

Novel BS_SM Nonlinear Control Structure for Field Oriented Control SPIM Drive

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Abstract: This study presents a novel structure of the Backstepping-Sliding mode nonlinear control (BS_SM) of the Six Phase Induction Motor (SPIM). 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. The simulation results confirmed the good dynamics and robustness of the proposed control algorithm based on the BS_SM technique.

Key words: Six phase induction motor, backstepping control, sliding mode, high accuracy, disturbances, robustness

INTRODUCTION

In recent decades, the multiphase motor drives are widely used in much applications due to their inherent features such as higher torque density, greater efficiency, reduced torque pulsations, fault tolerance and reduction in the required rating per inverter leg (Levi, 2008). 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 (Finch and Giaouris, 2008). With its reliable working characteristics and high failure tolerance now a days, these motors 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.

As the three phase induction motor when 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 (Alonge *et al.*, 2015; Abbas *et al.*, 2016), Sliding Mode (SM) (Orlowska-Kowalska *et al.*, 2009; Bartolini *et al.*, 2007), Backstepping control (BS) (Tan *et al.*, 2003; Jovanovic and Bamieh, 2004; Zaafour *et al.*, 2016; Traore *et al.*, 2010; Morawiec, 2014), Fuzzy Logic (FL) control (Padmanaban *et al.*, 2016; Masumpoor *et al.*, 2015) Neural Networks (NN) control (Fu and Li, 2015; Uddin *et al.*, 2013; Saghaforia *et al.*, 2013), predictive control (Liu *et al.*, 2019), Hamiltonian control (Cecati, 2000; Yu *et al.*, 2006a, b; Cheng and Jiao, 2013; Schaft, 1999; Ortega *et al.*, 2002). In the proposed technics, the BSC design techniques have received great attention due to its systematic and recursive design methodology for nonlinear feedback control. The BSC 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 informations about system dynamics are required when designing traditional BSC. To overcome this drawback many strategies have been proposed, Lee *et al.* (2006) 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. By Mehazzem *et al.* (2011) and Traore *et al.* (2010), 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 processor, since, the model will be increased by two states. Zaafour *et al.* (2016) 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 by Zaafour *et al.* (2016). 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 BSC and different robust adaptive control has been received more attentions (Liu *et al.*, 2016a-c; Su *et al.*, 2017; Chen *et al.*, 2014; Sun *et al.*, 2016; Yu *et al.*, 2018; Li *et al.*, 2016). Such as sliding mode control (Liu *et al.*, 2016a-c, 2019; Su *et al.*, 2017), neuron network (Chen *et al.*, 2014; Sun *et al.*, 2016; Yu *et al.*, 2018), Fuzzy Logic System (FLS) (Li *et al.*, 2016; Yuet *et al.*, 2015). In this study, the researcher 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 (Zaafour *et al.*, 2016). This novel BS_SM nonlinear combination structure ensure stability, robustness and fast error dynamics for SPIM drives. The effectiveness of this proposed control structure is verified by simulation using MATLAB/Simulink.

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 by Liu *et al.* (2019), the

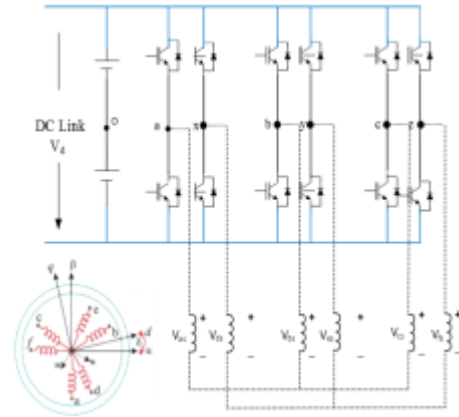


Fig. 1: A general scheme of an SPIM drive

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 (z1-z2). This transformation is obtained by means of 6×6 transformation matrix:

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

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] = Voltage vector
- [I] = Current vector
- [R] = Resistant vector
- [L] and [L_m] = Self and mutual inductance vectors
- P = The differential operator

where, subscript r and s related to the rotor and stator, respectively.

Since, the rotor is squirrel cage, $[V_r]$ is equal to zero. The electromechanical energy conversion only takes place in the DQ subsystem:

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

where, δ_r is the rotor angular position referred to the stator as shown in Fig. 1. As these equations implies, the electromechanical conversion, only takes place in the D-Q 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 6 PIM 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 (Levi, 2008) is necessary, a transformation matrix must be used to represent the stationary reference frame (DQ) in the dynamic reference (d-q). This matrix is given:

$$\begin{bmatrix} V_{sD} \\ V_{sQ} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + PL_s & 0 & PL_m & 0 \\ 0 & R_s + PL_s & 0 & PL_m \\ PL_m & \omega_l L_m & R_r + PL_r & \omega_l L_m \\ -\omega_l L_m & PL_m & -\omega_l L_m & R_r + PL_r \end{bmatrix} \begin{bmatrix} I_{s\alpha} \\ I_{s\beta} \\ I_{r\alpha} \\ I_{r\beta} \end{bmatrix} \quad (4)$$

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 (Dq(dq)) 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:

$$\psi_{rq} = 0; \psi_{rd} = \psi_{rd}$$

Using Eq. 1 and 4, the new model motor dynamics is described by the following space vector differential Eq. 5:

$$\begin{cases} \frac{d\omega}{dt} = \frac{3}{2} n_p \frac{\delta \sigma L_s}{J} (\psi_{rd} i_{sq}) - \frac{T_L}{J} - B\omega \\ \frac{d\psi_{rd}}{dt} = \frac{L_m}{\tau_r} i_{sD} - \frac{1}{\tau_r} \psi_{rd} \\ L_s \frac{di_{sD}}{dt} = -a i_{sD} + L_s \omega_s i_{sQ} + b R_r \psi_{rd} + c u_{sD} \\ L_s \frac{di_{sQ}}{dt} = -a i_{sQ} + L_s \omega_s i_{sD} + b_r \omega_r \psi_{rd} + c u_{sQ} \end{cases} \quad (5)$$

Where:

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

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

$$T_e = \frac{3}{2} n_p \frac{L_m}{L_r} \psi_{r\alpha} i_{r\beta} \quad (6)$$

$$\omega_s = \frac{L_m}{L_r} \psi_{r\alpha} i_{r\beta} \quad (7)$$

MATERIALS AND METHODS

Control design for the vector control of spim drive using BSC_SM techniques

Backstepping design for the outer speed and flux loops:

In this part, a modification on the BSC 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. 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 [20, TLTK]. In this proposal, the robustness of this scheme is improved by introducing integral terms of the tracking errors in the control design. The following tracking errors are defined:

$$\epsilon_\omega = \omega^* - \omega + k'_\omega \int_0^t (\omega^* - \omega) dt \quad (8)$$

$$\epsilon_\psi = \psi_{rd}^* - \psi_{rd} + k'_\psi \int_0^t (\psi_{rd}^* - \psi_{rd}) dt$$

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:

$$\epsilon_\omega = \omega^* - \frac{3}{2} n_p \frac{\delta \sigma L_s}{J} \psi_{rd} i_{sq} + \frac{T_L}{J} + B\omega + k'_\omega (\omega^* - \omega) \quad (9)$$

$$\epsilon_\psi = \psi_{rd}^* - \frac{L_m}{\tau_r} i_{sd} + \frac{1}{\tau_r} \psi_{rd} + k'_\psi (\psi_{rd}^* - \psi_{rd})$$

To design BSC scheme, the Lyapunov function is selected as:

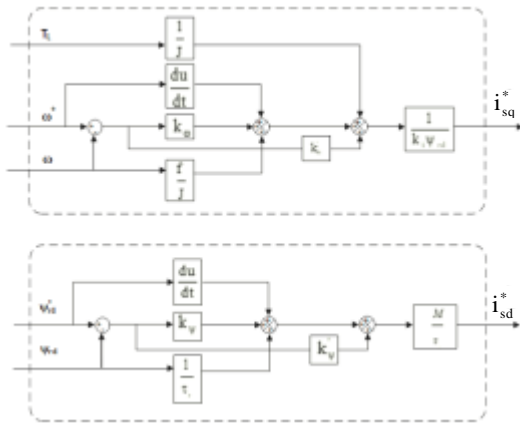


Fig. 2: The virtual inputs i_{sq}^* and i_{sd}^*

$$V_{(\omega, \psi)} = \frac{1}{2} (\varepsilon_{\omega}^2 + \varepsilon_{\psi}^2) \quad (10)$$

its derivative can obtain:

$$\begin{aligned} V_{(\omega, \psi)} &= \varepsilon_{\omega} \dot{\varepsilon}_{\omega} + \varepsilon_{\psi} \dot{\varepsilon}_{\psi} = \varepsilon_{\omega} \left[\dot{\omega}^* - k_t \psi_{rd} i_{sq}^* + \frac{T_l}{J} + B\omega + k_{\omega}' (\omega^* - \omega) \right] + \\ &\quad \varepsilon_{\psi} \left\{ \dot{\psi}_{rd}^* - \frac{L_m}{\tau_r} i_{sd}^* + \frac{1}{\tau_r} \psi_{rd} + k_{\psi}' (\psi_{rd}^* - \psi_{rd}) \right\} \quad (11) \\ k_t &= \frac{3}{2} n_p \frac{\delta s L_s}{J} \end{aligned}$$

where, to satisfy $V' < 0$, the BS control laws are designed as follows:

$$\begin{aligned} i_{sq}^* &= \frac{1}{k_t \psi_{rd}} \left\{ k_{\omega} \varepsilon_{\omega} + \dot{\omega}^* + B\omega + \frac{T_l}{J} + k_{\omega}' (\omega^* - \omega) \right\} \quad (12) \\ i_{sd}^* &= \frac{\tau_r}{L_m} \left\{ k_{\psi} \varepsilon_{\psi} + \dot{\psi}_{rd}^* + \frac{1}{\tau_r} \psi_{rd} + k_{\psi}' (\psi_{rd}^* - \psi_{rd}) \right\} \end{aligned}$$

where, k_{ω} , k_{ψ} are positive constants. Substituting 12 into 11, the derivative of the Lyapunov function can obtain as:

$$V_{(\omega, \psi)} = -k_{\omega} \varepsilon_{\omega}^2 - k_{\psi} \varepsilon_{\psi}^2 < 0 \quad (13)$$

Equation 12 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.

SMC design for in the inner current loops: In this study, the inner current control objective is to make the measured stator currents is reach the desired currents

value is*. SMC is adopted for the currents loop of SPIM drives, a 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:

$$\varepsilon_{i_{sd}} = i_{sd}^* - i_{sd}; \varepsilon_{i_{sq}} = i_{sq}^* - i_{sq} \quad (14)$$

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

$$\begin{aligned} s_1 &= \varepsilon_{i_{sd}} + k_1 \int_0^t \varepsilon_{i_{sd}} dt \\ s_2 &= \varepsilon_{i_{sq}} + k_2 \int_0^t \varepsilon_{i_{sq}} dt \end{aligned} \quad (15)$$

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

$$\dot{s}_1 = \varepsilon_{i_{sd}} + k_1 \varepsilon_{i_{sd}} \quad (16)$$

$$\dot{s}_2 = \varepsilon_{i_{sq}} + k_2 \varepsilon_{i_{sq}} \quad (17)$$

Substituting Eq. 5-17 and combining to the sliding mode exponential approach law, we get the following Eq. 18 and 19:

$$\begin{aligned} s_1 &= \varepsilon_{i_{sd}} + k_1 \varepsilon_{i_{sd}} = i_{sd}^* + \frac{1}{L_s} [a_{i_{sd}} - L_s \omega_s i_{sq} - b R_r \psi_{rd} - c u_{sd}] + \\ k_1 \varepsilon_{i_{sd}} &= -\alpha_1 \text{sign}(s_1) - \beta_1 s_1 \end{aligned} \quad (18)$$

$$\begin{aligned} s_2 &= \varepsilon_{i_{sq}} + k_2 \varepsilon_{i_{sq}} = i_{sq}^* + \frac{1}{L_s} [a_{i_{sq}} - L_s \omega_s i_{sd} - b_r \omega_r \psi_{rd} - c u_{sd}] + \\ k_2 \varepsilon_{i_{sq}} &= -\alpha_2 \text{sign}(s_2) - \beta_2 s_2 \end{aligned} \quad (19)$$

where, α_1 , α_2 , β_1 , β_2 are positive constants and the sign function is defined as:

$$\text{sign}(s_i) = \begin{cases} -1 & \text{for } s_i < 0 \\ +1 & \text{for } s_i > 0 \end{cases}; i = 1, 2$$

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

$$V = \frac{1}{2} (s_1^2 + s_2^2) \quad (20)$$

The time derivative of Lyapunov function (20) can be calculated as:

$$\dot{V} = s_1 \dot{s}_1 + s_2 \dot{s}_2 \quad (21)$$

According to Lyapunov theory, if the function 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. Combining Eq. 14-21 and the condition to satisfy the stability of the inner loops, the reference voltage of the stator d and the q axis are choiced as follows:

$$\begin{aligned} u_{sd} &= \frac{L_s}{c} \left(\alpha_1 \text{sign}(s_1) + \beta_1 s_1 + \dot{i}_{sd}^* + \frac{1}{L_s} (a_{id} - L_s \omega_s i_{sq} - b R_r \psi_{rd}) + k_1 \varepsilon_{i_{sd}} \right) \\ u_{sq} &= \frac{L_s}{c} \left(\alpha_2 \text{sign}(s_2) + \beta_2 s_2 + \dot{i}_{sq}^* + \frac{1}{L_s} (a_{iq} + L_s \omega_s i_{sd} + b_r \omega_r \psi_{rq}) + k_2 \varepsilon_{i_{sq}} \right) \end{aligned} \quad (22)$$

This ensure that:

$$\dot{V} = -\alpha_1 \text{sgn}(s_1) s_1 - \beta_1 s_1^2 - \alpha_2 \text{sgn}(s_2) s_2 - \beta_2 s_2^2 < 0 \quad (23)$$

RESULTS 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_SM 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_SM control to disturbances of the load, the speed variations.

SPIM parameters: The 1 Hp, 220 V, 50 Hz, 4 pole, 1450 rpm. $R_s = 10.1\Omega$, $R_r = 9.8546\Omega$, $L_s = 0.833457$ H, $L_r = 0.830811$ H, $m = 0.783106$ H, $J_i = 0.0088$ kg/m². R_s is nominal value of stator resistance.

Dynamic performance of SPIM on speed reversal: The speed, torque and current stator responses are shown in Fig. 4. The speed reference in this case is set up speed reversal from 1000 to -1000 rpm at rated load for PI and BS_SM controllers, respectively. Initially, motor is accelerated in both the cases is is easy to see that BS_SM controller can provide stability and fast dynamic responses, speed transient time from 0-1000 rpm at in the case of PI controller is 0.17 and 0.13 sec in the case of BS_SM controller as shown in Fig. 5, respectively. When motor runs at steady state at 1000 rpm, a step speed command of -1000 rpm is applied at $t = 1$ sec. 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 0.15 and 0.1 sec using BS_SM controller, respectively. Comparison the response time of load torque dynamics of BS_SM and PI techniques for the FOC SPIM drive its speed reverse from 1000 to -1000 rpm is 0.185 sec in case of PI controller and 0.12 sec in case of BS_SM cotroller.

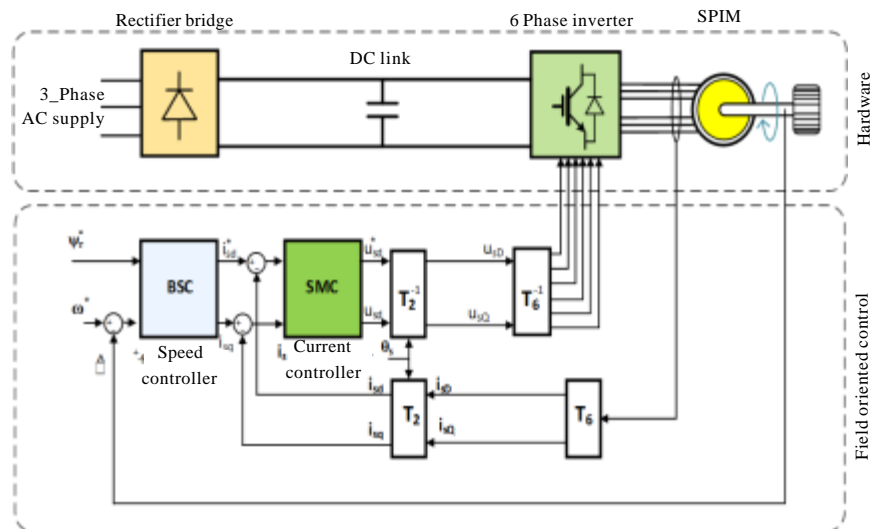


Fig. 3: The vector control of SPIM drive using BS_SM control

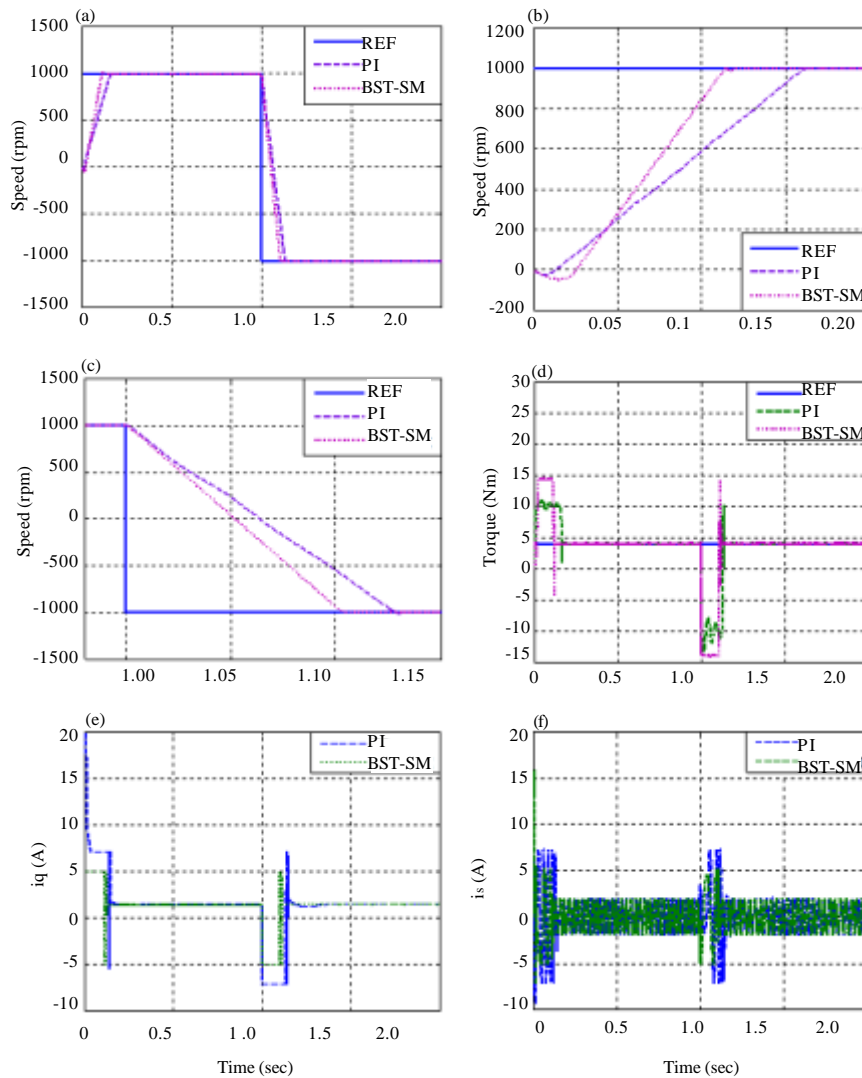


Fig. 4: a-f) The dynamics performance of SPIM drive with PI and BS_SM controller

From the simulation results show that the dynamic performance of the vector control of SPIM drive using BS_SM is very good, the real 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_SM controller gives better dynamic performance than using conventional PI controller. In this proposed vector control, tracking performance, overshoot, transition time are better. Also, the proposed controller has the fast torque response and low torque ripple.

Performance of IM on step load disturbance: The SPIM is started without load torque until the sudden rated load is supplied at $t = 1$ sec. The reference speed is increased

from 1000-1400 rpm at $t = 0.5$ sec and decreased from 1400-800 rpm at $t = 1.5$ sec. The responses of SPIM drive are shown in Fig. 5. In the PI control, it reached 1000 rpm in 0.1 and 0.75 sec with BS_SM control. The transition time of BS_SM controller is shorter than PI controller for all reference speed. In the PI control study, the speed dips to 1372 rpm and takes 0.35 sec to recover the speed to reference value. In the BS_SM, the speed dips to 1390 rpm and takes 0.21 sec to recover the speed to reference value. Figure 5 shows that BS_SM controller has a shorter rise time, settling time and recovery time than PI controller. Also, the proposed controller has the fast torque response and low torque ripple. The simulation results show that the characteristic robustness of the BS_SM control to disturbances of the load and the speed variations is better than conventional PI control.

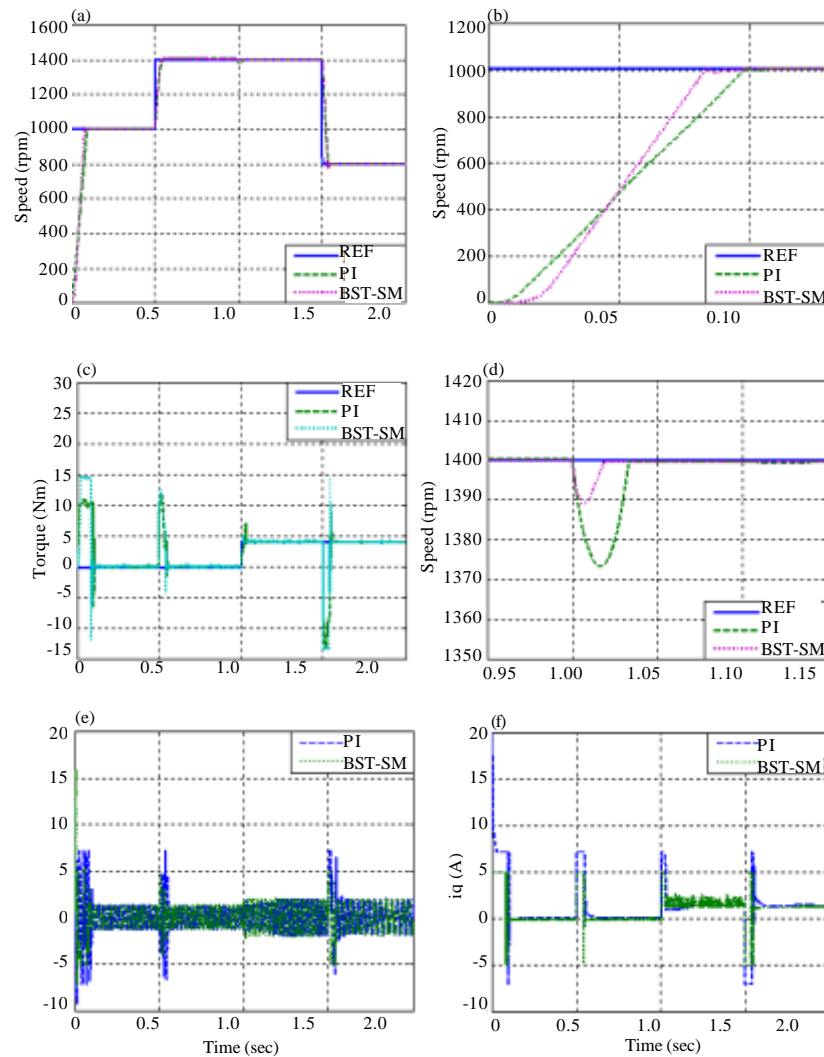


Fig. 5: a-f) Performance of SPIM drive on the load disturbance

CONCLUSION

This study proposes a novel control structure combining 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. The BS controller is proposed in outer speed closed loop control, the BS-based controller design, the integral error tracking component added to improve its sustainability. The SM control is proposed in 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. The proposed vector 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_SM technique.

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