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Design of Sliding Mode Control using SVPWM Modulation Method for Speed Control of Induction Motor

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Abstract

The sliding mode control method is a highly accurate and easy-to-implement approach that can be effectively utilized in the control of high-dimensional nonlinear systems that operate under uncertain conditions. In this study based on Matlab/Simulink, a Proportional-Integral-Integral Sliding Mode Control (PI-ISMC) method has been developed to control the mechanical speed of a three-phase squirrel cage induction motor. The modeling of the induction motor and the design of the proposed controller have been conducted in the qd0 reference frame. The asymptotic speed tracking under uncertainty and different loading conditions has been ensured by tuning the parameters of the PI-ISMC controller. Additionally, field-oriented control (FOC) with space vector modulation has been applied to the same motor to evaluate the performance of the sliding mode control topology in induction motor control, and its performance has been compared with the sliding mode control method.

Keywords: Induction Motor; SMC Control; FOC Control; Matlab/Simulink

1. Introduction

Due to their robust structure and easy adaptability to various operating modes in dynamic conditions, induction motors (IMs) are widely used in industrial applications where mechanical energy is required. Recently, with the diversification of power electronics devices used in IM control technology and advancements in microprocessor technology, their use has become more efficient. However, the complex structure of IMs makes position and speed control more challenging and intricate compared to DC machines. Industrial systems require control methods that can

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provide smooth and effective electromagnetic torque, asymptotic speed tracking, and disturbance rejection. Sliding Mode Control (SMC), built on top of the Variable Structure Control (VSC) algorithm, is a robust and nonlinear control method that can achieve the desired dynamic behaviors for the controlled system, even in the presence of external and internal disturbances and uncertainties, provided that suitable conditions are met (Panchade et al., 2013). SMC technique, as a nonlinear control method, has become a focus of research in the literature due to its strong robustness, fast response, and simple software and hardware implementation, which have led to successful results in controlling IMs under complex and uncertain conditions.

Variable structure systems, sliding mode control, and mathematical models for high-dimensional nonlinear systems, with a focus on controlling various types of electric motors under uncertain conditions, have been discussed by Utkin in (1993). Parthan et al. (2019) discussed indirect field-oriented control and SMC for an IM. They demonstrated through simulation that the performance of both controllers is equal for steady-state operation, but SMC exhibits superior performance for unstable and transient operations. Shiravani et al. (2022) developed a mathematical model for an IM in the dq0 synchronous reference frame and focused on Integral Sliding Mode Control (ISMC) for speed control. The stability of the proposed controller has been ensured using Lyapunov stability theory under parameter uncertainties and load disturbances. Benchaib et al. (2000) proposed a nonlinear sliding mode controller for IMs that aims to achieve asymptotic tracking of speed and flux. Amali. (2014) focused on SMC and fuzzy logic-based control design for DTC in asynchronous motors. The proposed control methods showed better performance in both transient and steady-state compared to the traditional hysteresis control method.

Barambones et al. (2005) proposed a neural network-based rotor speed estimator and sliding-mode vector control for induction motors. They used a feedforward multilayer neural network trained with backpropagation and momentum algorithms to estimate the rotor speed. Demirtas. (2009) optimized sliding-mode controller parameters for IM by first obtaining an artificial model of the system using neural networks, and then using genetic algorithms to optimize the sliding surface slope and boundary layer thickness. A control scheme proposed by Peng Kang et al. (2010) addresses the coupling effect problem of stator currents in IM drives using SMC and RBFNN. Two RBFNN-based sliding mode controllers were employed to separate the d-axis and q-axis stator currents. Barazane et al. (2006) developed multi-input multi-output control structures for a multi-motor system using a combination of artificial neural network and sliding mode control (ANN-SMC). The goal of using ANN-SMC is to eliminate chattering and improve SMC error performance. Kumar et al. (2016) focused on energy-saving in IMs through a neural network-based sliding mode controller. The study aims to achieve optimal efficiency by controlling the stator voltage for the motor under various operating conditions. The advantage of adding robust artificial neural network controllers (RANNC) in the implementation of the incremental sliding mode control used in the FOC control of the IM is discussed to reduce chattering on the sliding surface (Barazane et al., 2006). A reverse rotor time constant observer system, based on the model reference adaptive system theory, was designed by Wai et al. (2003) to maintain the decomposition control feature of the indirect field-oriented control (IFOC) driver for the induction motor. A high sampling rate digital signal processor was used to obtain a good dynamic response from the observer system. Additionally, a sliding mode control and wavelet-neural-network (WNN) control system were developed to increase the robustness of the indirect field-oriented IM driver with the adaptive observer system for high-performance applications. Orlowska et al. (2009) focused on designing a sliding mode neuro-fuzzy controller for the speed control of an IM. The connection weights of the controller were trained online based on the error between the motor speed and the reference speed. A feedback linearization-neuro-fuzzy sliding mode control (FBI-NFSMC) design methodology was proposed to achieve speed and torque control in IM motors by Mishra et al. (2018). The proposed method significantly reduces torque and speed oscillations with optimal drive performance under system uncertainties and disturbances. Vahedi et al. (2015) conducted a study on neuro-fuzzy dynamic sliding mode control for speed control of medium-sized IMs. To reduce chattering, the dynamic sliding mode control employed a secondary PID-type sliding surface. Neuro-fuzzy systems were used to estimate uncertainties, eliminating the need for trial-and-error procedures in determining the upper bound of uncertainties.

This study aimed to regulate the mechanical rotor speed of an induction motor using the IP-ISMC method to achieve asymptotic speed tracking and mitigate steady-state error and disturbances. To achieve fast dynamic performance, FOC theory was applied in the controller design process. Additionally, suitable SMC parameters were selected to eliminate steady-state error and solve the chattering problem. The study compared the SMC control method proposed with FOC performance under different loading conditions and no-load operation of the motor.

2. SMC Control Design

The modeling of IM and its controller is based on the Clark and Park transformations, which include the electrical frequencies of the stator and rotor, respectively ω_s and ω_r. In this case, the stator and rotor voltage and flux equations of the IM in matrix form in the qd0 stationary reference frame ($\omega_s = 0$) can be expressed as follows:

$$\begin{bmatrix} v_s^q \\ v_s^d \\ v_s^0 \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \lambda_s^q \\ \lambda_s^d \\ \lambda_s^0 \end{bmatrix} + \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}\begin{bmatrix} i_s^q \\ i_s^d \\ i_s^0 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_r^q \\ v_r^d \\ v_r^0 \end{bmatrix} = (-\omega_r)\begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \lambda_r^q \\ \lambda_r^d \\ \lambda_r^0 \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \lambda_r^q \\ \lambda_r^d \\ \lambda_r^0 \end{bmatrix} + \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix}\begin{bmatrix} i_r^q \\ i_r^d \\ i_r^0 \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \lambda_s^q \\ \lambda_s^d \\ \lambda_s^0 \\ \lambda_r^q \\ \lambda_r^d \\ \lambda_r^0 \end{bmatrix} = \begin{bmatrix} L_{1s}+L_m & 0 & 0 & L_m & 0 & 0 \\ 0 & L_{1s}+L_m & 0 & 0 & L_m & 0 \\ 0 & 0 & L_{1s} & 0 & 0 & 0 \\ L_m & 0 & 0 & L_{1r}+L_m & 0 & 0 \\ 0 & L_m & 0 & 0 & L_{1r}+L_m & 0 \\ 0 & 0 & 0 & 0 & 0 & L_{1r} \end{bmatrix}\begin{bmatrix} i_s^q \\ i_s^d \\ i_s^0 \\ i_r^q \\ i_r^d \\ i_r^0 \end{bmatrix} \tag{3}$$

The mechanical equations for calculating the torque T_{EM} and the angular velocity ω_m of the IM are given in equations (4) and (5), respectively.

$$T_{EM} = \frac{3}{2}\frac{P}{2}L_m\left(i_r^d i_s^q - i_r^q i_s^d\right) = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\lambda_r^d i_s^q - i_r^q \lambda_s^d\right) \tag{4}$$

$$\omega_m = \frac{1}{J}\int (T_e - B\omega_m - T_L)\, dt \tag{5}$$

When designing an SMC-based speed controller for the IM , using the mathematical model in the qd0 rotor reference plane under full field-oriented control, $\lambda_r^q = 0$. Therefore, equation (4) can be rearranged as follows:

$$T_{EM} = K_T i_s^q \qquad K_T = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\lambda_r^d\right) \tag{6}$$

Equations (5) and (6) can be rearranged into equation (7).

$$\frac{d\omega_m(t)}{dt} = \frac{1}{j}\left(K_T i_s^q(t) - B\omega_m(t) - T_L\right) \tag{7}$$

In the presence of uncertainties in the system, equation (7) can be expressed as follows.

$$\frac{d\omega_m(t)}{dt} = \frac{1}{j}\left[(K_T + \Delta K_T) i_s^q(t) - (B+\Delta B)\omega_m(t) - (T_L + \Delta T_L)\right] \tag{8}$$

The tracking speed error between the reference speed ω_r and the rotor speed ω_m is defined as follows:

$$e(t) = \omega_r(t) - \omega_m(t) \tag{9}$$

When the time derivative of equation (9) is taken, the following expression is obtained.

$$\frac{d\,\mathrm{e}(t)}{dt} = \frac{d\omega_r(t)}{dt} - \frac{d\omega_m(t)}{dt} = \frac{B}{J}e(t) + u(t) + d(t) \tag{10}$$

Here,

$$u(t) = \frac{1}{j}\left(K_T \mathrm{i}_\mathrm{s}^\mathrm{q}(t) - B\omega_m(t) - T_L\right) - \frac{d\omega_m(t)}{dt} \tag{11}$$

$$d(t) = \frac{1}{j}\left(\Delta K_T \mathrm{i}_\mathrm{s}^\mathrm{q}(t) - \Delta B\omega_m(t) - \Delta T_L\right) - \omega_m \tag{12}$$

The first step in designing a sliding mode controller is to introduce the switching function. For the IM speed controller, the switching function S(t) with an integral component and the variable structure controller u(t) are defined as follows:

$$S(t) = e(t) - \int_0^t \left(k - \frac{B}{J}\right) e(t)dt \tag{13}$$

$$u(t) = ke(t) - Csgn\big(S(t)\big) \tag{14}$$

where k is a constant gain. The gain should be chosen such that k < 0 to ensure the stability of the sliding mode control system. When equations (11) and (14) are rearranged, equation (15) is obtained, which represents the $i_s^{q^*}$ current expression responsible for IM rotor speed control. Here, C is the switching gain defined as C ≥ d(t).

$$\mathrm{i}_\mathrm{s}^{\mathrm{q}*} == \frac{J}{K_T}\left(ke(t) - Csgn\big(S(t)\big) + \frac{B}{\mathrm{J}}\omega_m(t) + \frac{T_L}{\mathrm{J}} + \frac{d\omega_m(t)}{dt}\right) \tag{15}$$

The intended control method for IMs shown in Fig. 1 involves a block diagram consisting of several components. As depicted in the diagram, firstly, the stator phase currents are transformed into i_s^q and i_s^d current components using Park and Clark transformations. These current components are responsible for magnetizing the rotor flux and producing electromagnetic torque, respectively. The angular position of the rotor is calculated using the deta block diagram.

Next, the error between the reference speed and the system speed is given as input to SMC block. The output of the SMC block is the $i_s^{q^*}$ current, which is responsible for producing the electromagnetic torque reference. In addition, two PI controllers are used to control the expected ($i_s^{q^*}$, $i_s^{d^*}$) and calculated (i_s^q , i_s^d) torque and flux currents, which provide the relevant v_s^q and v_s^d voltage references in the rotating reference frame.

Finally, the inverse Park transformation block ($qd0 \rightarrow \alpha\beta$) is used to convert the v_s^q and v_s^d voltage into the stationary reference frame (v_α ,and v_β voltages). These two voltages are applied to Space Vector Pulse Width Modulation (SVPWM) to drive the three-phase power inverter IGBT.

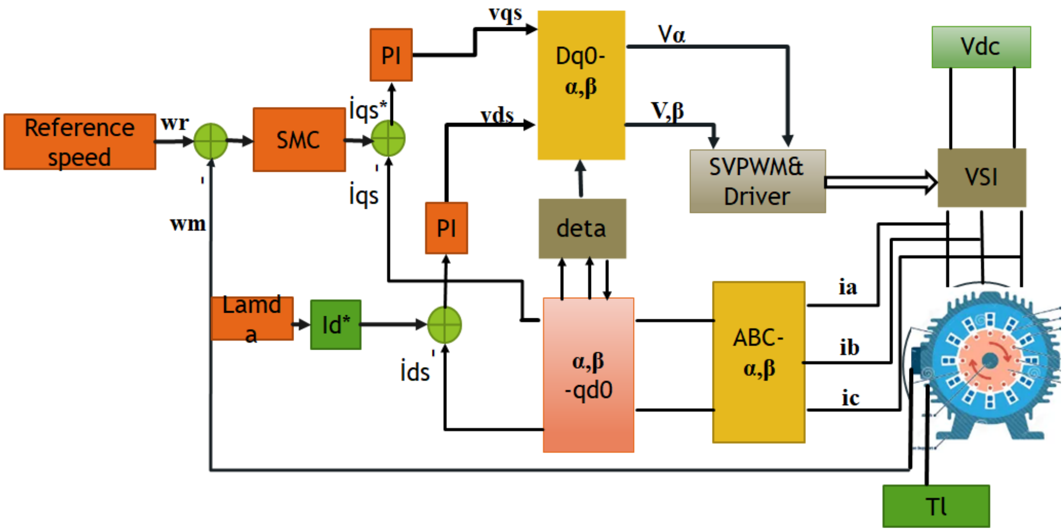

Fig. 1. SMC controlled IM block diagram.

3. Simulation Results and Discussion

The control scheme demonstrated in Fig.1 has been implemented in the Matlab-Simulink environment with a 1µs sampling period and with motor parameters: V_s =460 V, f_s =50 Hz, B =0.1 Kgm^2 , J = 0.662 Kgm^2, L_m =3.47 mH, L_{1s} =0.1 mH , L_{1r} = 228 mH, R_s =0.087 Ω , R_r =0.228 Ω and P =4 . The reference value for the rotor flux along the d-axis has been set to 0.99 Wb. Using the Simulink model shown in Fig.2 , simulations have been conducted with fixed reference speed, as well as no-load, full-load, and step-function reference speed scenarios to investigate the effects of the SMC controller in the IM speed control application and evaluate the performance of SMC and FOC methods.

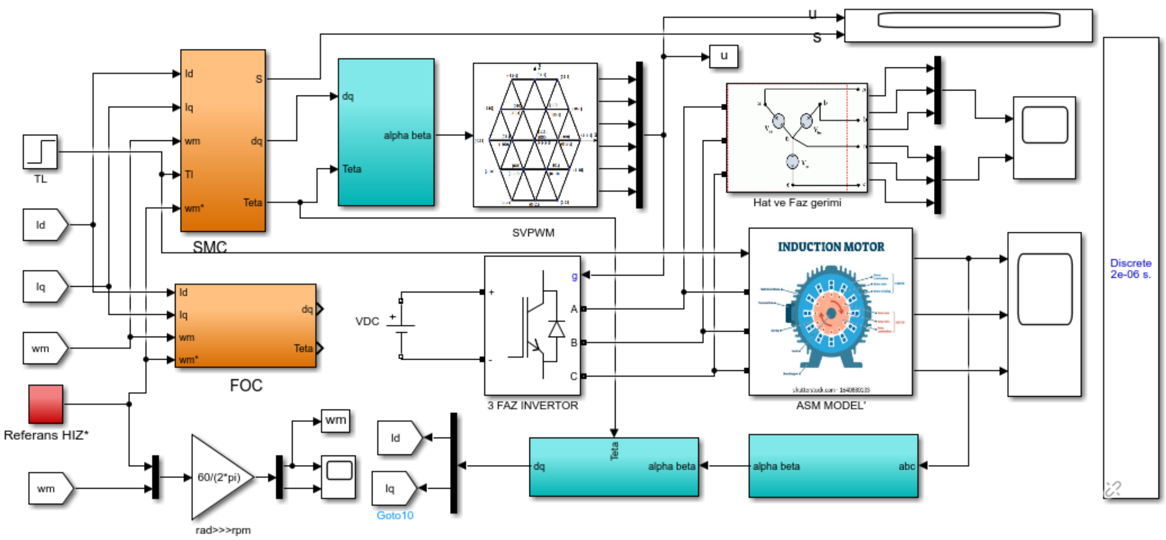

Fig. 2. Simulink model of IM controlled by SMC and FOC.

In Fig. 3a and Fig. 3b, the dynamic behavior of the stator A phase voltage and stator currents of the motor is depicted under IP-SMC using SVPWM modulation method during nominal operating conditions. As there is no filtering system implemented in the system, the current signals contain oscillations. Fig. 3d and Fig. 3c illustrate the behavior of the controller and sliding surface during the no-load running condition. The controller reached the sliding surface after 0.2 sec, allowing the motor to reach the desired speed value.

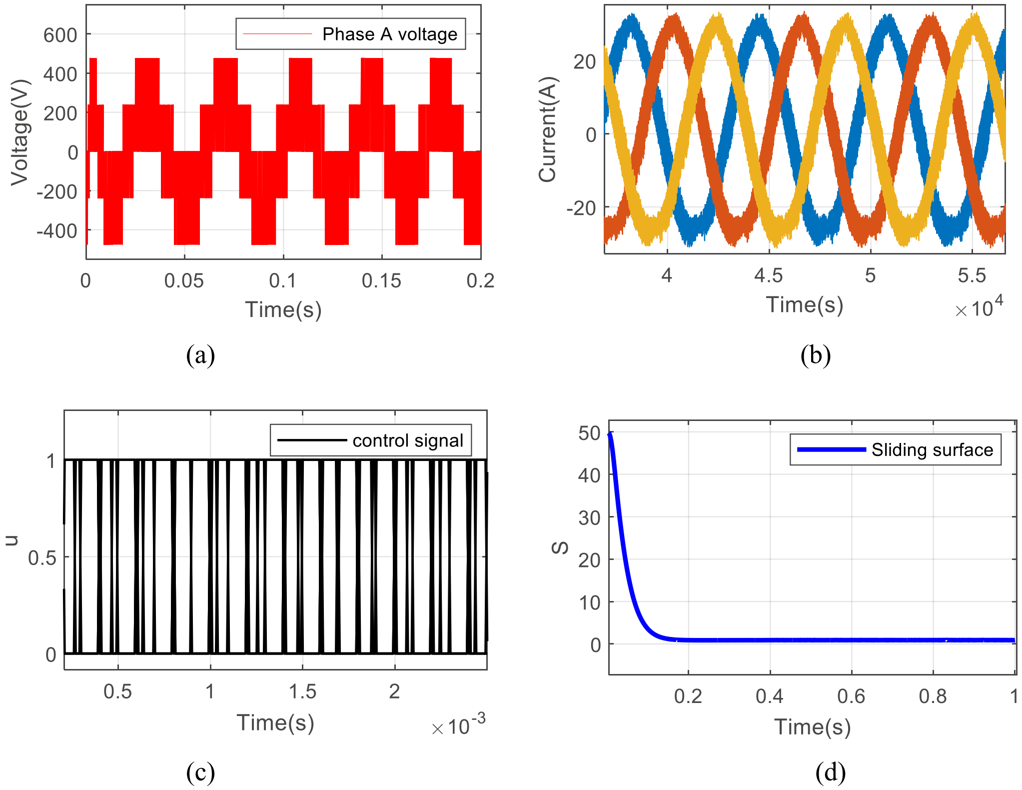

Fig. 3.Simulations output of (a): phase A voltage, (b): stator currents, c: Control signal, d: Sliding surface.

In Fig. 4, the rotor speed and torque behaviors are presented for the fixed reference speed under no-load and full-load conditions after 1.2sec using SMC and FOC methods. With SMC, the rotor speed smoothly reached the desired reference without overshooting within a short time period of 0.23sec under no-load condition. However, a steady-state error of 10% was observed under full load after 1.2sec. On the other hand, FOC reduced the rise time of the rotor speed under no-load condition but led to increased overshooting and settling time. Additionally, a steady-state error of 15% was observed under full-load conditions. The performance of SMC and FOC in IM control application under steady state and transient state summarized in Table 1.

Table 1. Performance evaluation of SMC and FOC

Control Method	**Rise time (sec)**	**Settling time (sec)**	**Steady-State Error**		**Overshoot rate (RPM)**
			no-load condition	full-load condition	
SMC	0.23	0.26	%1	%10	0
FOC	0.0654	0.98	%1,9	%15	68

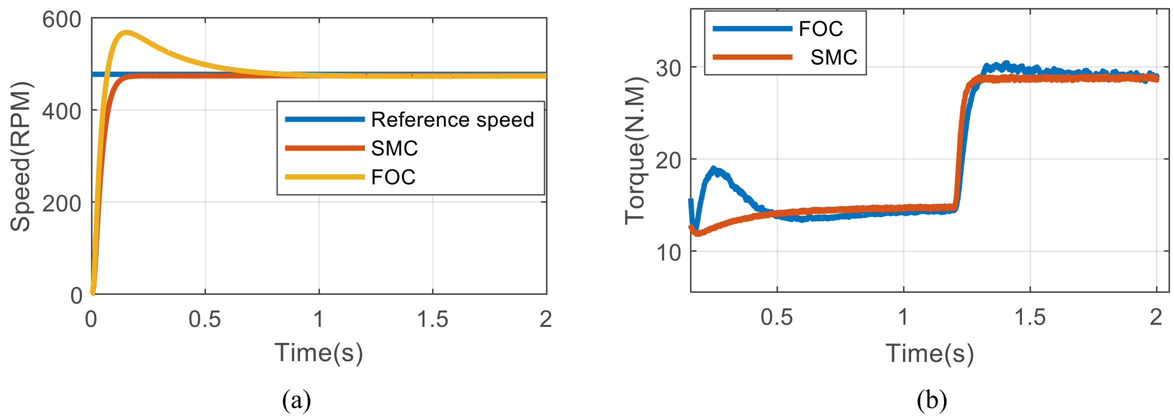

Fig. 4. Simulation output after 1.2 sec under full load condition using SMC and FOC methods: (a) the rotor speed, **(b)** torque.

Fig. 5 shows the rotor speed obtained under the reference speed applied to the motor as a step function [50 95 60 100 100] rad/sec within [0 1.5 3 4.5 6.5]sec under SMC and FOC control. The motor speed trajectory controlled by SMC exhibits less steady-state error and no overshoot compared to the FOC controller.

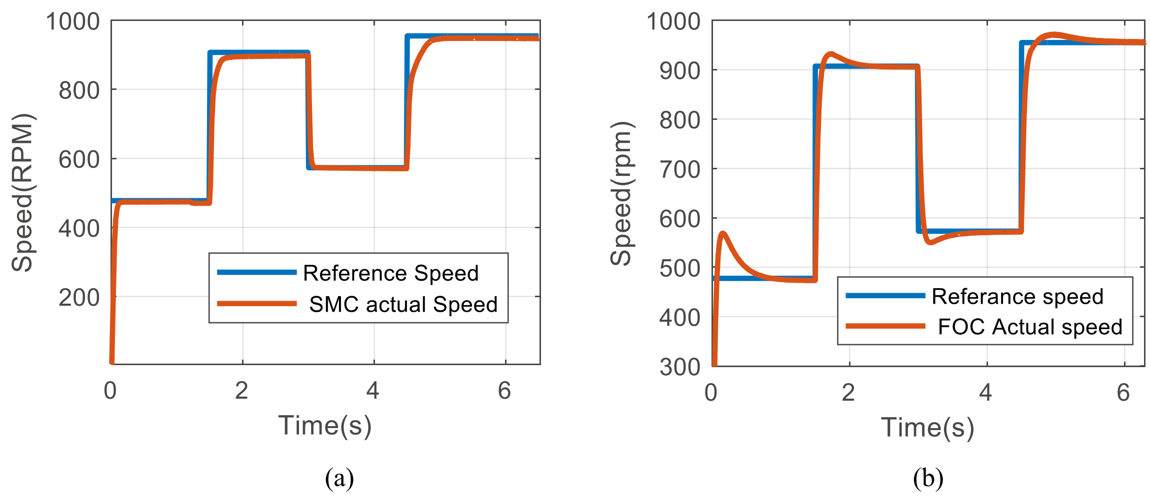

Fig. 5. Simulation outputs under step function reference speed , (a) speed behavior obtained by the SMC method, and (b)speed behavior obtained by the FOC method.

4. Conclusion

In this study, the IP-ISMC method was applied on the IM to regulate the rotor mechanical speed and eliminate load disturbances and parametric changes. The focus of the study was on developing a Simulink model for the IM and evaluating SMC and FOC methods for motor speed control, along with the design of the SMC controller. The IM speed was successfully controlled using both SMC and FOC control methods. Based on simulation results, it was observed that the SMC was more effective in controlling the speed of the IM compared to the FOC controller, due to advantages such as asymptotic speed tracking, absence of steady-state error and overshooting, and faster settling time.

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