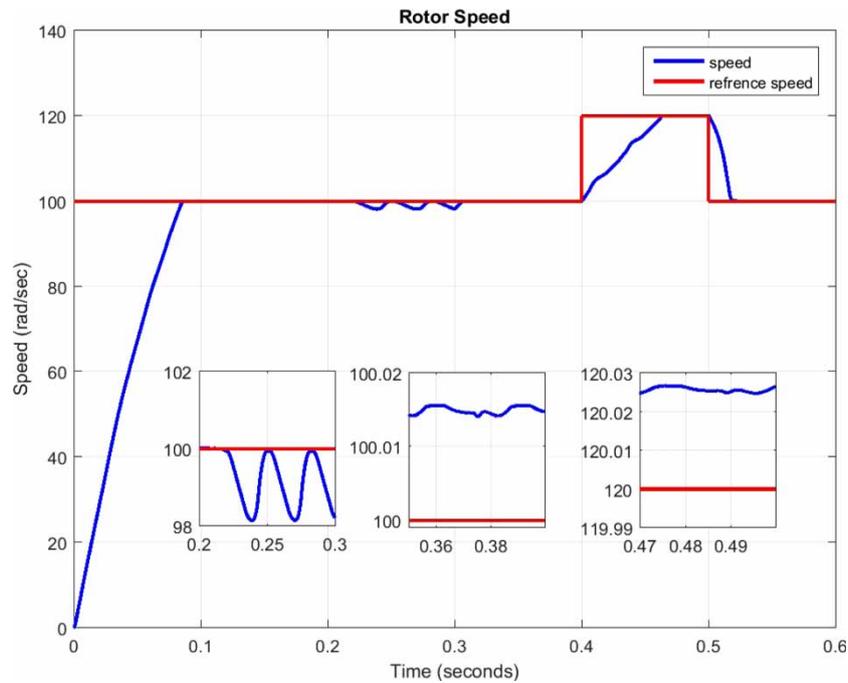


Figure 14. Rotor speed.

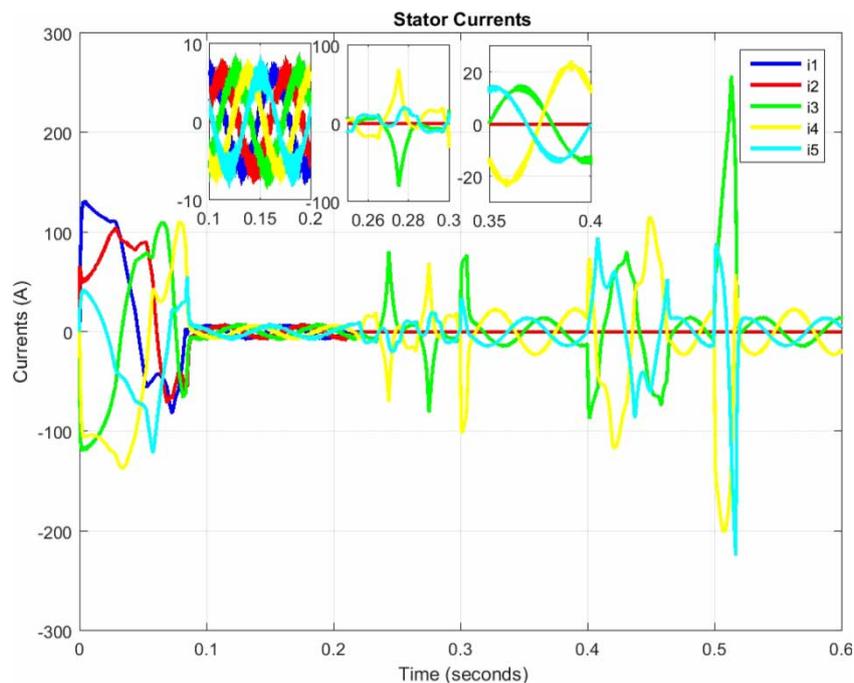


Figure 15. Stator currents.

shows the reference and actual rotor speed, and in Figure 15 the IPMSM stator currents have been presented.

Figures 16 and 17 give the simulation results of SMC in the presence of the mentioned changes. Figure 16 shows the reference and actual rotor speed and Figure 17 illustrates the IPMSM stator currents.

Figures 18 and 19 show the simulation results of FITSMC in the presence of the mentioned changes. Figure 18 shows the reference and actual rotor speed,

and in Figure 19 the IPMSM stator currents have been presented.

In open two-phase drive, on the occurrence of a fault, 0.1 second is considered to cover FDD block delay, which causes the current increase and distortion more than an open one phase. However, it is both restrained and reformed well following the matrix change. Moreover, the FITSMC performance is much better than PI and SMC. In details, it has better tracking error and faster response than the PI and SMC.

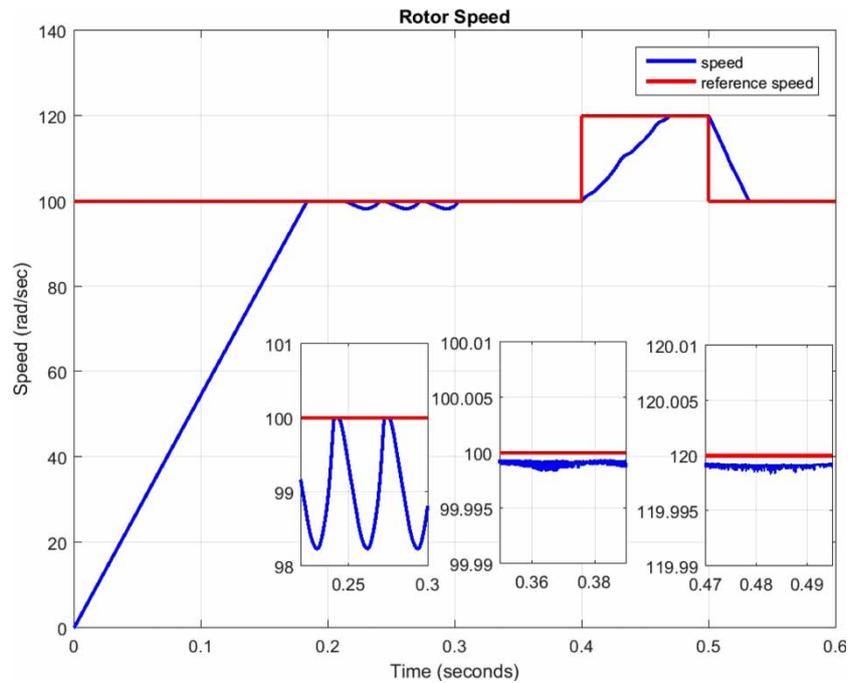


Figure 16. Rotor speed.

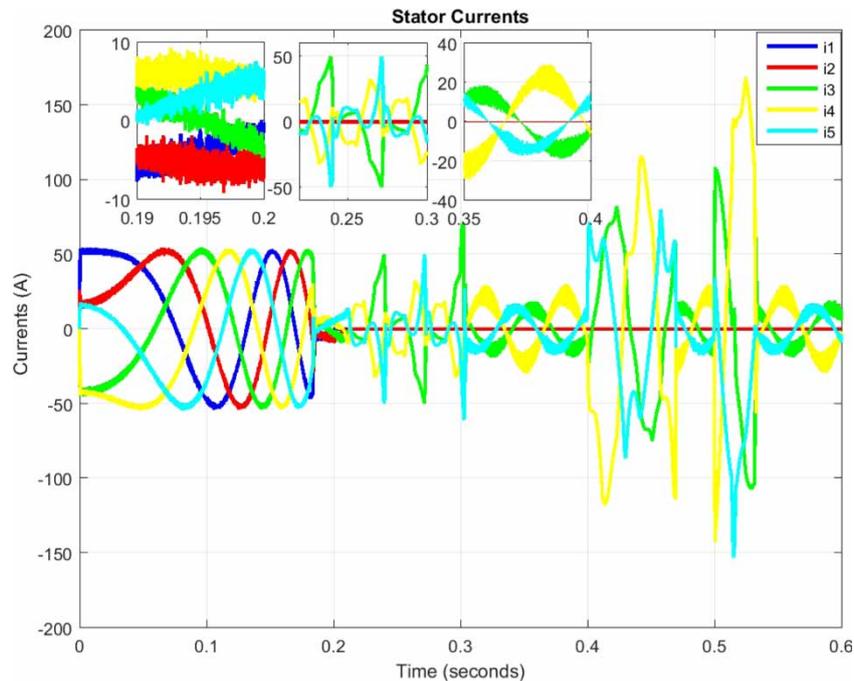


Figure 17. Stator currents.

9. Conclusion

In this paper, speed control of the Five-Phase IPMSM in normal and open one- and two-phase faulty conditions with the FITSM controller have been discussed for a first time. Simulation results have been compared with the conventional SMC and PI controllers. The proposed FITSM controller utilizes the rotor speed as the state variables which can tolerate well against open phases faults. The FITSM controller has very limited steady-state error even with two opened phase fault after the compensation matrix application. Also, it has better

tracking performance vs. the conventional SMC and PI controllers in steady-state error. Moreover the currents increase after open phase fault has been restrained well.

The practical stability of controller is guaranteed by the Lyapunov stability theorem. The Simulation results testify the effectiveness of the proposed robust controller.

As for the future works, it is possible to consider other terminal sliding surfaces or extract other inverter matrixes to include other targets such as minimizing the copper losses.

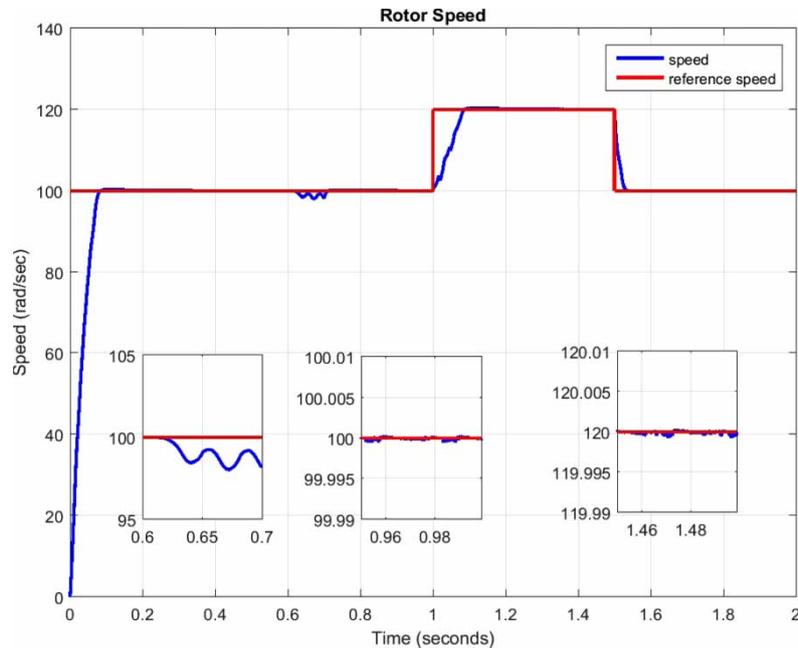


Figure 18. Rotor speed.

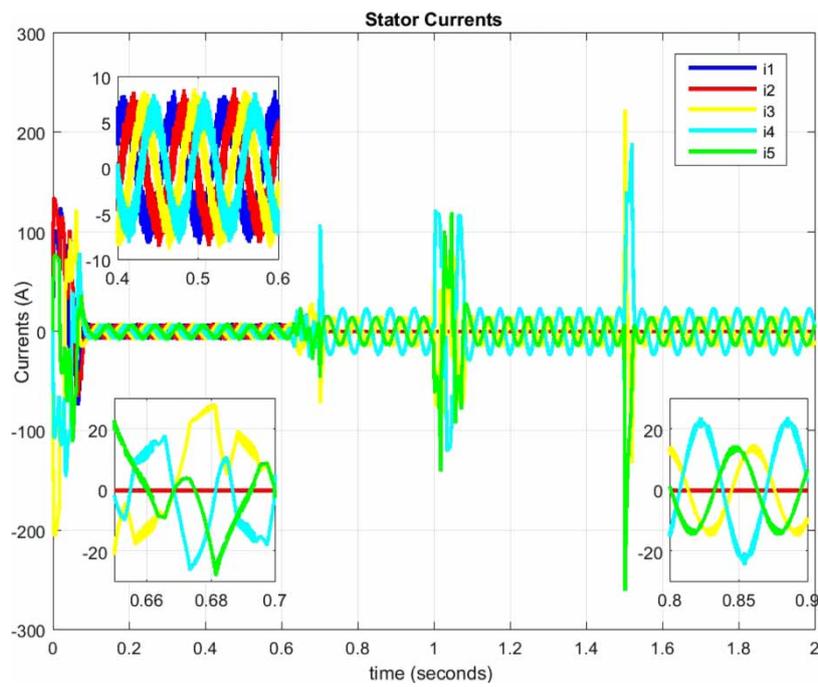


Figure 19. Stator currents.

Note

1.

$$T(\theta) = \frac{2}{5} \begin{bmatrix} \cos \theta & \cos \left(\theta - 2\frac{\pi}{5} \right) & \cos \left(\theta - 4\frac{\pi}{5} \right) & \cos \left(\theta + 4\frac{\pi}{5} \right) & \cos \left(\theta + 2\frac{\pi}{5} \right) \\ \sin \theta & \sin \left(\theta - 2\frac{\pi}{5} \right) & \sin \left(\theta - 4\frac{\pi}{5} \right) & \sin \left(\theta + 2\frac{\pi}{5} \right) & \sin \left(\theta + 4\frac{\pi}{5} \right) \\ \cos \theta & \cos \left(\theta + 4\frac{\pi}{5} \right) & \cos \left(\theta - 2\frac{\pi}{5} \right) & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin \theta & \sin \left(\theta + 4\frac{\pi}{5} \right) & \sin \left(\theta - 2\frac{\pi}{5} \right) & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & & \end{bmatrix} \quad (4)$$

Disclosure statement

No potential conflict of interest was reported by the authors.

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