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Differential Evolutionary Optimized Sliding Mode Control For Pmsm Drives

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Abstract: Increasing environmental concerns and fluctuating oil prices have paved way to adopt an alternative to combustion engines. At this instance, electric vehicles could be the most viable solution. Permanent magnet synchronous motors (PMSMs) have high power density, relatively smaller size and high torque-inertia ratio. However, it has series of challenging problems due to model mismatch, load disturbance, and nonlinear in nature. These challenges demand a robust controller. Sliding Mode Controller (SMC) is one such controller that eliminates internal parameter variations and external disturbances. This motivates the design of SMC for speed control of PMSM. The parameters of the SMC are optimized using Differential Evolutionary algorithm and performance of PMSM servo system is validated.

Keywords: Sliding Mode Controller; Differential evolutionary algorithm

1. INTRODUCTION

PMSM consists of permanent magnets which produce the air gap magnetic field instead of using electromagnets. The rotating magnetic field is produced by stator windings which receives AC supply from mains. At synchronous speed, the rotor poles lock to the rotating magnetic field. The use of sliding mode control in nonlinear system is justified by the fact that it can drive its system trajectory into the defined sliding manifold and has the capability to hold on there for all subsequent time.

Zhonggang Yin et.al., have proposed an Integrated Sliding Mode Control (ISMC) approach for control of PMSM, which simplifies the control structure by combining the position and speed control loops. The parameters of ISMC are updated appropriately using Differential Evolution algorithm to strengthen the robustness of the controller [6].

Xiaoguang Zhang et.al., introduced an exponential reaching law based SMC accounts for faster reaching of sliding manifold in PMSM. This reaching law helps in dealing with chattering and reaching time dilemma. Extended Sliding Mode Observer (ESMO) which is well known for its disturbance rejection and robust nature is designed [8].

S.Li et.al., employed terminal sliding mode based control method for speed tracking of PMSM. A terminal mode sliding mode control involves a nonlinear term in sliding surface which ensures accurate speed regulation [2].

Vadim I. Utkin et. al., discussed in detail about the basic concepts, mathematics, and design aspects ofslidingmode control especially for various electrical drives. The sliding mode control

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law is designed for electric drives which forces the state trajectories to reach the sliding surface infinite time and has the better effect to attenuate the disturbances [5].
Xudong Liu et. al., addresses the current control of permanent magnet synchronous motor (PMSM) for electric drives with model uncertainties and disturbances. A generalized predictive current control method combined with sliding mode disturbance compensationis proposed to satisfy the requirement of fast response and strong robustness [7].
Su Dandanet. al., proposed a sliding mode torque controller to decouple the currents of the q axis and d-axis. A law of exponential reach is applied to remove the chattering issue. The suggested technique may also ensure robust PMSM management via model parameters (resistance, inductance) and fluctuations in load torque [2].
Qiang Song et. al designed a novel integral sliding mode controller which guarantees the robustness against load variation in PMSM. Both conventional proportional-integral-derivative control system and the proposed sliding mode control system are simulated, and the results validatethe effectiveness of the proposed Integral Sliding Mode Control algorithm [4].

PMSM Model

The PMSM rotates due to the magnetic attraction between the rotor and the stator poles. When the rotor poles are facing stator poles of the opposite polarity, a strong magnetic attraction is set up between them. The mutual attraction locks the rotor and the stator poles together and the rotor is literally yanked into step with the revolving stator magnetic field. At no-load conditions, rotor poles are directly opposite to the stator poles and their axes coincide. At load conditions the rotor poles lag behind the stator poles, but the rotor continues to turn at synchronous speed, the mechanical angle 'θ' between the poles increases progressively as the load increases. During development of the model it is assumed that saturation is neglected, as PMSM is supplied with sinusoidal, the induced electromotive force (emf) is also sinusoidal. As there are eddy currents and hysteresis losses are negligible they are not included in system model also no field current dynamics in PMSM.

Voltage equations

$$v_q = R_s i_q + \omega_r \phi_d + \rho \phi_q \qquad (2.1)$$

$$v_d = R_s i_d - \omega_r \phi_q + \rho \phi_d \qquad (2.2)$$

Flux linkages are given by

$$\phi_q = L_q i_q \qquad (2.3)$$

$$\phi_d = L_d i_d + \phi_f (2.4)$$

The developed torque is derived as

$$T_e = \frac{3}{2} * \frac{n_p}{2} (\phi_d \phi_q - \phi_q \phi_d) \qquad (2.5)$$

$$T_e = T_L + B\omega + J\frac{d\omega}{dt} \qquad (2.6)$$

The transformation from the a-b-c (three phase) components to the d-q (direct and quadrature axes) components and vice versa are simple linear transformations. The transformation and inverse transformation matrices are as follows:

$$P = \frac{2}{3}\begin{pmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin(\theta) & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} (2.7)$$

$$P^{-1} = \frac{2}{3}\begin{pmatrix} cos(\theta) & -sin(\theta) & 1 \\ cos(\theta - \frac{2\pi}{3}) & -sin(\theta - \frac{2\pi}{3}) & 1 \\ cos(\theta + \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) & 1 \end{pmatrix} \quad (2.8)$$

Incorporating the transformations, the mathematical model of PMSM is given as

$$\dot{\omega} = \frac{K_t}{J} i_q - \frac{B}{J}\omega - \frac{T_L}{J} \quad (2.9)$$

$$\dot{i}_d = -\frac{R_s}{L_d} i_d + n_p \omega i_q + \frac{V_q}{L_q} \quad (2.10)$$

$$\dot{i}_q = -\frac{R_s}{L_q} i_q - n_p \omega i_d - \frac{n_p \phi_v \omega}{L_q} + \frac{V_q}{L_q} \quad (2.11)$$

where,
L_d = Direct axis inductance
L_q = Quadrature axis inductance
$L_d = L_q = L$
u_d = Direct axis voltage
u_q = Quadrature axis voltage
R_s = Stator resistance
ω = Rotor angular velocity
n_p = Number of pole pairs
φ_v= Rotor flux linkage
φ_d = Direct axis flux linkage
φ_q = Quadrature axis flux linkage
B = Viscous friction coefficient
T_L = Load torque
J = Moment of inertia
i_d = Direct axis current
i_q = Quadrature axis current
$K_t = 3n_p\varphi_v/2$

Closed loop control of PMSM

Field Oriented Control (FOC) represents the independent torque and speed control for every electromagnetic state of PMSM. Decoupled control, the torque is adjusted as per requirement by maintaining the magnetization state of motor at the suitable level. The FOC can be achieved using a linear transformation from rotating three phase quantities into two phase stationary quantities (d and q frame). The reference inputs for FOC are applied at q and d axes for torque and flux components respectively.

3.1. Clark Transformation

The transformation matrix helps to convert time varying a,b and c quantities into linear time invariant
α and β quantities by the following transformation matrix:

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$$i_{\alpha\beta 0} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3.1)$$

Keeping α in the same direction as the axis and an axis orthogonal as β, Fig. 1 obtained. Three phase system is modified into the (α, β) two dimension orthogonal system as given below which still depends on time and speed.

$$i_{s\alpha} = i_{\alpha} \quad (3.2)$$

$$i_{s\beta} = \frac{i_a}{\sqrt{3}} + \frac{2i_b}{\sqrt{3}} \quad (3.3)$$

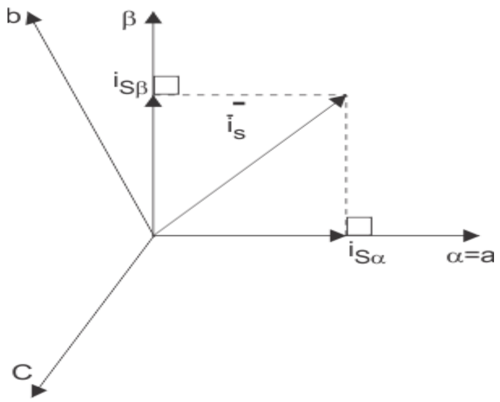

Fig 1 Vector diagram of stator currents

3.2. Park Transformation

A rotating reference frame (α, β) can be obtained from two phase fixed orthogonal system using this transformation. The transformation matrix is given by

$$i_{\alpha\beta 0} = \frac{2}{3} * \begin{bmatrix} cos\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ sin\theta & sin\left(\theta - \frac{2\pi}{3}\right) & sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} (3.4)$$

The angle between the rotating and fixed coordinate system is designated as θ. If the d axis aligned with the rotor flux, the relationship between the reference frames is depicted in Fig. 2.

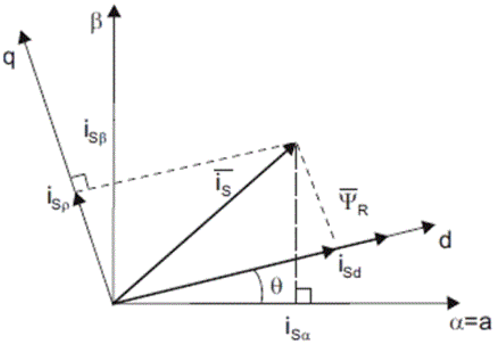

Fig.2. Reference frames

where, θ is the rotor flux position.

$i_{sq} = i_{s\alpha} sin\theta + i_{s\beta} cos\theta$ *(3.5)*

$i_{sd} = i_{s\alpha} cos\theta + i_{s\beta} sin\theta$ *(3.6)*

Equations (3.5) and (3.6) provide the torque and flux components of the current vector respectively. These components depend on the current vector (α, β) components and on the rotor flux position. Therefore it is possible to compute the d, q component. The torque may therefore be directly regulated by the independence of the flux component (isd) and the torque component (isq).

The currents represented in two axis stator reference frame (x-y) are rotated to align with the rotor flux using a transformation angle obtained by estimating the position of rotor. Now the currents are represented in the rotor reference frame (d-q). These currents are compared with its reference values obtained from the speed reference or torque reference. The error signals are input to the PI controllers. The output of the controller provides quadrature components of voltage vector in rotor reference frame (d-q). It is rotated back to stationary reference frame (x-y) using the same transformation angle. The voltage vector represented in two axis stationary reference frame is converted back to three axis system in the same reference plane.

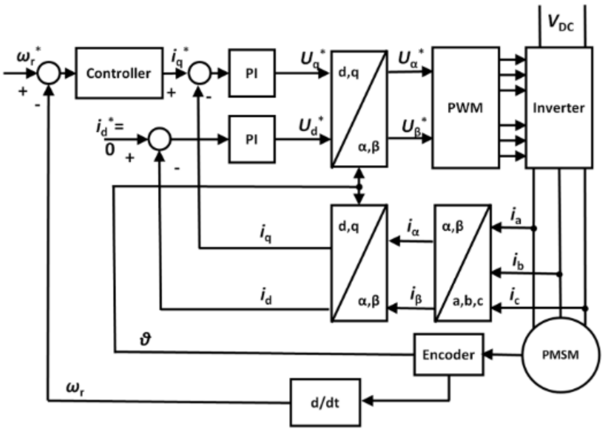

Fig 3 Closed loop control of PMSM

The required voltage vector is generated using Space vector pulse width modulation technique by applying suitable duty cycle in each arm of the three phase bridge.

Sliding mode controller design

State variables are expressed as

$x_1 = \omega_{ref} - \omega$ (4.1)

$x_2 = \dot{x}_1$ (4.2)

The sliding surface s is chosen as

$s = ax_1 + x_2$ (4.3)

Differentiation of (4.3) will give

$\dot{s} = ax_2 + \dot{x}_2 = ax_2 - b\dot{i}_q$ (4.4)

where a and b are positive adjustable parameters.

$b = 3n_p \frac{\phi_v}{2J}$ (4.5)

To ensure better dynamic performance and tracking capability for PMSM, the exponential reaching law is adopted. The exponential reaching function can be chosen as

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$$\dot{s} = -\varepsilon sgn(s) - cs \quad (4.6)$$

Where ε and c are positive adjustable parameters and sgn() represents the signum function. The output current of the sliding-mode controller can be obtained as

$$i_q^* = \frac{1}{b}\int_0^t [a\,x_2 + \varepsilon sgn(s) + cs]dt \quad (4.7)$$

where i_q^* is the output current of SMC in q axis.In order to test the stability of the designed controller, Lyapunov function candidate is chosen as

$$V = \frac{1}{2}s^2 \quad (4.8)$$

$$\dot{V} = s\dot{s} = s[-\varepsilon sgn(s) - cs]$$
$$= -s\varepsilon sgn(s) - cs^2 \quad (4.9)$$

If ‘a’ in Equation (4.3) is chosen as a real number, then $\dot{V} < 0$. According to the Lyapunov theory, the designed controller is stable.

Differential evolution

Evolutionary strategies have mutationas the primary search mechanism[7].It has the ability to handle non-differentiable, nonlinear and multimodel cost function, computation intensive cost function and good convergence properties.

5.1. Initialization

An initial population is created with random values for each decision parameter. Such values should be within the feasible bounds of the decision variable. Then, adding normally distributed random deviations to the nominal solution provides the initial population.

$$X_i = [x_{i1,}x_{i2}, \dots \dots, x_{ip}] \quad (5.1)$$

where, p is solution space dimension

Individual vector of X_i is found by using

$$x_{i,j} = x_{i,jmin} + rand(0,1) * (x_{i,jmax} - x_{i,jmin}) \quad (5.2)$$

where$x_{i,j}, x_{i,jmin,}x_{i,jmax}$are the j[th] component, minimum and maximum bounds of an individual vectors.

5.2. Mutation

Mutation and cross over operators produces the off spring. Perturbation to randomly selected vectors with other similar random vectors gives a mutation operator. Thus creating new particles into the population.

$$m_{i,j}^{k+1} = x_{r1,j}^k + F(x_{r2,j}^k - x_{r3,j}^k) \quad (5.3)$$

where F mutation factor

$m_{i,j}^{k+1}$is the mutated vector

$x_{r1,j}^k, x_{r2,j}^k, x_{r3,j}^k$are three different vectors

5.3. Crossover

It creates trial vectors used in the selection process. The combination of a mutant vector and a parent (target) vector will results in a trial vector. Binomial and exponential crossover techniques are used in DE. In binomial type DE, [0 1] is the random number at which a random number is generated which is further compared with crossover constant Cr. This decides whether the parameter is a mutant vector or parent vector. It is the first one if the random number is less than or equal to Cr. The other one will be selected if it is not following the earlier condition. More chances for selection of target vector in the trial vector as the Cr value approaches zero.

$$c_{k,j} = \begin{cases} m_{i,j}^{k+1} if j = q_j \\ x_{r1,j}^{k} otherwise \end{cases} \quad (5.4)$$

where$q_j$is random integer that belongs to (1, p)

5.4. Selection

Population in next generation is usually decided by the selection operator. Always one among trial vector and corresponding target vector which performs better will be selected in this process.

$$x_{i,j}^{k+1} = \begin{cases} c_{i,j}^{k+1} iff(c_{i,j}^{k+1}) < f(x_{i,j}^{k}) \\ x_{i,j}^{k} otherwise \end{cases} \quad (5.5)$$

The chosen parameters of DE algorithm are *NP* = 100, *F* = 0.5, *CR* = 0.9 in the proposed Sliding mode controller.

2. RESULTS AND DISCUSSIONS

The parameters used in PMSM model and the design of Sliding mode controller are presented in Table 1.The dynamics of PMSM are simulated using MATLAB/Simulink. The Sliding mode controller is designed by implementing the control law. The tuning of control gain is done in offline mode using Differential Evolution algorithm.
The gain values used for designing the controller are
a =0.15
c =20
ε =30

Table 1

PMSM Parameters

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S.no.	Parametername	Symbol	Value	Unit	
1	Coefficient of friction	B	$7.403*10^{-1}$	$N.m.s^{1}rad^{-1}$	
2	Moment of inertia	J	$1.74*10^{-4}$	$N.m.s^{2}rad^{-1}$	
3	Stator resistance	R_s	1.74	Ω	
4	Direct axis inductance	L_d	0.004	H	
5	Quadrature axis inductance	L_q	0.004	H	
6	Number of pole pairs	n_p	4	No unit	
7	Rotor flux linkage	Φ_v	0.1167	Wb	
8	Motor constant	K_t	0.3501	$N.m.A^{-1}$	
9	Set point	-	2000	RPM	
10	Load torque	T_L	0	Nm	
11	Maximum stator current error	$i_{s,max\ error}$	±1%	A	
12	Maximum stator current	$i_{s,max}$	5	A	
13	Maximum rotor speed	ω_{max}	10	$rad.s^{-1}$	

For different values of gain sliding surface is plotted and analyzed.

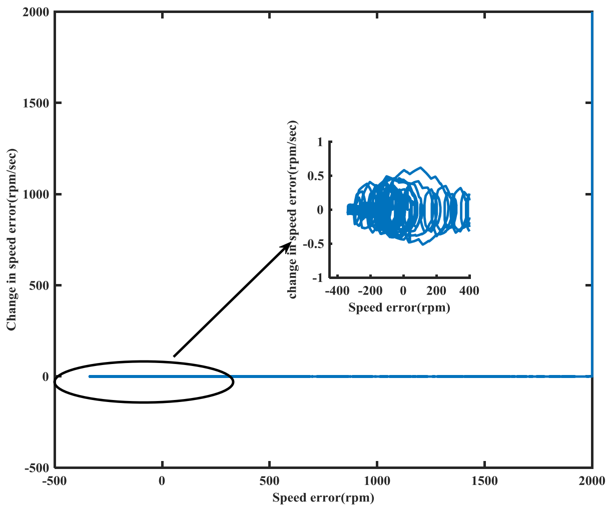

Fig. 4. Sliding surface (with optimal gain '0.15')

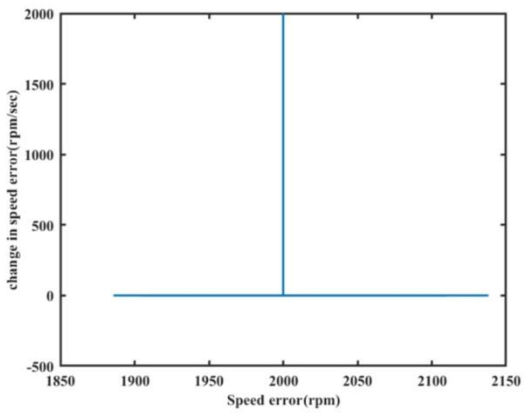

Fig. 5.Sliding surface (with gain '0.05')

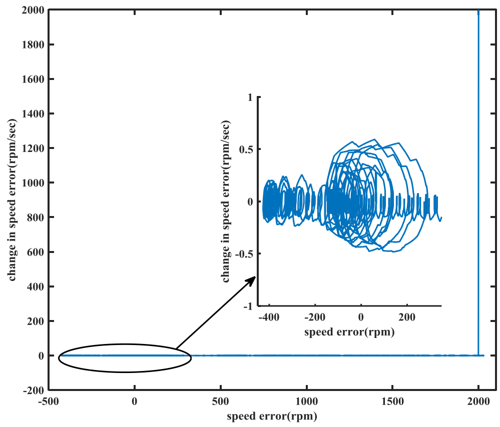

Fig.6. Sliding surface (with gain '0.55')

From Fig. 4 to 6, it is proven that the surface plot of The output is disturbed by the reference change at 0.1 sec. Initially, response takes 53 ms to settle. After the reference change, the settling time of the controller becomes 27.5ms.

6.1 Steady State Response

The response of the controller without any disturbance is checked. A reference of 3000rpm is set. It can be seen from Fig.7 that the controller tries to makes the system to settle near the set point with the settling time of 0.081 seconds with minimum overshoot of 13%.

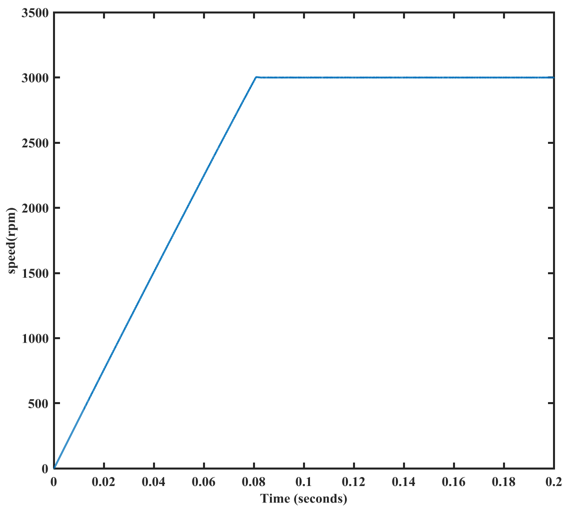

Fig.7 Steady state performance of SMC

6.2. Servo Response

A reference of 2000rpm is set initially. It is then increased to 3000rpm at t= 0.1s. The proposed sliding mode controller's tracking capability is analyzed using the Fig. 8

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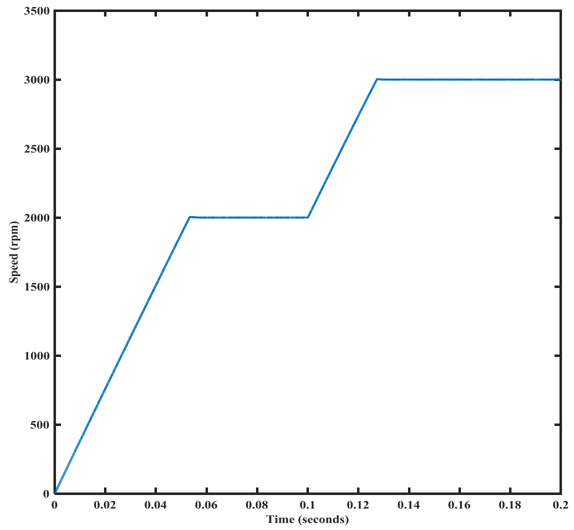

Fig.8.Tracking performance of SMC

The output is disturbed by the reference change at 0.1 sec. Initially, response takes 53 ms to settle. After the reference change, the settling time of the controller becomes 27.5ms.

6.2.Regulatory Response

The disturbance (load torque) is introduced and the performance of the motor is examined. A step load of 2 Nm is added to the motor at t=0.08s to check the load rejection capability of the proposed controller.

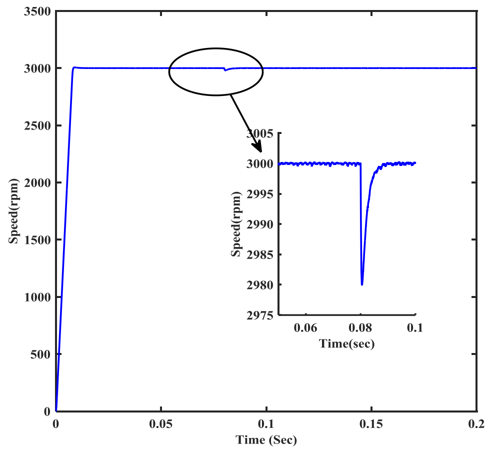

Fig. 9. Regulatory response of SMC

There is an undershoot of 0.66% at t=0.08 sec because of the addition of the load.
The response regains the reference speed within no time at t= 0.084 seconds.

3. CONCLUSION

Robust control laws are needed to achieve a high level of precision and accuracy. SMC is a robust control technique used for the non-linear dynamic systems having uncertainties and the convergence of states is guaranteed in finite time. In this project Sliding mode control scheme is implemented to achieve the speed control of PMSM. The Differential Evolution Technique is followed to improvise the controller design. After suitable iteration of DE algorithm, main parameters of SMC are optimized. Based on the results that are obtained, it is concluded that DE algorithm have strengthen the robustness of the controller.

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