Speed Tracking of Field Oriented Control SPIM Drive using (BS_SOSM) Nonlinear Control Structure

NGOC THUY PHAM
Faculty of Electrical Engineering Technology
Industrial University of Ho Chi Minh City (IUH)
Ho Chi Minh City, Vietnam
Ngocpham1020@gmail.com

Abstract: - In this paper, a novel control structure combing the adaptive backstepping (BS) and sliding mode (SM) control techniques to improve the performance and enhance the robustness of the vector control of six phase induction motor (SPIM) drives is proposed. The outer speed closed loop control uses the BS controller with the integral error tracking component added to improve its sustainability. Second order sliding mode controller is proposed for the inner current closed loop control to can effectively compensate for load disturbance in the system so the proposed method is more robust, stability and faster dynamics response, chattering free performance. The proposed speed control scheme is validated through Matlab-Simulink. The simulation results confirm the good dynamics and robustness of the proposed control algorithm based on (BS_SOSM) technique.

Key-Words: - Six phase induction motor drive, Backstepping control, Sliding Mode.

1 Introduction

Multi-phase ac motor drives are strong candidatures for variable speed application, due to numerous advantages that they offer when compared to their three phase counterparts such as higher torque density, greater efficiency, reduced torque pulsations, fault tolerance, and reduction in the required rating per inverter leg [1]. Especially, These drives are often considered in some applications such as locomotive traction, electrical ship propulsion, in high power applications such as automotive, aerospace, military and nuclear [2]. With its reliable working characteristics and high failure tolerance nowadays, They are even considered in the small power applications requiring high reliability and fault tolerance, where are expected that the loss of one or more phases the machine still can provide a significant electromagnetic torque to continue operating the system. Among the many types of multiphase motors, SPIM is one of the most widely used multiphase motors.

For SPIM drives, in cases uncertainties and disturbances are appreciable, traditional control techniques using PID control for SPIM drives are not able to guarantee optimal performance or can require a considerably time consuming and plant dependent design stage. Therefore, to overcome these drawbacks the nonlinear control techniques have been followed, such as, for instance, linear output feedback control [3,4], Sliding mode (SM) [5-6], Backstepping control (BS) [8-12], Fuzzy Logic (FL) control [13-14] neural networks (NN) control [15-17], predictive control, [18], Hamiltonian control [19-24]. In the proposed techniques, the BS have received great attention due to its systematic and recursive design methodology for nonlinear feedback control. The BS design can be used to force a nonlinear system to behave like a linear system in a new set of coordinates. The major advantages are that it has the flexibility to avoid cancelations of useful nonlinearities and pursues the objectives of stabilization and tracking. However, the detailed and accurate information about system dynamics are required when designing traditional BS. To overcome this drawback many strategies have been proposed, in [25] the authors proposed a new BS control scheme using a dynamical induction motor model based on the traditional BS control with the unknown of the damping coefficient, the motor inertia, the load torque and the uncertainty of the machine parameters. The tests carried out without applying a load torque. However, the speed ripple and the performance of the tracking the reference speed is not good, and it also does not guarantee a total rejection of the load torque disturbance. In [26,27], an integral version of the control and an adaptive observer using the backstepping technique was proposed. The results show the good performance of the control law and the observer, but it may be noted that the problem with this method is the complexity of solving differential equations, which require more computing time for the processor, since the model will be increased by two states. In [10] proposed a BS design method for both the control and observer, by adding the integral error tracking component to increase the stability of the transmission system, this method for good dynamic response, precise controls. However, the torque ripple is recorded as quite large, the performance at low speed range and regenerating modes not reported in [10]. From the above analysis it is easy to see that the BS control, which represents a precise model based control method, was difficult to obtain satisfactory control performance when using independently, especially in the cases applied to control the nonlinear systems. Therefore, the combination of BS and different robust adaptive control has been received more attentions [28]–[37]. Such as sliding mode control [28-30], neuron network [31-35], fuzzy logic system (FLS) [36,37]. In this paper, the author proposes a new combined control structure: The BS controller is applied in outer speed closed loop control. In this proposed BS-based controller design, the integral error tracking component added to improve its sustainability. Due to the fact that SM control can effectively compensate for load disturbance so the proposed method use SM in inner current control closed loop is more robust than the conventional adaptive backstepping control used in inner current closed loop control [10]. The success of this SM type of control for electric drives are mainly due to its disturbance rejection, strong robustness, and simple implementation, as shown by many papers on AC drives, that use the standard approach of SM control. The main obstacle to put this technique into industrial application is the chattering behavior, which consists in a high frequency oscillation when the sliding mode takes place. The higher order sliding mode algorithm is one of the solutions to alleviate the chattering behavior with the robustness unchanged unchanged. In this paper, second order sliding mode controller is proposed for the inner current closed loop control to can effectively compensate for load disturbance in the system so the proposed method is not only more robust, stability and faster dynamics response but also chattering free performance. The novel BS_SOSM nonlinear combination structure is proposed in this paper to ensure stability, robustness and fast error dynamics for SPIM drives. The effectiveness of this proposed control structure is verified by simulation using MATLAB/ Simulink.

The paper is organized into five sections, in section 2, the basic theory of the model of the SPIM and the SPIM drive are presented. Section 3 introduces the proposed (BS_SOSM) controller. Simulation and discuss are presented in Section 4. Finally, the concluding is provided in Section 5.

2 Model of SPIM

The system under study consists of an SPIM fed by a six-phase Voltage Source Inverter (VSI) and a DC link. A detailed scheme of the drive is provided in Fig.1. By applying the Vector Space Decomposition (VSD) technique introduced in [18], the original six-dimensional space of the machine is transformed into three two-dimensional orthogonal subspaces in the stationary reference frame (D-Q), (x - y) and (zl -z2). This transformation is obtained by means of 6 x 6 transformation matrix (1).

$$T_6 = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & \frac{\sqrt{3}}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & -\frac{\sqrt{3}}{2} & -1 \\ 1 & -\frac{\sqrt{3}}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{\sqrt{3}}{2} & -1 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \quad (1)$$

In order to develop SPIM model for control purposes, some basic assumptions should be made. Hence, the windings are assumed to be sinusoidally distributed, the magnetic saturation, the mutual leakage inductances, and the core losses are neglected. The electrical matrix equations in the stationary reference frame for the stator and the rotor may be written as

$$\begin{aligned} [V_s] &= [R_s][I_s] + P([L_s][I_s] + [L_m][I_r]) \\ 0 &= [R_r][I_r] + P([L_r][I_r] + [L_m][I_s]) \end{aligned} \quad (2)$$

where: [V], [I], [R], [L] and [Lm] are voltage, current, resistant, self and mutual inductance vectors, respectively. P is differential operator. Subscript r and s related to the rotor and stator resistance respectively. Since the rotor is squirrel cage, [Vr] is equal to zero.

As these equations implies, the electromechanical conversion, only takes place in the DQ subspace and the other subspaces just produce losses. Therefore, the control is based on determining the applied voltage in the DQ reference frame. With this transformation, the 6PIM control technique is similar to the classical three phase IM FOC. The control for the motor in the stationary reference frame is difficult, even for a three phase IM, so the transformation of SPIM model in a dq rotating reference frame to obtain currents with dc components is necessary, a transformation matrix must be used to represent the stationary reference fame (DQ) in the dynamic reference (d-q). This matrix is given:

$$T_{dq} = \begin{bmatrix} \cos(\delta_r) & -\sin(\delta_r) \\ \sin(\delta_r) & \cos(\delta_r) \end{bmatrix} \quad (3)$$

where δr is the rotor angular position referred to the stator as shown in Fig. 1.

The field oriented control (FOC) is the most used strategy in the industrial field. Its objective is to improve the static and dynamic behavior of asynchronous machine unlike the scalar control. It allows decoupling the electromagnetic quantities in order to make the control similar to DC machine. The principle of the FOC is to align the d axis of the rotating frame (d-q) with the desired flux as shown in Fig. 1. Therefore, the flux will be controlled by the direct component of the stator current (isd) and the torque by the quadratic component (isq). In this case we obtain as follows: $\psi_{rq} = 0; \psi_{rd} = \psi_{rd}$. The model motor dynamics is described by the following space vector differential equations:

$$\begin{cases} \dfrac{d\omega}{dt} = \dfrac{3}{2} n_p \dfrac{\delta \sigma L_s}{J}(\psi_{rd} i_{sQ}) - \dfrac{T_L}{J} - B\omega \\ \dfrac{d\psi_{rd}}{dt} = \dfrac{L_m}{\tau_r} i_{sD} - \dfrac{1}{\tau_r}\psi_{rd} \\ L_s \dfrac{di_{sD}}{dt} = -a i_{sD} + L_s \omega_s i_{sQ} + bR_r \psi_{rd} + c u_{sD} \\ L_s \dfrac{di_{sQ}}{dt} = -a i_{sQ} + L_s \omega_s i_{sD} + b_r \omega_r \psi_{rd} + c u_{sQ} \end{cases} \quad (4)$$

where

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}; a = \frac{L_m^2 R_r + L_r^2 R_s}{\sigma L_r^2}; c = \frac{1}{\sigma}; b = \frac{L_m^2 R_r}{\sigma L_r^2}$$

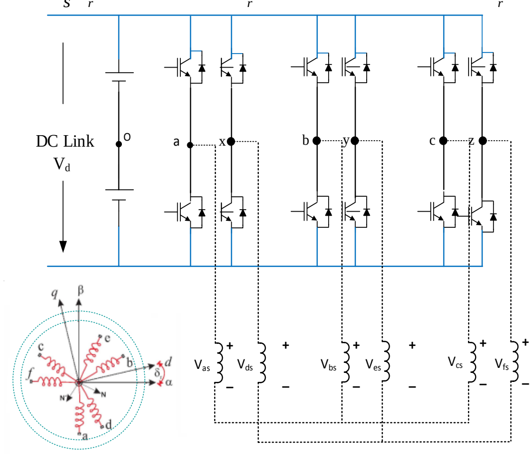

Fig. 1. A general scheme of an SPIM drive

The new expression of the electromagnetic torque and the slip frequency are given by:

$$T_e = \frac{3}{2} n_p \frac{M}{L_r} \psi_{rd} i_q \quad (5)$$

$$\omega_{sl} = \frac{M}{L_r} \psi_{rd} i_{sq} \quad (6)$$

3 Control Design for the Vector Control of SPIM Drive using BS_SOSM

3.1 Backstepping Design for the Outer Speed and Flux Loops

In this part, a modification on the BS technique SPIM is proposed for vector control of SPIM drives. As part of the trajectory tracking, the basic idea of the BSC is to make the system equivalent to a cascade first order subsystems, giving it strength qualities and overall stability of the asymptotic tracking error. The stability and performance of the systems is studied using the Lyapunov theory [2]. BSC technique is a systematic and recursive method for synthesizing nonlinear control laws. So a virtual command, that will be generated to ensure the convergence of the systems to their equilibrium states. it allows the synthesis of robust control law despite different types of disturbances and parametric uncertainties. In this proposal, the robustness of this scheme is improved by introducing integral terms of the tracking errors in the control design.

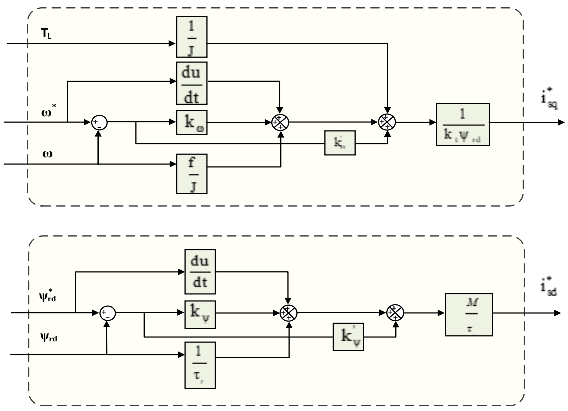

Fig. 2. The virtual inputs i sq and i sd.

The following tracking errors are defined:

$$\begin{aligned} \varepsilon_\omega &= \omega^* - \omega + k'_\omega \int_0^t (\omega^* - \omega)\,\mathrm{d}t \\ \varepsilon_\psi &= \psi^*_{rd} - \psi_{rd} + k'_\psi \int_0^t (\psi^*_{rd} - \psi_{rd})\,\mathrm{d}t \end{aligned} \quad (7)$$

To ensure the stability of the outer loops, the virtual inputs isq and isd are used. The dynamics of the tracking errors are given by:

$$\begin{aligned}\dot{\varepsilon}_{\omega} &= \dot{\omega}^{*} - \frac{3}{2} n_{p} \frac{\delta\sigma L_{s}}{J} \psi_{rd} i_{sq} + \frac{T_{l}}{J} + B\omega + k_{\omega}^{'}(\omega^{*} - \omega) \\ \dot{\varepsilon}_{\psi} &= \dot{\psi}_{rd}^{*} - \frac{L_{m}}{\tau_{r}} i_{sd} + \frac{1}{\tau_{r}} \psi_{rd} + k_{\psi}^{'}(\psi_{rd}^{*} - \psi_{rd})\end{aligned} \quad (8)$$

To design BSC scheme, the Lyapunov function is selected as

$$V_{(\omega,\psi)} = \frac{1}{2}(\varepsilon_{\omega}^{2} + \varepsilon_{\psi}^{2}) \quad (9)$$

its derivative can obtain:

$$\dot{V}_{(\omega,\psi)} = \varepsilon_{\omega} \dot{\varepsilon}_{\omega} + \varepsilon_{\psi} \dot{\varepsilon}_{\psi} = \varepsilon_{\omega}[\dot{\omega}^{*} - \mathrm{k}_{t} \psi_{rd} i_{sq} + \frac{T_{l}}{J} + B\omega + k_{\omega}^{'}(\omega^{*} - \omega)$$

$$+ \varepsilon_{\psi_{rd}} \left\{ \dot{\psi}_{rd}^{*} - \frac{L_{m}}{\tau_{r}} i_{sd} + \frac{1}{\tau_{r}} \psi_{rd} + k_{\psi}^{'}(\psi_{rd}^{*} - \psi_{rd}) \right\} \quad (10)$$

where $\mathrm{k}_{t} = \frac{3}{2} \mathrm{n}_{p} \frac{\delta\sigma L_{s}}{J}$ To satisfy V'< 0, BS control laws are designed as follows:

$$\begin{aligned} i_{sq} &= \frac{1}{\mathrm{k}_{t} \psi_{rd}} \left\{ k_{\omega}\varepsilon_{\omega} + \dot{\omega}^{*} + B\omega + \frac{T_{l}}{J} + k_{\omega}^{'}(\omega^{*} - \omega) \right\} \\ i_{sd} &= \frac{\tau_{r}}{L_{m}} \left\{ k_{\psi}\varepsilon_{\psi} + \dot{\psi}_{rd}^{*} + \frac{1}{\tau_{r}} \psi_{rd} + k_{\psi}^{'}(\psi_{rd}^{*} - \psi_{rd}) \right\} \end{aligned} \quad (11)$$

where k_{ω} , k_{Ψ} are positive constants. Substituting (11) into (10), the derivative of the Lyapunov function can obtain as:

$$\dot{V}_{(\omega,\psi)} = -k_{\omega}\varepsilon_{\omega}^{2} - k_{\psi}\varepsilon_{\psi}^{2} < 0 \quad (12)$$

The Eq. (11) can be summarized as follows (Fig. 2)
In order to realize the tracking of the stator current of induction motors, the SM control is used in the inner loop of SPIM motor.

3.2 SOSM Design for in the Inner Current Loops

In this paper, the inner current control objective is to make the measured stator currents reach the desired currents value i_s. SMC is adopted for the currents loop of SPIM drives, an adaptation law for this SMC scheme is derived based on Lyapunov theory to ensure stability and fast error dynamics.
Defining the current tracking errors as

$$\varepsilon_{i_{sd}} = i_{sd}^{*} - i_{sd} ; \varepsilon_{i_{sq}} = i_{sq}^{*} - i_{sq} \quad (13)$$

Consider s_1 and s_2 are the two sliding surfaces are defined for isd and i_{sq}, respectively. These sliding surfaces can be described as

$$s_{1=}\ \varepsilon_{i_{sd}} + k_{1}\int_{0}^{t} \varepsilon_{i_{sd}} dt \quad (14)$$

$$s_{2=}\ \varepsilon_{iq} + k_{2}\int_{0}^{t} \varepsilon_{i_{sq}} dt \quad (15)$$

where, k_1 and k_2 are the undetermined coefficient.
The time derivative of Lyapunov function yields:

$$\dot{s}_{1} = \dot{\varepsilon}_{i_{sd}} + k_{1}\varepsilon_{i_{sd}} \quad (16)$$

$$\dot{s}_{2} = \dot{\varepsilon}_{iq} + k_{2}\varepsilon_{i_{sq}} \quad (17)$$

Substituting Equation (4) to Equation (16-17) and combinating to the sliding mode exponential approach law, we get the following equation:

$$\begin{aligned}\dot{s}_{1} &= \dot{\varepsilon}_{i_{sd}} + k_{1}\varepsilon_{i_{sd}} = \dot{i}_{sd}^{*} + \frac{1}{L_{s}}\left[ai_{sd} - L_{s}\omega_{s}i_{sq} - bR_{r}\psi_{rd} - cu_{sd}\right] + k_{1}\varepsilon_{i_{sd}} = u_{s1} \\ \dot{s}_{2} &= \dot{\varepsilon}_{iq} + k_{2}\varepsilon_{i_{sq}} = \dot{i}_{sq}^{*} + \frac{1}{L_{s}}\left[ai_{sq} - L_{s}\omega_{s}i_{sd} - b_{r}\omega_{r}\psi_{rd} - cu_{sD}\right] + k_{2}\varepsilon_{i_{sq}} = u_{s2}\end{aligned} \quad (18)$$

The second order sliding controller which was proposed:

$$\begin{cases} u_{s_1} = -\left[\alpha_{1} sign(s_{1}) + \beta_{1} sign(ps_{1})\right] \\ u_{s_2} = -\left[\alpha_{2} sign(s_{2}) + \beta_{2} sign(ps_{2})\right] \end{cases} \quad (19)$$

where, α_1, α_2, β_1, β_2 are positive constants with: $\begin{cases}\alpha_1 > \beta_1 > 0 \\ \alpha_2 > \beta_2 > 0\end{cases}$. The sign(s) function is defined as:

$$sign(s_{i}) = \begin{Bmatrix} -1 & \text{if} & s_{i} < 0 \\ 0 & \text{if} & s_{i} = 0 \\ +1 & \text{if} & s_{i} > 0 \end{Bmatrix} \quad with \quad i = 1;2 \quad (20)$$

The SM control law can be found using Lyapunov theory and defining the Lyapunov function candidate:

$$V = \frac{1}{2}(s_{1}^{2} + s_{2}^{2}) \quad (21)$$

The time derivative of Lyapunov function can be calculated as:

$$\dot{V} = s_{1}\dot{s}_{1} + s_{2}\dot{s}_{2} \quad (22)$$

According to Lyapunov theory, if the function $\dot{V}$ is negative definite, this will ensure that the state trajectory will be driven and attracted toward the sliding surface s and once reached, it will remain sliding on it until the origin is reached asymptotically.

$$u_{sd} = \frac{L_s}{c}\Big[\alpha_1 sign(s_1) + \beta_1 sign(ps_1) + pi_{sd}^* + \frac{1}{L_s}\big(ai_{sd} - L_s\omega_s i_{sq} - bR_r\psi_{rd}\big) + k_1\varepsilon_{isd}\Big]$$
$$u_{sq} = \frac{L_s}{c}\Big[\alpha_2 sign(s_2) + \beta_2 sign(ps_2) + pi_{sq}^* + \frac{1}{L_s}\big(ai_{sq} - L_s\omega_s i_{sd} - b\omega_r\psi_{rd}\big) + k_2\varepsilon_{isq}\Big] \quad (23)$$

This ensure that:

$$\dot{V} = -\big[\alpha_1 sign(s_1) + \beta_1 sign(ps_1)\big][s_1] - \big[\alpha_2 sign(s_2) + \beta_2 sign(ps_2)\big][s_2] < 0 \quad (24)$$

4 Simulink and Discussion

The vector control for IFOC induction motor drive system is simulated by using MATLAB software. The block diagram of system is shown in Fig. 3. The proposed BS_SOSM control is compared to the classical control using a PI controller, to show the effectiveness of the proposed algorithm. The results analysis shows the characteristic robustness of the BS_SOSM control to disturbances of the load, the speed variations.

SPIM parameters: 220V, 50 Hz, 4 pole, 1450 rpm. Rs = 10.1Ω, Rr = 9.8546Ω, Ls = 0.833457 H, Lr = 0.830811 H, m = 0.783106H, Ji = 0.0088 kg.m2. Rs is nominal value of stator resistance.

4.1 Dynamic Performance of SPIM on Speed Reversal

The speed reference in this case is set up speed reversal from 1000 rpm to −1000 rpm under load torque for PI and BS_ SOSM controllers, respectively. The speed, torque and current stator responses are shown in Fig. 4. Initially, motor is accelerated in both the cases, is easy to see that BS_ SOSM controller can provide stability and faster dynamic responses than PI controller, speed transient time from zero to 1000 rpm in the case of PI controller is 0.177s and 0.081s in the case of BS_ SOSM controller as shown in Figure 5, respectively. When motor runs at steady state at 1000 rpm, a step speed command of −1000 rpm is applied at t = 1s. As soon as −1000 rpm is applied, negative torque is developed on the shaft of the rotor, consequently motor starts decelerating achieving zero speed and then starts accelerating in reverse direction and finally get in settled down at −1000 rpm. Total time taken speed reversal of the SPIM drive using PI controller is 0.112s, and 0.075s using BS_SOSM controller, respectively. Comparison the dynamic response time of torque and current of the FOC SPIM drive using PI controller is 0.185s, 0.103s using BS_SOSM controller in the start mode and its speed reverse from 1000 rpm to −1000 rpm is 0.155 s in case using PI controller and 0.1s using BS_ SOSM controller.

From the simulation results show that the dynamic performance of the vector control of SPIM drive are using BS_ SOSM very good, the measured speed follows the reference speed, the speed tracking efficiency is high, fast dynamic responses. Compare with the results obtained using PI controller, we can see that the proposed SPIM vector control strategy using BS_ SOSM controller give better dynamic performance for using conventional PI controller. In this proposed vector control, tracking performance, overshoot, transition time are better. Beside, the simulation results is also evident that the proposed SOSM controller can provide the load torque and isq current component with the better quality than the conventional SM controller (low torque and current ripple), whereas the conventional SM controller is remarkably affected by the chattering problem.

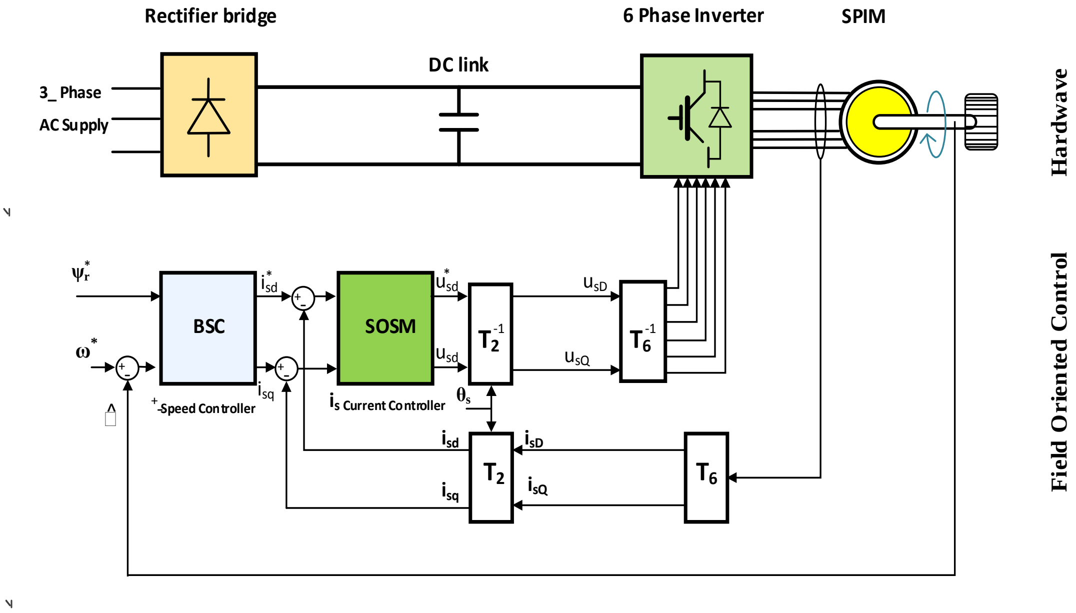

Fig. 3. The vector control of SPIM drive using BS_ SOSM control

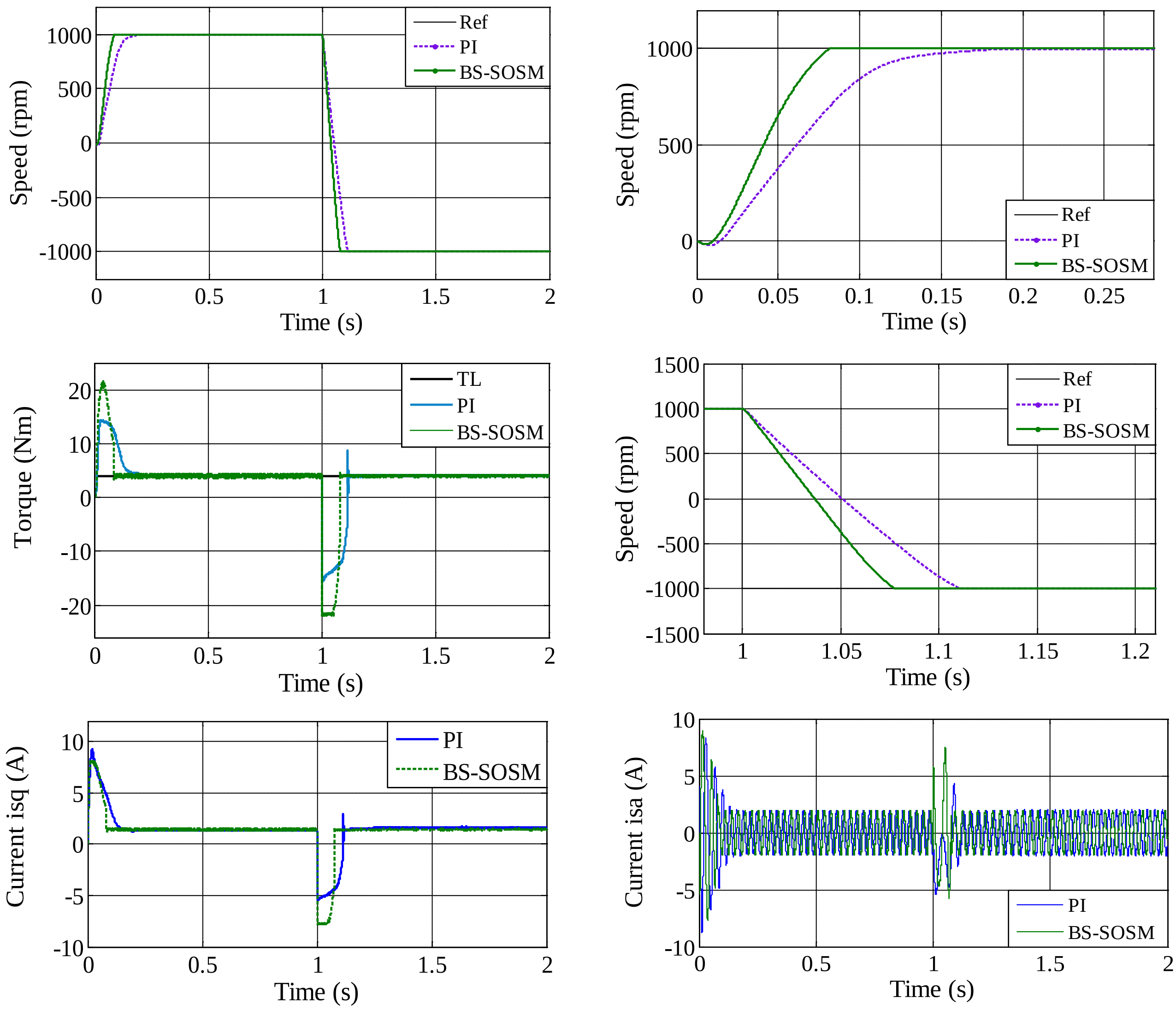

Fig. 4: The dynamics preformance of SPIM drive with PI and BS_ SOSM controller

4.2 Performance of IM on Step Load Disturbance

In this second case, the reference speed is increased from 800 rpm to 1200 rpm at t = 0.5s and decreased from 1200 rpm to 600 rpm at t = 1.5s. The responses of SPIM drive are shown in Fig.5. SPIM is started without load torque until the sudden rated load is supplied at t = 1s. The PI controller reaches 800 rpm in 0.096s, and the BS_ SOSM controller is 0.063s. The transition time of BS_ SOSM controller is shorter than PI controller for all reference speed. When the rated load torque is applied at 1s for the PI controller, the real speed dips to 1353 rpm and takes 0.5s to recover the speed to reference value, the BS_ SOSM controller, the speed dips to 1393 rpm and takes 0.16s to recover the speed to reference value. The speed error in steady state is near zero for the BS_ SOSM control and is 6.8 rpm for PI control. Fig. 5 shows that BS_ SOSM controller has a shorter rise time, settling time, and recovery time than PI controller. Also, proposed controller has the fast torque response and very low torque ripple. The simulation results show that the characteristic robustness of the BS_ SOSM control to disturbances of the load and the speed variations are better than conventional the PI control. The torque and isq current component ripple are improved significantly than the conventional SM controller due to using second order sliding mode (SOSM) controller for the inner current closed loop control to free of chattering problems.

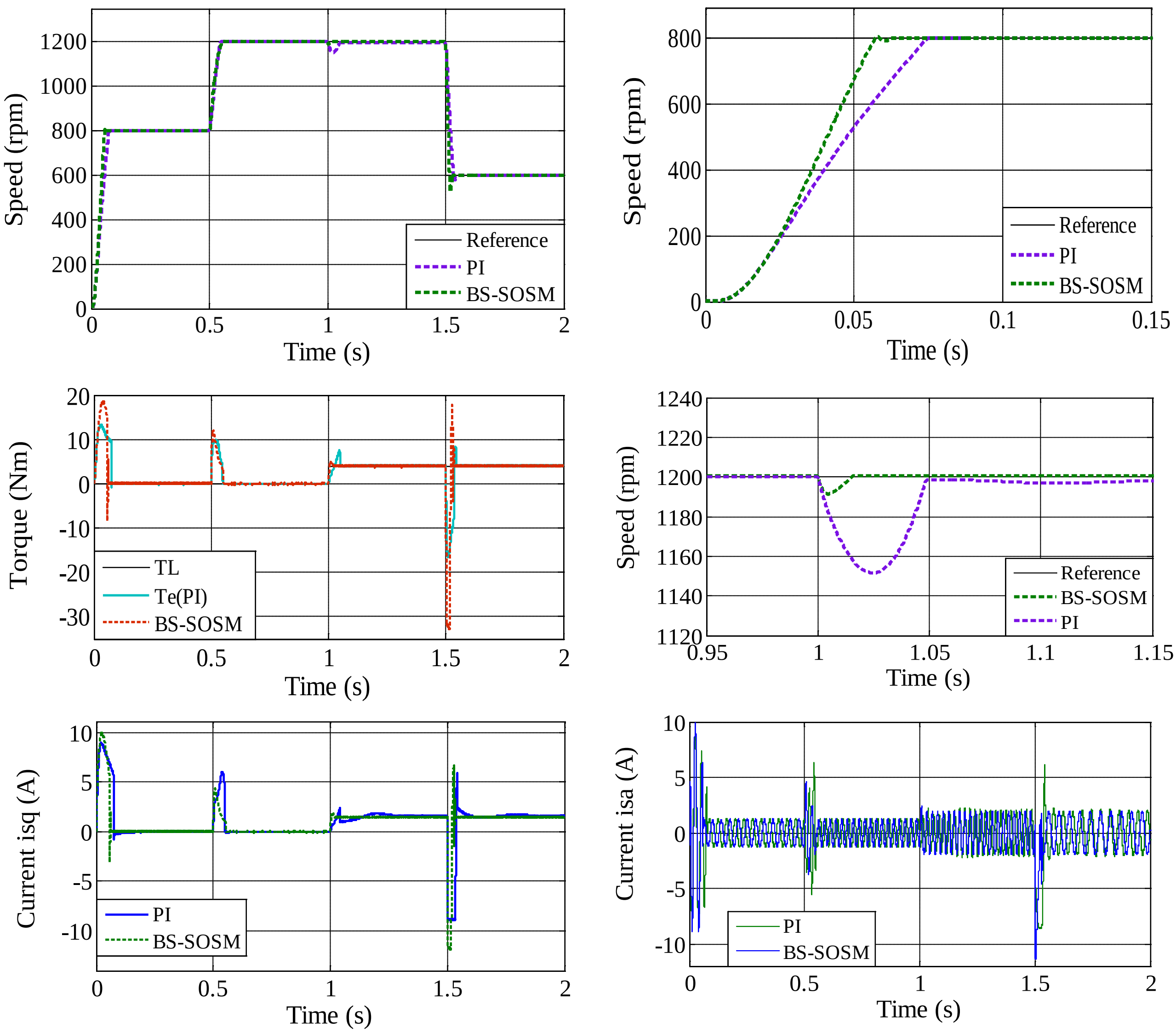

Fig.5 Performance of SPIM drive on the load disturbance

5 Conclusions

In this paper, a novel structure of Backstepping _ Second Order Sliding Mode nonlinear control (BS_SOSM) of the six phase induction motor (SPIM) is presented. The control design is based on combination SM and BS techniques to improve its performance and robustness, enables very good static and dynamic performance of SPIM drive system, perfect tuning of the speed reference values, fast response of the motor current and torque, high accuracy of speed regulation, and robust for the disturbances of the load, the speed variations and chattering free performance. The simulation results and discussion in section 4 confirmed the good dynamics and robustness of the proposed control algorithm based on the BS_SOSM.

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