

Sliding mode control with observer for permanent magnet synchronous machine drives

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ABSTRACT

This paper aims to develop the sliding mode control (SMC) scheme in sensorless permanent magnet synchronous machine (PMSM) drives to replace conventional proportional integral (PI) speed control. The SMC is formulated based on the integral sliding surface of the speed error. And the error is corrected based on the concept of Lyapunov stability. The SMC is designed with the load torque observer so that the disturbance can be estimated as feedback to the controller. The vector control technique which is also known as field-oriented control (FOC) is also used to split the stator current into the magnetic field generating part which is the direct axis and the torque generating part which is the quadrature axis. This can be done by using Park and Clarke transformations. The performance of the proposed SMC is tested under changes in load-torque and without load for different speed commands. The results prove that the SMC produces robust performances under variations of speeds and load disturbances. The effectiveness of the proposed method is verified and simulated by using MATLAB/SIMULINK software.

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1. INTRODUCTION

In recent years, sensorless machine drive has been widely used in servo applications because of its high reliability, low cost and also its smaller size. Permanent magnet synchronous machine (PMSM) is a popular machine drive that has advantages such as higher efficiency due to the absence of the magnetizing current, lower losses and lowers current for no-load conditions. PMSM also uses decoupling control, which makes it less sensitive to the speed and load variations of the motor [1]-[3]. PMSM is usually used for application which requires higher performance and higher efficiency for machine drives. High-performance machine control is classified as smooth running for all ranges of speed with full torque control at zero speed operation. To achieve that type of control, the field-oriented control (FOC) is the most commonly used control strategy of PMSM and it is preferable by the industry. However, this type of control technique is sensitive to parameters variation and load disturbances.

To solve these problems, many nonlinear control strategies have been implemented such as sensorless drives [4]-[6], model predictive control (MPC) [7], [8], backstepping control [9], [10], Kalman filtering [11], [12], and sliding mode control [13]-[15]. The FOC technique is also called vector control. The main objective of the field oriented control method is to produce the part of generating the magnetic field and the part of generating torque from the stator current part. Both components can be controlled separately after the transformation.

Subsequently, the structure of the machine control is almost similar to separately excited DC motor, which makes the control of a permanent synchronous machine (PSM) drives easier.

Previously, the control method using the sliding mode control (SMC) has been the focus of studies and researches for machine drive systems. This is due to many features which are fast dynamic response, robustness to parameter variation and also simplicity of design and implementation. In SMC strategy, the drive's response is forced to follow along predefined trajectory by switching the signal in a phase plane. Other than that, the strategy of SMC can be divided into different strategies such as using state observer [16]-[18] and disturbance observer [19]. Through these strategies, the observer is introduced to estimate the disturbance so that it can be compensated based on the observed value. This topology is expected to reduce the chattering system and giving a faster speed response and reduce the ripple during the loaded condition. Other researchers also use sliding surface [20], [21], and terminal SMC [22]-[24]. While another strategy is using control law [25]-[27], which introduce the non-linear term by choosing the appropriate law so that it can reduce the chattering problem and reduce the convergence rate. Other than that, few researchers are trying to use fuzzy logic control with SMC [28], [29] and applying optimization for SMC [30] to control the machine drives. This current research chooses the disturbance observer based on the load torque estimation so that it can be controlled by the sliding mode controller.

This paper presents the performance of the SMC with the load torque observer. It is arranged such in part 1 is about the introduction of SMC, part 2 presents the model and derivation of the proposed method which consists of PMSM modelling, sliding mode control and the torque load observer. Part 3 shows the simulation results and the analysis of the results with and without the SMC during parameter variations and load disturbances. The validity of the proposed method is verified using MATLAB/SIMULINK software. Lastly, the discussion is included is in part 4.

2. MATHEMATICAL MODEL OF PMSM

An equivalent circuit of PMSM which being used to develop the dynamic equations in the *d-q* axis [1] is shown in Figure 1. The quadrature and direct voltage equations (V_q and V_d) for the stator flux linkage (λ) along the *d-q* axis are presented in (1) and (2). While, i_d and i_q are the currents in the *q-d* axis and ρ is the differential factor. The *q-d* axis stator flux linkage based on rotor reference frames are then shown in (3) and (4).

$$V_q = R_q i_q + \omega_r \lambda_d + \rho \lambda_q \tag{1}$$

$$V_d = R_d i_d - \omega_r \lambda_q + \rho \lambda_d \tag{2}$$

$$\lambda_q = L_q i_q \tag{3}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{4}$$

Where L_d and L_q are the inductances for the *d-q* axis. Substituting (3) and (4) into (1) and (2), rearrange the equations in matrix form, the voltages equations will be written as (5),

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \tag{5}$$

where R_s is the stator resistance and λ_f is the field flux. Then, with P is the pole pair, the electromagnetic torque T_e , can be formularized as (6).

$$T_e = \frac{3}{2} \left(\frac{P}{2} \right) (\lambda_d i_q - \lambda_q i_d) \tag{6}$$

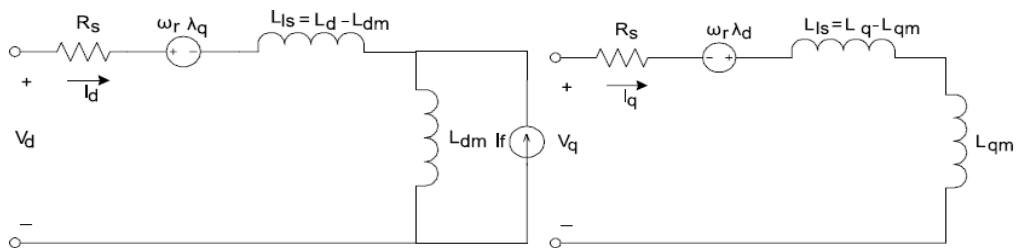


Figure 1. Equivalent circuit for permanent magnet synchronous machine (PMSM)

2.1. Field oriented control (FOC)

A FOC or vector control (VC) can be developed from the dynamic model of the PMSM based on Figure 2. Using the Park’s transformation, the 3-phase currents, i_a, i_b and i_c in the stator windings can be transformed into the rotor reference frame’s currents. Considering the three-phase line current (i_a, i_b, i_c) as input:

$$i_a = I_s \sin(\omega_r t + \alpha) \tag{7}$$

$$i_b = I_s \sin(\omega_r t + \alpha - \frac{2\pi}{3}) \tag{8}$$

$$i_c = I_s \sin(\omega_r t + \alpha + \frac{2\pi}{3}) \tag{9}$$

Transform (7) to (9) into the matrix form,

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\omega_r t + \alpha) \\ \cos(\omega_r t + \alpha - \frac{2\pi}{3}) \\ \cos(\omega_r t + \alpha + \frac{2\pi}{3}) \end{bmatrix} [I_s] \tag{10}$$

“ α ” is the different angle between stator and rotor currents in phasor and ω_r is the electrical rotor speed. The d - q currents (i_q and i_d) are constant in the rotor reference frame due to fix “ α ” for a given load torque. They could be written as (11),

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = I_s \begin{bmatrix} \sin \alpha \\ \cos \alpha \end{bmatrix} \tag{11}$$

the electromagnetic torque T_e equation is presented as (12),

$$T_e = \frac{3P}{2} \left[\frac{1}{2} (L_d - L_q) I_s^2 \sin 2\alpha + \lambda_f I_s \sin \alpha \right] \tag{12}$$

which L_d and L_q are the inductances for the d - q axis. And the electrical speed, ω_e is formularized as (13),

$$\dot{\omega}_e = \frac{P}{J} \left(T_e - T_L - \frac{B}{P} \omega_e \right) \tag{13}$$

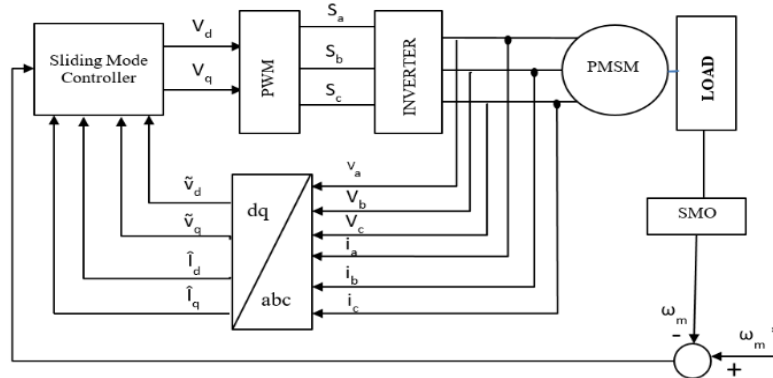


Figure 2. Block diagram for PMSM drive with sliding mode control (SMC)

2.2. Sliding mode control (SMC)

In this research, the SMC will be used to investigate its usefulness as a tracking controller for the speed of a PMSM. The controller aims to follow the reference speed ω_{ref} with the angular speed of the rotor ω_e (the acceleration and position are not considered). The error signal “ e ”, between the reference speed and actual speeds is determined as $e = \omega_{ref} - \omega_e$, which will represent the sliding surface “ s ”. Since the speed control loop is based on a first-order system, the derivation of the SMC design is based on the concept of Lyapunov stability. With the Lyapunov candidate function, “ V ” as written [24],

$$\dot{V} = \frac{1}{2} \dot{s}^2$$

the equation must be in positive definite. The derivation is written as (14),

$$\dot{V} = s\dot{s} < 0 \quad \forall s \quad (14)$$

which must be in negative definite. Because it has the sliding surface “s” in the form of,

$$s = \omega_{ref} - \omega_e, \text{ Then } \dot{s} = \dot{\omega}_{ref} - \dot{\omega}_e$$

now substitute for $\dot{\omega}_e$ and get,

$$\dot{s} = \dot{\omega}_{ref} - \frac{P}{J} \left[T_e - \frac{B}{P} \omega_e - T_L \right]$$

substituting T_e , then obtain,

$$\dot{s} = \dot{\omega}_{ref} - \frac{3P^2\phi_m}{2J} I_q + \frac{B}{J} \omega_e + \frac{P}{J} T_L \quad (15)$$

now, need to force \dot{s} to zero. At no-load condition ($T_L = 0$), (15) becomes,

$$\dot{\omega}_{ref} - \frac{3P^2\phi_m}{2J} I_q + \frac{B}{J} \omega_e = 0$$

where ϕ_m is the magnitude of flux linkage by the permanent magnet of phases, B and J are the friction coefficient and moment of inertia of the motor respectively. Then, the equation can solve for I_q ,

$$I_q = \frac{2J}{3P^2\phi_m} \left[\dot{\omega}_{ref} + \frac{B}{J} \omega_e \right] \quad (16)$$

The (16) is used to make sure that the trajectory system will lead to the sliding surface “s”, $\dot{s} = 0 \rightarrow s = \text{constant}$. And also to make sure that results $\dot{V} = s\dot{s} = 0$. However, the trajectory of the sliding surface is not enough for the state of stability, as it requires the system to maintain on the surface $s = 0$, where the error signal “e” is equal to zero, to achieve $\dot{V} < 0$. Other than that, in (16) requires another term to make sure that the trajectory is still on the sliding surface $\forall s$. This term is involved by a switching function, such as the sign function, which is presented by,

$$\text{sgn}(s) = \begin{cases} 1 & s > 0 \\ 0 & s = 0 \\ -1 & s < 0 \end{cases}$$

therefore, the reference q-axis current I_q^* is determined with the following scheme,

$$I_q^* = \frac{2J}{3P^2\phi_m} \left[\dot{\omega}_{ref} + \frac{B}{J} \omega_e \right] + k_c \text{sgn}(s) \quad (17)$$

which the constant k_c is again to satisfy the stability. Then, substitute I_q^* into (15),

$$\dot{s} = -K_a \text{sgn}(s) \quad (18)$$

where $K_a = \left(\frac{3P^2\phi_m}{2J} \right) k_c$. Hence, the stability in the no-load condition, as in (13) becomes $\dot{V} = s(-K_a \text{sgn}(s))$. Then,

$$\dot{V} = -K_a |s| \quad (19)$$

providing $K_a > 0$ in (18), it guarantees that $\dot{V} < 0$ or negative definite. So, the stability condition is satisfied $\forall s$.

2.3. Observer

An observer is formularized based on the error signal ($\hat{e} = \omega_e - \hat{\omega}_e$). It will be used in the feedback into the system back to increase the performance of the drive, in particular, to compensate for the disturbances.

The observer is to calculate the estimated torque-load, “ T_L ” and to compensate for other system variations that make the system robust in terms of uncertainties in modelling the nonlinear functions in the model. The observer output signal \hat{T}_L will be fed-forward to the controller. The estimated torque-load \hat{T}_L compensates the steady-state error between the actual electrical speed ω_e and the estimated electrical speed $\hat{\omega}_e$. Figure 3 depicts the structure of the proposed SMC observer.

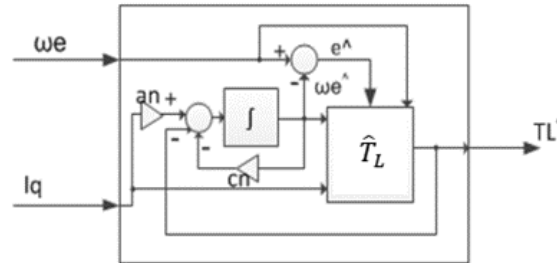


Figure 3. The structure of the SMC observer

Then, the proposed SMC is derived as derived in (17), and then to be substituted in (13). Therefore, an observer is proposed to estimate the torque-load based on the d - q axis model, so that it can reduce the chattering phenomenon and improve the speed response of the drive. The estimated load torque is presented in (20),

$$\hat{T}_L = \frac{J}{p} \left(-\dot{\omega}_e + \frac{3P^2 \phi_m}{2J} I_q - \frac{B}{J} \hat{\omega}_e \right) - k_o \hat{e} \tag{20}$$

3. RESULTS

The Simulation results of the PMSM drives using the proposed SMC scheme are presented in this part. Figure 4 shows the overall Simulink model of PMSM with SMC using MATLAB/SIMULINK. To show the effectiveness of the proposed control system, two tests were conducted which are performed with a variety of speeds under no-load conditions and performance under load variation. The system also is compared with the proportional integral (PI) controller which represents the system “without SMC”. The specification of the PMSM is tabulated in Table 1.

Table 1. Motor parameters

Parameter	Value
Stator phase resistance (R_s)	0.2 Ω
Inductance (L_d)	8.5e-3
Inductance (L_q)	8.5e-3
Magnetic flux linkage (ϕ_m)	0.175 Wb
Inertia (J)	0.0027 kg.m ²
Viscous damping (B)	0.0004924 N.m.s
Pole pairs	4
Rated torque (T_{rated})	8 Nm
Rated speed (ω_{rated})	1000 rpm

The system is tested under three-speed operations which are at rated speed 1,000 rpm, half of the rated speed 500 rpm and low speed, 300 rpm. Figure 5(a) shows the speed response at rated speed, 1,000 rpm with no load conditions. When the PMSM with SMC is tested running at rated 1,000 rpm, the speed response during transient has overshoot 1.5 rpm and the system reached steady state at 0.15 s. Meanwhile, in Figure 5(b), for speed 500 rpm, the system has an overshoot of 1.2 rpm and a steady-state at 0.08 s. Lastly, at speed 300 rpm, in Figure 5(c), the system has an overshoot of about 0.8 rpm and reach steady-state at the fastest time 0.046 s. Its shows that the proposed controller can response well under variation of speed condition without large overshoot. Since SMC is the robust controller, the motor was run at all test speeds under load conditions which are at $TL=8$ Nm, at half of rated load $TL=4$ Nm and also at $TL=2.4$ Nm. The objective of the test is to verify the robustness of the SMC under a variety of loads. Figures 6(a), (b), and (c) show the system speed response when the load is applied at 0.5 s at three different speed commands. When the motor is operated at a rated speed of 1,000 rpm, the system has undershoot 50 rpm and recovered within 0.018 s for a full rated load 8 Nm applied during steady state.

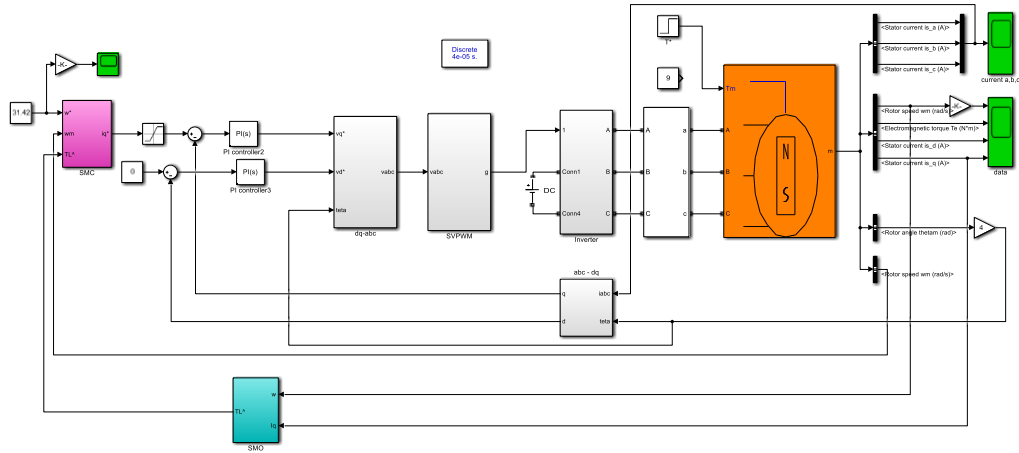


Figure 4. Simulink model of PMSM with SMC

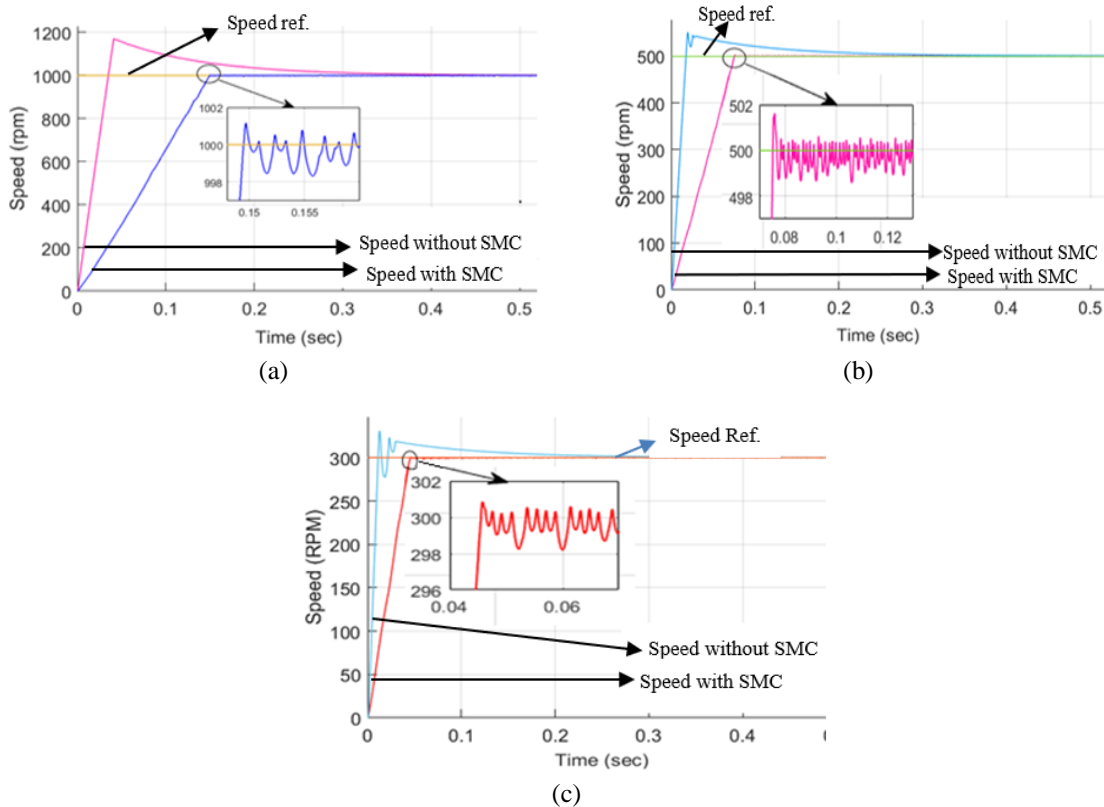


Figure 5. Speed performance when $T_L=0$ at a different speed at (a) at rated 1000 rpm, (b) at 500 rpm, and (c) at 300 rpm

Meanwhile, the undershoot and recovery time when a half rated load 4 Nm is given are 16 rpm and 0.005 s respectively. Then, load 2.4 Nm is applied gives undershoot 5 rpm with 0.004 s recovery time. Besides, the motor-operated at half rated speed 500 rpm. During load, 8 Nm has applied the system has the undershoot 68.75 rpm with settling time 0.02s. At 4 Nm load disturbance, the system undergoes 21.8 rpm of undershoot within 0.011 s recovery time. While the undershoot is 12.5 rpm and recovered in 0.009 s when the 2.4 Nm load is given to the system. Lastly, the motor is running at a speed of 300 rpm with the variation of load. At load 8 Nm, the system shows the largest undershoot about 90.909 rpm and settled down in 0.028s. At applied load 4 Nm, the undershoot is about 31.818 rpm with a recovery time of 0.027 s to get a steady-state. Meanwhile, the undershoot and recovery time for 2.4 Nm applied load are 13.636 rpm and 0.019 s respectively.

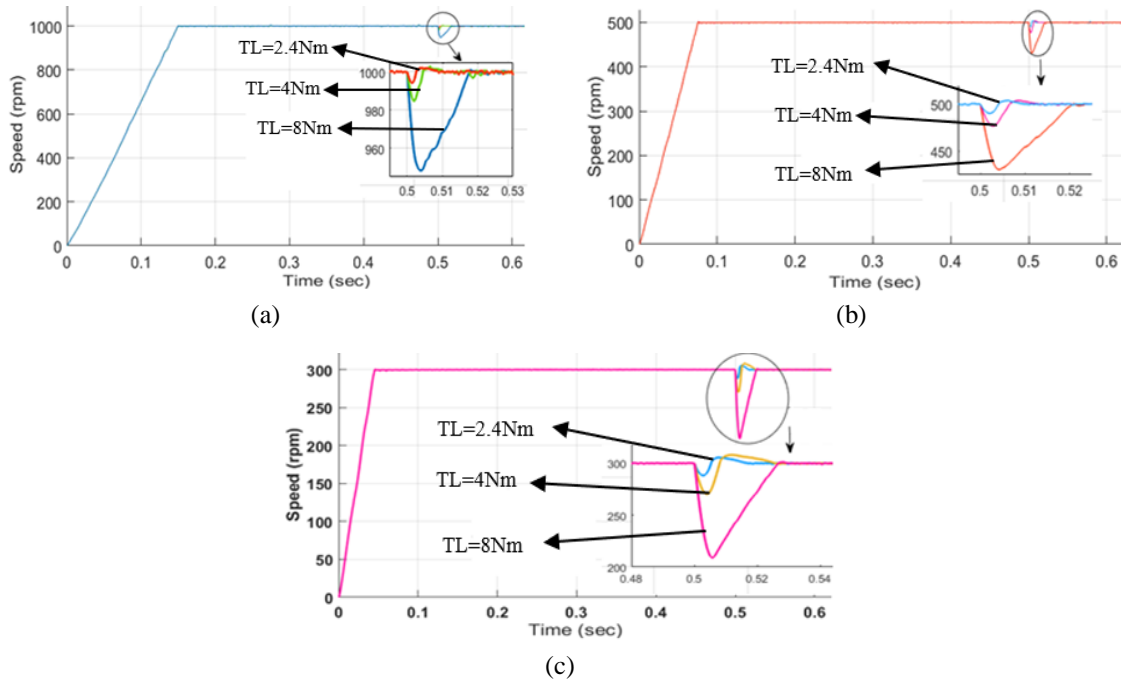


Figure 6. Speed performance when torque load is applied at a different speed at (a) at rated 1000 rpm, (b) at 500 rpm, and (c) at 300 rpm

4. CONCLUSION

A SMC with an observer for PMSM has been presented in this paper. The indirect field orientation control is used to ensure the control torque and magnetizing flux separately. Based on the results obtained, it can be concluded that the proposed sliding mode control can provide robust performance for speed and load variation. These conditions show that SMC maintains robustness to the load disturbances. For recommendation, there are several implementation need to be done for further research which are, hardware implementation of the proposed control scheme and selective adjustable functional gain parameters in the functional gain SMC to work with a different PMSM with its parameters.

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