International Journal of Engineering & Technology, 7 (2) (2018) 725-731

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET
doi: 10.14419/ijet.v7i2.10847
Research paper

Sensor less control of PMSM fed from three phase four switch inverter based on back EMF observer and sliding mode controller with fast reaching law

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Abstract

Closed Loop control of PMSM drives require rotor position and angular velocity information, the use of position sensor increases cost of the drive and increases complexity in motor construction. A position sensor less vector control technique is proposed where a back EMF observer is used to estimate motors speed and position signal. Back EMF observer method is simple and has high accuracy in estimating speed of PMSM motor. Permanent magnet synchronous motor is fed from a three-phase four-switch inverter and sliding mode controller is used as a speed regulator. Fast reaching law is added to sliding mode speed controller, which replaces constant switching gain function by variable switching function based on sliding surface. Variable switching function for SMC eliminates the chattering problem that occurs due to high value of constant switching gain. The proposed reaching law for sliding mode controller reduces the time taken for the controller to reach convergence and also increases robustness of the drive during parameter variation and full load conditions. Use of sensor less control technique and four-switch inverter reduced the overall cost of the drive whilst maintaining the performance of the system. Merits of pro-posed sensor less control technique and sliding mode controller with fast reaching law is verified by simulations using MATLAB/Simulink software.

Keywords: *EMF Observer; Permanent Magnet Synchronous Motor (PMSM); Sliding Mode Controller with Fast Reaching Law; Speed Estimation; Three Phase 4 Switch Inverter (TPFSI).*

1. Introduction

Construction of permanent magnet synchronous motor is quite simple and PMSM motor has high efficiency and high density due to its ruggedness. Hence it has been preferred in wide range of fields like automotive industry, traction device and hybrid electric vehicles [1-5]. Nevertheless, the closed loop speed control of PMSM motor requires the rotor position information and speed [6-7]. Encoders and position sensors are used to calculate speed of PMSM motor from low to high range, these sensors and encoders are to be mounted inside the motor case or on motors shaft, which is a difficult process. However, at low and high speeds motor causes vibrations, which reduce the accuracy of speed measurement using optical encoders and position sensors. Position Sensor less control has been the new trend for research in PMSM motor control applications [8-10]. It is possible with the development of speed estimation techniques based on machine parameters like voltage, current, flux and Back-EMF.

Sensor less control methods has two major classifications: Flux, EMF and current Observers based speed and position estimation method and the other methodology is based on injecting high frequency using motors salient effect. There are different speed estimation methods based on observers like model reference adaptive system [11], extended kalman filter [12-13] and sliding mode observers [14-15]. Among these methods MRAS is widely used in estimating motors speed and there are different types of observers like rotor flux, stator current and back EMF are employed in MRAS system. This method employs a PI controller as a model for adaptation mechanism. Function of PI controller is to compensate error between calculated and estimated values from observer. The performance of any MRAS system relies on tuning of this PI controller. This is the major drawback of a MRAS observer for speed estimation and sensor less control. Extended Kalman Filter is based on measuring system noise due to ripples caused by switching frequencies of PWM and measurement error in any parameters. However, kalman filter is not applicable for motor with nonlinear characteristics because this method employs a linear approximation law. Sliding mode observers are preferred for PMSM motors since it is highly applicable for nonlinear system. This method possess properties such as fast dynamic response, compensate for disturbances in the system and responds for time varying parameters in the system. This method needs to reduce chattering problem in estimating speed of the motor at full load condition. Due to drawbacks of various sensor less observer methods discussed, a back EMF observer [16] scheme based on model of motor is proposed for estimating motor speed in position sensor less approach. This method is easier to implement and no tuning process is involved for estimating speed.

In PMSM speed control applications dynamic speed controllers are required with faster convergence and must ensure stability during load disturbances. Sliding mode controller [17-18] is suitable for speed regulation with nonlinear property, but it exhibits a chattering phenomenon when tuned for quick response while tracking speed of a motor. This is due to the constant switching function gain of sliding mode controller with large value. A fast reaching law [19] is proposed for sliding mode controller; it provides a variable switching function gain and minimizes the chattering problem in reference speed tracking. Overall structure of proposed sensor less control method using back EMF observer method and speed regulation using sliding mode controller with fast reaching law for three phase four switch inverter fed permanent magnet synchronous motor vector control is explained in next chapter.

2. Objectives

To reduce the speed settling time of permanent magnet synchronous motor by using sliding motor control based fast reaching law and to reduce the rise time of motor performance using fast reaching algorithm.

3. Methods

3.1. Proposed sensor less PMSM drive

Block Diagram of sensor less vector controlled PMSM drive fed from a three-phasefour-switch inverter with fast reaching law sliding mode controller as speed regulator is shown in Figure 1. Here Sensor less control technique is used to reduce the cost of the drive system by applying back EMF observer for estimating speed of the motor. Estimate speed is given as input to sliding mode controller with fast reaching law. In general sliding mode controller uses a constant switching gain function whereas reaching law provides a variable switching function gain which helps in faster convergence where sliding mode controller is set to track a particular speed reference. It also reduces the chattering problem that occurs with high value of constant switching gain which is used for faster settling of sliding mode controller. The power circuit consists of a DC source and a three phase voltage source inverter with four power electronic switches driving PMSM motor. With four switches two legs of inverter is formed which excites any two phase of PMSM motor and third phase is excited from a capacitor leg which has two capacitors connected in series. For generating switching pulses for power switches a vector control technique is used in which speed regulator provides the reference current signal in quadrature axis and the direct axis reference current is given as zero. Then two PI controllers are added in the inner loop of vector control system, which acts as a current regulator of the drive, and the output of current regulator is kept within limits. Then the current regulator output and actual phase currents are compared using single band hysteresis comparator which produces switching pulses for inverter. Hysteresis comparator ensures same switching frequencies for all switches and limits the current to produce smooth current waveform.

3.2. PMSM

PMSM motors machine mathematical modeling in three phase ABC parameter is given in this section and the motor is made of four pole pairs. This model is used and depending upon vector control algorithm machine parameters in ABC form is converted into alpha-beta and d-q frame using clarks and parks transformations.

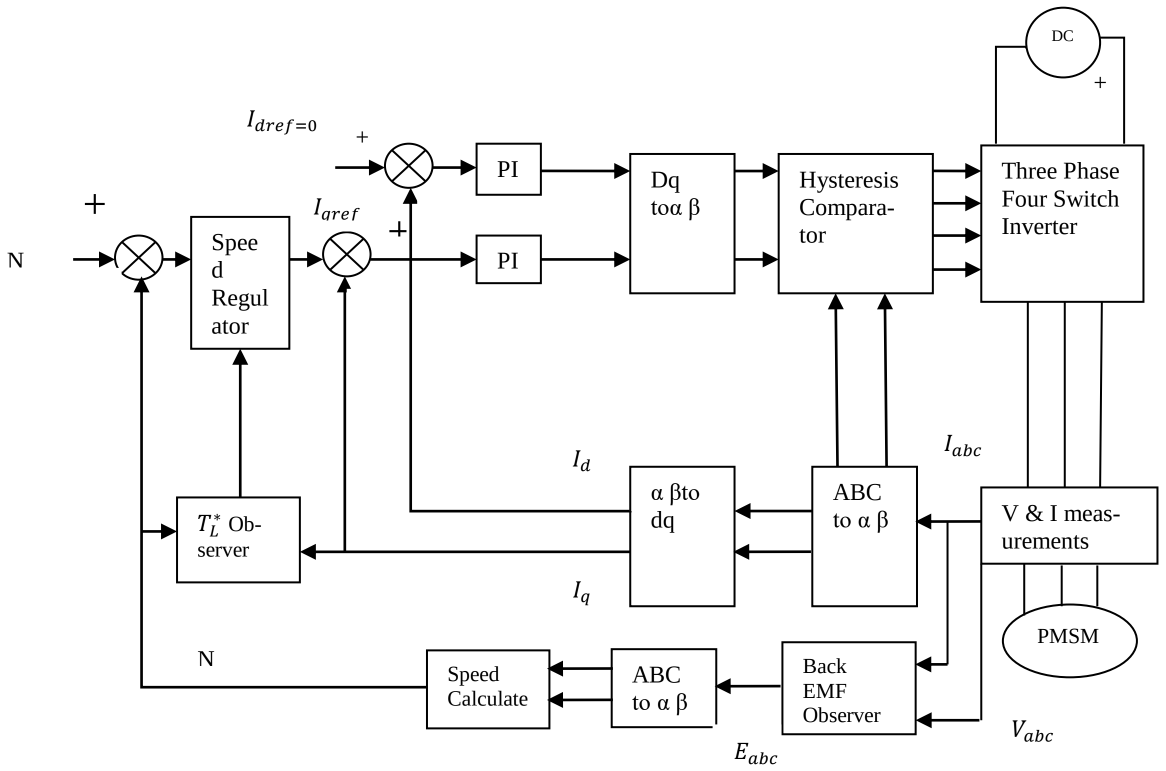

Fig. 1: Block Diagram of Proposed Sensor Less PMSM Drive.

$$\begin{bmatrix}V_a\\V_b\\V_c\end{bmatrix}=\begin{bmatrix}R_s&0&0\\0&R_s&0\\0&0&R_s\end{bmatrix}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix}\begin{bmatrix}L_s+L_m&-\frac{1}{2}L_m&-\frac{1}{2}L_m\\-\frac{1}{2}L_m&L_s+L_m&-\frac{1}{2}L_m\\-\frac{1}{2}L_m&-\frac{1}{2}L_m&L_s+L_m\end{bmatrix}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix}+\omega_e\begin{bmatrix}\phi_m\cos\theta_e\\\phi_m\cos\theta_e+\frac{2pi}{3}\\\phi_m\cos\theta_e-\frac{2pi}{3}\end{bmatrix}\tag{1}$$

Where $v_a, v_b and v_c$ are phase voltages of PMSM motor, $i_a, i_b and i_c$ are phase currents of PMSM motor R_s is stator resistance of PMSM, L_s is stator inductance of PMSM, L_m is mutual inductance of PMSM, ϕ_m is the flux linkage of PMSM

$$\theta_m=\frac{\theta_{\theta e}}{P}\tag{2}$$

$$\omega_m=\frac{\omega_e}{P}\tag{3}$$

$$T_e = \frac{3}{2} P \phi_m i_q \tag{4}$$

Whereθ_m and $\theta_e$mechanical and electrical angle (rotor position) of PMSM respectively, $\omega_m and \omega_e$are mechanical and electrical speed of PMSM and T_e is electrical torque of PMSM motor.

The mathematical equations of PMSM motors stator current in a dq synchronously rotating frame is given by

$$\frac{d}{dt} i_q = \frac{1}{L_q}\left(v_q - R i_q - \omega_e \phi_d\right) \tag{5}$$

$$\frac{d}{dt} i_d = \frac{1}{L_d}\left(v_d - R i_d - \omega_e \phi_q\right) \tag{6}$$

$$\phi_d = \phi_f + L_d i_d \tag{7}$$

$$\phi_q = L_q i_q \tag{8}$$

Where $v_q and v_d$are stator voltages in dq frame, $i_q and i_d$ are stator currents in dq frame, $L_q and L_d$ are motor inductances in dq frame, $\phi_d and \phi_q$are flux of PMSM motor in dq frame, T_e is electro-magnetic torque developed by PMSM motor.

3.3. Back EMF observer

To estimate the speed and position of motor for applying sensor less control technique back EMF observer is used. This method is based on PMSM motor mathematical model with simple calculations and no tuning process involved. The function of observer is to estimate back EMF of PMSM motor from sensed value of terminal voltage and currents at PMSM motor windings. Back EMF is calculated from line voltage and line currents using relation given in equation (9). Back EMF in three phase ABC parameter is converted into two phase alpha and beta parameters and then the magnitude of back EMF is calculated and the speed of PMSM motor can be estimated using (11) and (12). Flow chart of back EMF observer based speed estimation method is given in Figure 2.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} E_{alpha} \\ E_{beta} \\ E_{zero} \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} * \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{10}$$

$$E_{hypot} = \sqrt[2]{E_{alpha}^2 + E_{beta}^2} \tag{11}$$

$$\omega_r = \frac{E_{hypot}}{2 * p * flux} \tag{12}$$

$$\theta_r = arctan\left(\frac{E_{alpha}}{E_{beta}}\right) \tag{13}$$

Where V_a, V_b, V_c are phase voltages, I_a, I_b, I_c are phase currents, $e_a, e_b, e_c$are back EMF of PMSM motor. ω_rIs the rotor speed of PMSM motor and p is the number of pole pairs. Flux is the flux linkage established by magnets. Theta θ_r is the rotor angle or position of rotor.

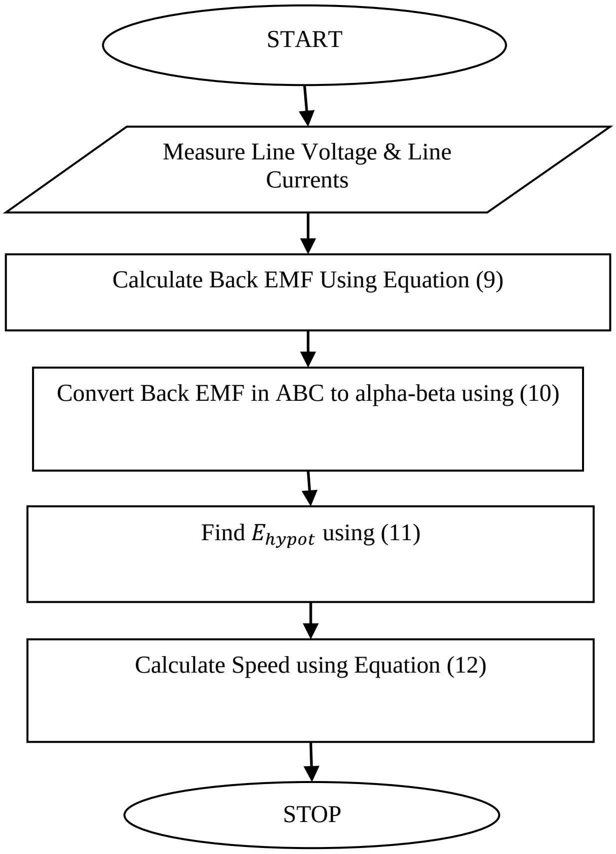

Fig. 2: Flow Chart of Back EMF Observer Based Speed Estimation Method.

3.4. Sliding mode controller with fast reaching law

Sliding mode controllers employ a constant switching gain which determines the reaching time of controller. For faster convergence high value of gain is chosen, this results in a chattering phenomenon while tracking set point using sliding mode controller. Hence a reaching law is presented which eliminates the constant switching gain and provides a variable switching gain for sliding mode controller. Reaching law results in faster convergence for set point tracking and reduces the chattering problem where the response of controller oscillates about steady state. Design of sliding mode controller with variable switching gain provided by reaching law along with load torque observer is presented in this section. The function of sliding mode controller is to control speed of motor with respect to set reference speed. Initial stage of SMC is selecting sliding surface and in speed control applications error between actual motor speed and reference speed is taken as sliding surface.

$$S = \omega_{ref} - \omega_e \tag{14}$$

$$\dot{S} = \omega_{\dot{r}ef} - \omega_e \tag{15}$$

$$\dot{S} = \omega_{\dot{r}ef} - \frac{P}{J}\left[T_e - \frac{B}{P}\omega_e - T_L\right] \tag{16}$$

$$\dot{S} = \omega_{\dot{r}ef} - \frac{3P^2\phi_m}{2J} I_q + \frac{B}{J}\omega_e + \frac{P}{J} T_L \tag{17}$$

Where S is the sliding surface, ω_{ref} is speed reference, ω_e is actual speed, B is Friction coefficient, J is Moment of Inertia and P is number of pole pairs

It is known that in SMC's sliding surface should reach zero to attain stability, that is by substituting$\dot{S} = 0$ in (17) we get,

$$I_q = \frac{2J}{3P^2\phi_m}\left[\omega_{\dot{r}ef} + \frac{B}{J}\omega_e\right] \tag{18}$$

$$I_{q-ref} = \frac{2J}{3P^2\phi_m}\left[\dot{\omega_{ref}} + \frac{B}{J}\omega_e\right] + K(s) * sgn(s) \tag{19}$$

Where $sgn(s) = \begin{cases} 1, s > 0 \\ 0,\ s = 0 \\ -1,\ s < 0 \end{cases}$ and K(s) is variable switching function gain determined using reaching law which ensures faster reaching and settling time of SMC.

3.4.1. Fast reaching law

To minimize the effect of high constant switching gain of sliding mode controller chosen for faster convergence, a variable switching function gain is introduced based on fast reaching law given in equation (20). Variable switching gain reduces the chattering effect on SMC outputI_{q-ref}. It improves the performance of SMC during full load conditions.

$$K(s) = \frac{K}{\epsilon + \left(1 + \frac{1}{|x_1|} - \epsilon\right)e^{-\delta|s|}} \tag{20}$$

Where k is the constant and k>0, 0 <ϵ< 1 and x_1 is state of SMC. Reaching law is analyzed for different values of$|s|$ sliding surface for faster reaching time and chattering suppression. It is known that if the value of$|s|$ increases during starting conditions then the output of reaching law reduces to $K(s) = \frac{K}{\epsilon}$ and hence $K(s)$ will become larger and the SMC will reach its surface quickly. Suppose if value of $|s|$decreases then the variable switching function is reduced to,$K(s) = \frac{K|x_1|}{\left(1+\frac{1}{|x_1|}\right)}$in which the state of SMC x_1 will reduce to zero. Hence, in this case also system reaches the sliding surface quickly and remains on it to reduce chattering.

3.4.2. Load torque observer

Disturbances in the system can degrade performance of SMC and the cause of disturbances is due to system parameter variations and load torque variations. It is necessary to compensate the disturbances in the system to enhance the robustness of controller on system performance. A Feed forward controller is used which is added to the output of sliding mode controller to compensate for the effect of disturbances. Feed forward controller is nothing but an observer which estimates the disturbances and load torque of PMSM motor based on equation (22). It reduces the steady error in tracking reference speed of PMSM motor with full load.

$$\hat{e} = \omega_{ref} - \omega_e \tag{21}$$

$$\widehat{T_L} = \frac{J}{P}\left(-\dot{\omega}_e + \frac{3P^2\phi_m}{2J}I_q - \frac{B}{J}\dot{\omega_e}\right) - K_o\hat{e} \tag{22}$$

Where$\widehat{T_L}$ is estimated load torque, K_o is observers gain and $\hat{e}$ is error in speed.

4. Simulation results and discussions

The proposed sensor less PMSM drive using back EMF observer for speed estimation and sliding mode controller with fast reaching law as speed regulator is implemented in MATLAB/Simulink and the implementation diagram is shown in Figure 3. PMSM motor parameters applied in simulation is given in Table I. Response of sensor less PMSM drive for set speed tracking and sensor less speed estimation is shown from Figure 4 to figure 9.

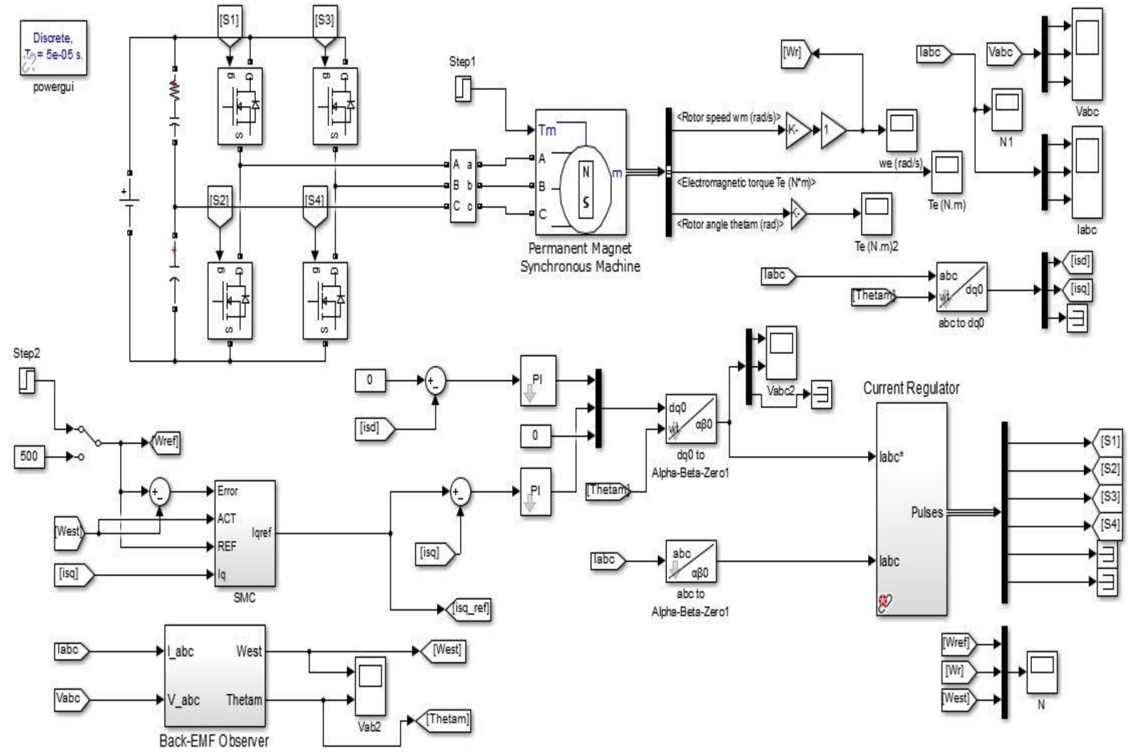

Fig. 3: Simulink Implementation of Sensor Less PMSM Drive.

Table I: Motor Parameters

S.No	PMSM MOTORPARAMETERS	
	Name	Range
1	Stator Resistance (Rs)	0.2 ohms
2	Stator Inductance (Ls)	8.5mH
3	Rotor Speed	500 rpm
4	Flux Linkage	0.175 V.s
5	Poles	4
6	Torque Constant	1.05N.m/A

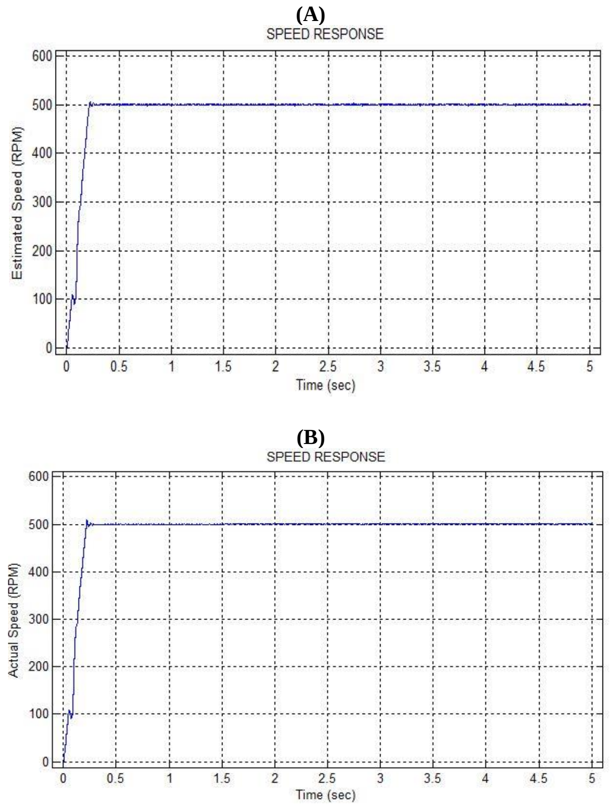

Fig. 4: Speed Response Using SMC (A) Estimated Speed Using Back EMF Observer (B) PMSM Motor Actual Speed.

Estimated Speed response of sensor less control of PMSM motor using sliding mode controller with fast reaching law is shown in Figure 4(A) and actual speed is shown in Figure 4(B). It is clear that estimated speed matches with actual speed of motor which verifies the accuracy of speed estimation using Back EMF observer method. Reaching time for set speed tracking is 0.21s and settling time is 0.26s with the proposed reaching law which is quicker than constant switching gain sliding mode controller.

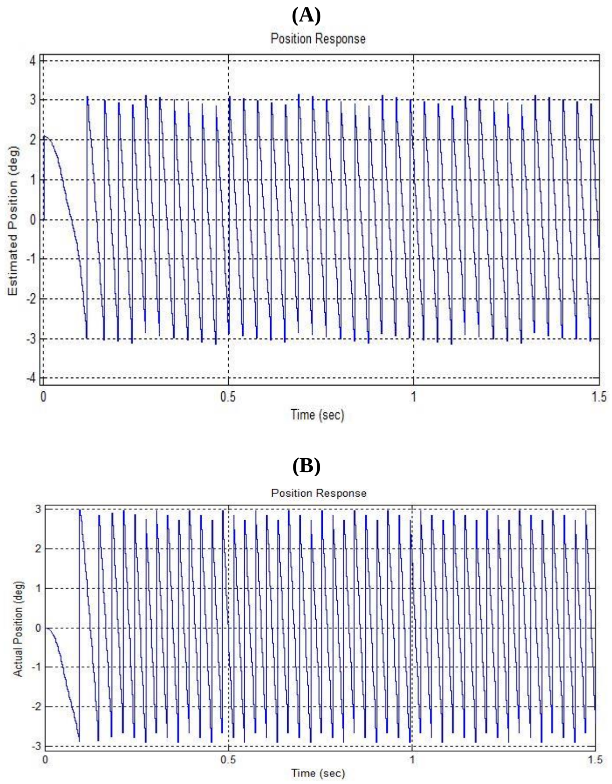

Fig. 5: Position Response Using SMC (A) Estimated Position Signal Using Back EMF Observer (B) Actual Position

Estimated position of sensor less control of PMSM motor using sliding mode controller with fast reaching law is shown in Figure 5(A) and actual position is shown in Figure 5(B). It is clear that estimated position matches with actual rotor position signal of motor which verifies the accuracy of position estimation using Back EMF observer method.

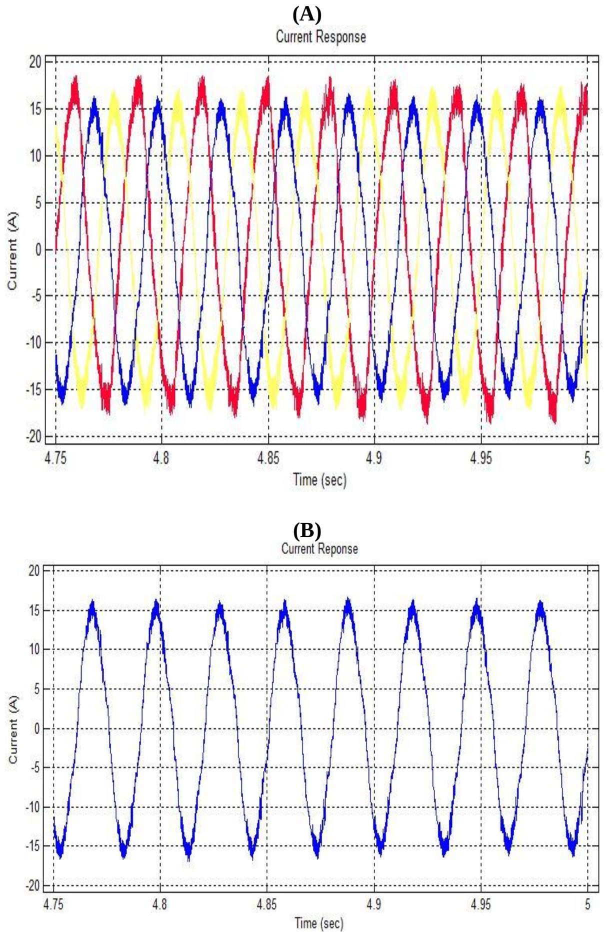

Fig. 6: Stator Current Response Using SMC (A) Combined Three Phase Current (B) Per Phase Current

Three phase Stator Current response of sensor less control of PMSM motor using sliding mode controller with fast reaching law is shown in Figure 6(A) and per phase current is shown in Figure 6(B). It is clear that current waveform of all three phases symmetrical even when motor is fed from a four switch inverter where the third phase is fed from a split capacitor leg.

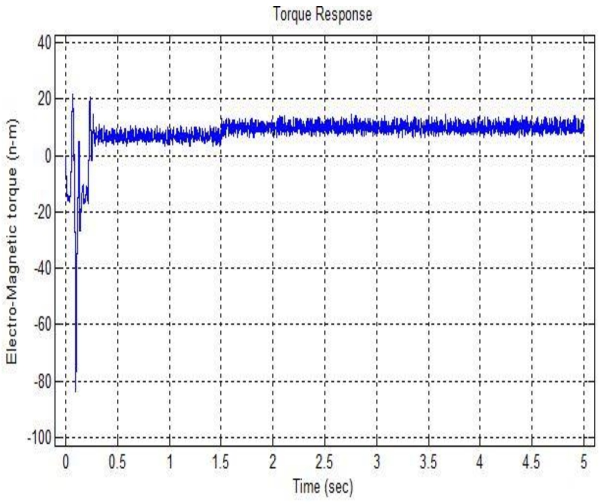

Fig. 7: Torque Response Using SMC.

Torque response of sensor less control of PMSM motor using sliding mode controller with fast reaching law is shown in Figure 7. Torque developed before controller reaching steady state that is not reaching the set speed is quite large and it settles to load torque once controller reaches steady state.

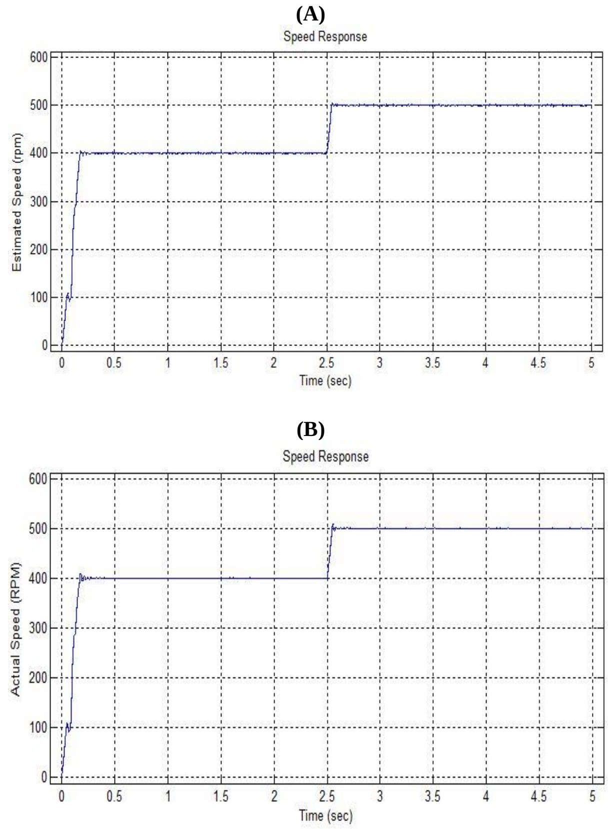

Fig.8: Speed Response Using SMC for Variable Speed Reference (A) Estimated Speed Using Back EMF Observer (B) Actual Speed

Estimated Speed response of sensor less control of PMSM motor using sliding mode controller with fast reaching law for variable speed reference is shown in Figure 8(A) and actual speed is shown in Figure 8(B). It is clear that the speed response for tracking set point during starting is quicker and when speed reference is changed at t=2.5 sec controller takes little time to track new speed reference.

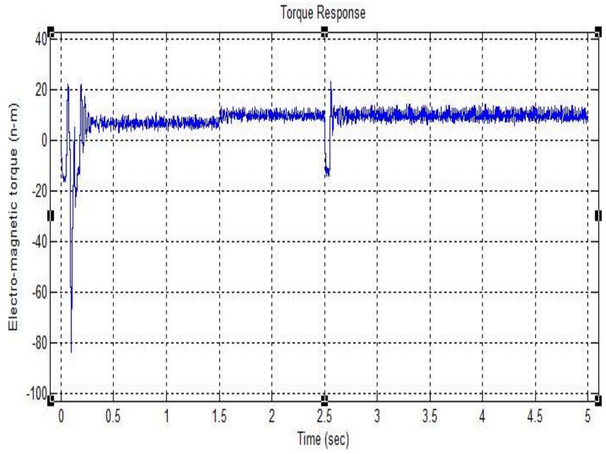

Fig. 9: Torque Response Using SMC for Variable Speed Reference.

Torque response of sensor less control of PMSM motor using sliding mode controller with fast reaching law for variable speed reference is shown in Figure 9. Developed Torque slightly oscillates when reference speed value is suddenly changed at t=2.5 sec.

5. Conclusion

Sensor less control of PMSM motor is presented in which Back EMF observer estimates the speed and position of motor with high accuracy. This algorithm is simple to implement since no tuning process involved and is based on mathematical model of PMSM motor. Fast reaching law has been proposed for sliding mode controller which provides a variable switching gain function and eliminates the chattering problem that occurs due to high constant switching gain function. Reaching law reduces the time taken for convergence in set speed tracking for speed control of PMSM motor during starting and varying reference speed with respect to time. PMSM motor is driven by three phase four switch inverter which reduces the cost of the drive with application of sensor less control strategy. The performance of the sensor less control using back EMF observer method and speed regulation of PMSM motor using sliding mode controller with fast reaching law is verified by simulations in MATLAB/Simulink platform.

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