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Controlling Strategies to Reduce Torque Ripple in Switched Reluctance Motor in Series Hybrid Electric Vehicle

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Abstract—Switched reluctance motor (SRM) are gaining wider popularity among variable-speed applications. This is due to their simple, low-cost construction characterized by an absence of magnets and rotor winding, high level of performance over a wide range of speeds, and fault-tolerant power stage design. Availability and the moderate cost of the necessary electronic components make SRM a viable alternative to other commonly used motors like AC, BLDC, PM Synchronous or universal motors for numerous applications. Switched reluctance motor's (SRM) double salient structure makes its magnetic characteristics highly nonlinear. The motor flux linkage and generated electric torque is a nonlinear function of stator currents as well as rotor position. All these make the control of the SRM a tough challenge. This thesis attempts to investigate the different controlling strategies for switched reluctance motor from the motor's structure properties, model equations, and operation principle. These controlling strategies are Proportion Integral and Derivative (PID) and Sliding Mode Control (SMC).

The performance comparison is done through rigorous Matlab/Simulink simulations.6/4 switched reluctance motor's Non-linear model is implemented for investigation.

***Index Terms*—Comparative study, Electric Vehicle, Switched reluctance motor (SRM), Slide Mode Controller (SMC),**

I. INTRODUCTION

At an age of more than 150 years, and counting, the switched reluctance motor (SRM) represents one of the oldest electric motor designs around [1,2].

The concept of the switched reluctance machine is actually very old, going back to the 19th century inventions called "electromagnetic engines" [3],which were the forerunners of modern stepper motors. The switched reluctance motor is basically a stepper motor and has had many applications as both rotary and linear steppers. The idea of using the SR configuration in a continuous mode (on contrast to a stepper mode) with power semiconductor control is due primarily to Nasar [4], French [5], Koch [6] and Lawrenson [7] in the 1960's. At that time, only thyristor power semiconductors were available for the relatively high-current, high-voltage type of control needed for SR machines. These years, power transistors, GTOs, IGBTs, and power MOSFETs

have been developed in the power ranges required for SRM control.

Partly as a result of recent demand for variable-speed drives and primarily as a result of the development of power semiconductors, a variation on the conventional reluctance machine has been developed and is known as the switched reluctance" (SR) machine. The name "switched reluctance", first used by one of the authors of [4], describes the two features of the machine configuration: (a). switched the machine must be operated in a continuous switching mode, which is the main reason the machine developed only after good power semiconductors became available; (b). reluctance it is the true reluctance machine in the sense that both rotor and stator have variable reluctance magnetic circuits, or, more properly, it is a double salient machine. Simple construction is a prime feature. SR motors eliminate permanent magnets (PMs), brushes and commutators. The stator consists of steel laminations forming salient poles. A series of coil windings, independently connected in phase pairs, envelops the stator poles. With no rotor winding, the rotor is basically a piece of steel (and laminations) shaped to form salient poles. It is the only motor type with salient poles in both the rotor and stator (double salient). As a result, and also because of its inherent simplicity, the SR machine promises a reliable and low-cost variable-speed drive and will undoubtedly take the place of many drives now using the cage induction and DC commutator machines in the short future.

Switched reluctance motors are a relatively new addition to the previously well-established albeit limited number of

different types of electrical machines. Like all its major rivals - the induction, synchronous, dc, and brushless dc motors the SR motor operates equally well as a generator. However, unlike the first three of these alternatives, the SR motor cannot operate directly from a mains ac or dc supply and requires a power electronic switching circuit to function. Whereas in the past this was a significant limitation, nowadays with relatively inexpensive switching devices and electronic controls available, most electric motors are now widely used with variable speed electronic controls so in this respect the SR machine is little different. [8] The principle of operation of the SR motor has been known since the earliest days of electric machines and it is probably the easiest electric motor to understand. The operation is illustrated by Figure 1 which shows in cross section a 6-4 SR motor (ie having 6 stator and 4 rotor poles).

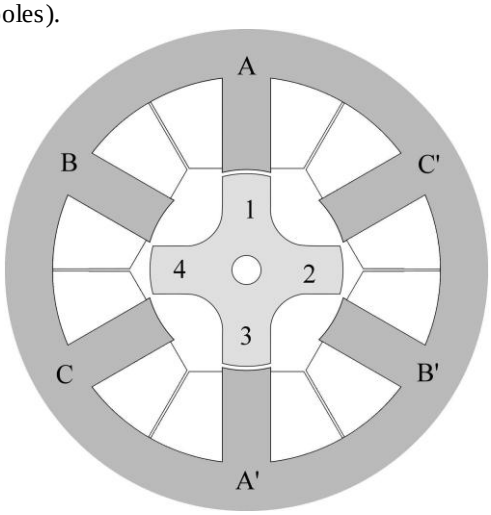

Fig. 1. Cross section of SR Motor

Both stator and rotor are assembled from steel laminations of the same grade and thickness as would be used for an equivalent induction motor. The stator poles have concentrated windings which are generally connected in diametrically opposed pairs to form phases, three phases in the case of Figure 1. There are no windings on the rotor. [9]

If in the position shown phase A is supplied with current the rotor poles 1 and 3 will be pulled into alignment with the phase A stator poles by magnetic attraction. If phase A is then turned off and phase B energized the rotor poles 2 and 4 will be pulled into alignment with phase B. Energizing phase C will then pull rotor poles 1 and 2 into alignment with phase C. By successively energizing the phases the rotor can be made to step around in a clockwise direction. Also by reversing the phase sequence to A-C-B the rotor will move in the opposite (counterclockwise) direction. A simple calculation will show that the step angle for the 6-4 motor is 30'.

At a first impression the SR motor appears to be very similar to a stepper-motor, known from the 1950s and used for positioning applications. However the stepper motor usually has multiple teeth per pole and as a result has a small step angle of typically 1.5'. The stepper motor is also not designed for efficient and smooth operation at speed and generally has difficulty in maintaining torque as speed increases. The SR motor is also similar to the conventional reluctance motor in that this also has salient rotor poles and no rotor windings.

The reluctance motor has a conventional three phase distributed winding (like the induction motor) which with ac supplies creates the well-known rotating field and, due to its saliency, the rotor is pulled around in synchronism by magnetic attraction. The SR motor differs in that it is energized by switching on and off discrete pulses of current in the phases hence the description "switched reluctance" to distinguish it from the conventional reluctance motor. The SR motor was previously referred to as "variable reluctance" and this description is still sometimes used.

II. SRM CONTROLLER ARCHITECTURE

Besides guaranteed stability, it is desirable for SRM controllers to have features such as parameter insensitivity, quick precise dynamic responses, and rapid recovery from load disturbances. Traditionally, SRMs are controlled by the combination of a conventional PI controller and switching controllers. The traditional control scheme is sensitive to variations in plant parameters and operating conditions. Hence, there have been demands for rigorous nonlinear control design methods for SRM to meet the performance criteria. The objectives of this paper work is as follows:

- To study and analyze the principle and operation of SRM
- To obtain the mathematical model of SRM
- To design and compare performance of PI controller and sliding mode controller for speed controller.

A. SRM DRIVE SYSTEM:

Adjusting the SRM torque to obtain constant speed under different load condition is the objective of the SRM controller. Figure 2 shows the block diagram of SRM connected to the load with current and speed feedback loop [9]. The function of the current controller is to adjust the

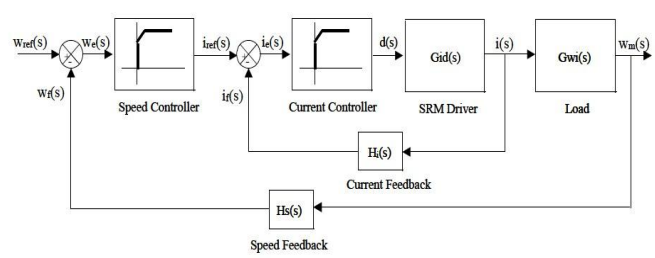

Fig.2: Block diagram of SRM controller.

Shape of the current waveform as well as the magnitude in order to maintain the desired torque under different load

condition. The input signal of the speed controller is the error between the reference speed and the feedback speed, which can be derived from the position encoder. The output of the speed loop is used as the reference of the current feedback loop.

B. SRM CURRENT CONTROL SCHEME

To maintain the desired torque at different loads, the current waveform should be shaped properly. Usually, there are two major factors that influence the current waveform. One is firing angle, another is switching method.

For the SRM, each phase current is always built up from zero. For the motoring operation, each phase is excited between the unaligned and aligned position. The dwell angle is defined as $\theta_c - \theta_0$, where θ_0 is the starting angle and θ_c is the commutation angle Figure 3 shows the firing angle varying with the rotor speed.

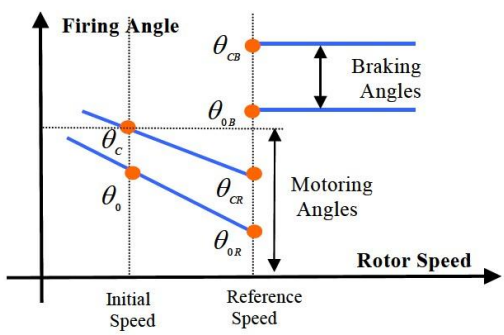

Fig.3 Firing Angle varies with the Rotor

C. SINGLE PULSE CONTROL

The way of the single-pulse control is that two main switches on each leg are simultaneously turned-on during the dwell angle, and then turned-off after the commutation angle. Figure 4 shows the idealized inductance, voltage applied to the phase winding, flux linkage and phase current. This control scheme is simpler and has less switching loss than other control scheme; also, it has high current rising rate

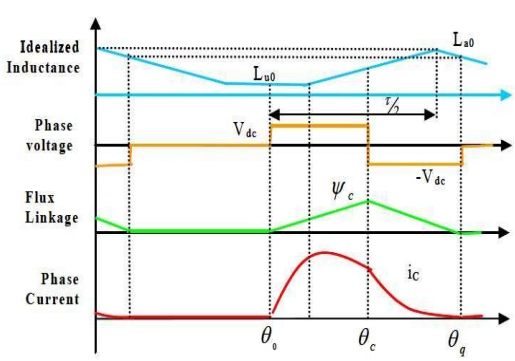

Fig. 4 Single Pulse Waveform

D. PWM CONTROL

Instead of the single-pulse control, the PWM (pulse width modulator) control scheme chops the dc voltage during the dwell angle period. The PWM control keeps switching frequency constant and regulates duty-cycle to ensure the phase current tracks the reference current. Figure 5 shows the ideal inductance profile, voltage applied to the phase winding, flux linkage and phase current for the PWM hard chopping control.

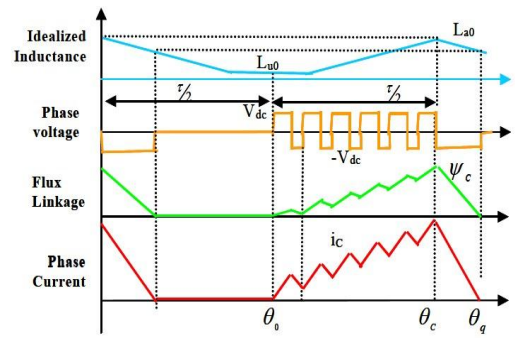

Fig.5 PWM hard Chopping Waveform

E. HYSTERSIS CONTROL

Hysteresis current regulator is another high frequency chopping current control, in which the main switches on each phase are switched on or off simultaneously with varying switching frequency to maintain constant current band. Figure 6 shows the idealized inductance, voltage applied to the phase winding, flux linkage and phase current for the Hysteresis hard chopping control.

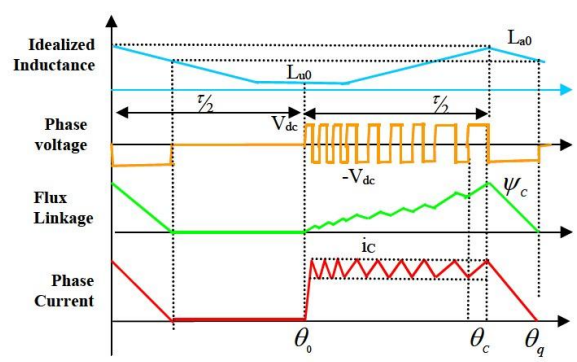

Fig. 6 Hysteresis Waveform

III. MODELLING OF SRM

A. ELECTROMAGNETIC EQUATION

The instantaneous voltage across the terminals of a single phase of an SR motor winding is related to the flux linked in the winding by Faraday's law, [10]

$$v = iR + \frac{d\phi}{dt} \tag{1.1}$$

Because of the double salient construction of the SR motor (both the rotor and the stator have salient poles) and because of magnetic saturation effects, in general, the flux linked in anSRM phase varies as a function of rotor position θ and the phase current i_k.

Thus, Equation 1.1 can be expanded as

$$v = i_k R + \frac{\partial\phi}{\partial i}\frac{di}{dt} + \frac{\partial\phi}{\partial\theta}\frac{d\theta}{dt} \tag{1.2}$$

Where, $\frac{\partial\phi}{\partial i}$ is defined as $L(\theta, i)$,the instantaneous inductance,

$\frac{\partial\phi}{\partial\theta}$ is defined as $K_b(\theta, i)$,the instantaneous back EMF,

$$v = iR + \mathrm{L}(\theta, \mathrm{i})\frac{di}{dt} + \mathrm{K_b}(\theta, \mathrm{i})\frac{d\theta}{dt} \tag{1.3}$$

B. SIMPLIFIED TORQUE EQUATION OF SRM

SRM torque is equation 1.4

$$T_k = \frac{i^2}{2}\frac{dL}{d\theta} \tag{1.4}$$

C. SWITCHED RELUCTANCE MOTOR MODEL

SRM's inductance profile $L(\theta)$ with each phase inductance displaced by an angle $\theta_s$given by

$$\theta_s = 2\pi\left(\frac{1}{N_r} - \frac{1}{N_s}\right) \tag{1.5}$$

Where Nr and Ns are the number of rotor and stator poles, respectively.

When the motor has equal rotor and stator pole arcs, $\beta_r = \beta_s$, one has the following angle relations

$$\theta_x = \left(\frac{\pi}{N_r} - \beta_r\right) \tag{1.6}$$

$$\theta_y = \left(\frac{\pi}{N_r}\right) \tag{1.7}$$

The angle δcorresponding to the displacement of a phase in relation to another, and given by

$$\delta = 2\pi\left(\frac{1}{N_r} - \frac{1}{N_s}\right) \tag{1.8}$$

The electric equation of each phase is given by

$$\frac{d\phi_k(\theta, i_k)}{dt} + i_k R = v \quad with\ k = 1, 2, 3 \tag{1.9}$$

While excluding saturation and mutual inductance effects, the flux in each phase is given by the linear equation

$$\phi_k\ (\theta, i_k\ ) = L(\theta) i_k \tag{1.10}$$

The total energy associated with the three phases (n =3) is given by

$$W_{Total} = \frac{1}{2}\sum_{k=1}^{3} L(\theta + (n-k-1)\theta_s) i_k^2 \tag{1.11}$$

And the motor total torque by

$$T_e = \frac{1}{2}\sum_{k=1}^{3} \frac{dL(\theta + (n-k-1)\theta_s)}{d\theta} i_k^2 \tag{1.12}$$

The mechanical equations are

$$J\frac{d\omega}{dt} = T_e - T_L - D\omega \tag{1.13}$$

And

$$\frac{d\theta}{dt} = \omega \tag{1.14}$$

Where$T_L$represents the load torque, and D the machine friction coefficient.

For simulation of machine 6/4 configurations have been used from SRM family.The parameters selected are tabulated below.

Table 1. The Switched reluctance Motor Parameter

S/No.	Parameters	6/4 Motor	8/6 Motor	Units
1	N_R	6	8	-
2	N_S	4	6	-
3	m	3	4	-
4	β_r	0.5236	0.35	rad
5	β_s	0.5236	0.42	rad
6	J	0.0013	0.0016	$Kg.m^2$
7	D	0.0183	0.004	Nm.s/rad
8	R	1.3	1.3	Ω
9	L_u=L_{min}	8	40	mH
10	L_a=L_{max}	60	240	mH
11	V	150	160	Volts
12	I_{sat}	5	8	A

IV. SPEED CONTROLLE DESIGN

In this section, two control methods for speed controlling of SRM has been investigated.

1. Integer Order PI Controller
2. Sliding Mode Controller

A. *Integer Order PI Controller*

In this work, we do not intend to linearize the plant since the SRM is inherently nonlinear. Main purpose is to examine the control performance when conventional PID control theory is applied in control of the nonlinear SRM drive system. Performance will be compared, as far as high performance applications of the SRM drive are concerned, with modern nonlinear control techniques such as sliding mode control. In order to reduce noise disturbances, Differential control is eliminated and PI control is adopted for the plant system. Because the state variables of the plant are highly nonlinearly coupled it is difficult to predict the plant dynamics through mathematical solution. So conventional pole-placement method is not suitable in designing a PI controller for the SRM. For a certain operating point trial-anderror method is used to find the optimum controller parameters Rotor position θ is fed back to the controller by the position sensor (or encoder). The source voltage $V_{sup}$of the chopper is provided by a bridge diode rectifier from the mains supply. The duty cycle k of the chopper is proportional to controller output c(t). The controller is expressed as

$$\left.\begin{aligned} e(t) &= \omega_{ref} - \omega(t) \\ c(t) &= K_c[e(t) + \frac{1}{T_i}\int_0^1 e(t)dt \\ k &= K1 * \frac{c(t)}{V_{\sup}} \\ V_{dc} &= k * V_{\sup} \end{aligned}\right\} \quad (1.15)$$

WhereK_c, is the gain, T_i, is the integral time constant, K_1, is a constant coefficient, e(t) is thespeed error between the reference speed and the motor speed.

B. *SLIDING MOTOR CONTROLLER*

There are two steps in designing a sliding mode variable structure controller designing [14] [15]

1. the switching function, that is to determine the switching surface s(x), then the sliding movement is stable gradually and it also has a good dynamic quality;
2. Designing the control law U(x), the reaching condition is satisfied, then urging the system state to enter the sliding mode state, and maintaining this state stably and reliably.

Equation of system state: According to system model, mechanical motion equation of rotor is listed under the effect of electromagnetic torque $T_e$and load torque T_L from Equation 2.31.

$$T_e = J\frac{d\omega}{dt} + D\omega + T_L \quad (1.16)$$

The speed is $\omega = \frac{d\theta}{dt}$

$\omega = x_1$,

$\omega^{\cdot} = x^{\cdot}_1 = x_2$

$$x_2 = \frac{1}{J}(T_e - T_L - Dx_1) \quad (1.17)$$

$$\dot{x}_2 = \frac{1}{J}(\dot{T}_e - Dx_2) \quad (1.18)$$

$$e_{x1} = x_1 - x_{1d} \quad (1.19)$$

Wheree_{x1} is speed error.

To design the sliding mode controller, the speed equation is expressed as state variables form [16]. From equation 1.16 to 1.19 state variable form can be given as

$$\begin{bmatrix} \dot{e_{x_1}} \\ \dot{e_{x_2}} \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 0 & -a \end{bmatrix} \begin{bmatrix} e_{x_1} \\ e_{x_2} \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} U \quad (1.20)$$

U is the output control volume of the sliding mode controller, after the effect of integrator,it can be changed into the total reference torque of SRM. Thus,

$$\begin{cases} a = \frac{D}{J}, \\ b = \frac{1}{J\tau} \end{cases} \quad (1.21)$$

$\tau$is the time constant of the integrator.

Sliding Surface Design:The switching function of the sliding mode controller can be selected as [17]

$$s = c^T e_x \quad (1.22)$$

Where, $c^T$is sliding surface matrix.
To maintain on to sliding surface s=0; Hence

$$s = [c \quad 1] \quad [\begin{matrix} e_{x1} \\ ex_2 \end{matrix}] \quad (1.23)$$

$$s = ce_{x1} + e_{x2} \quad (1.24)$$

$$s = c\dot{e}_{x1} + \dot{e}_{x2} \quad (1.25)$$

$$\dot{s} = c\dot{x}_1 + \dot{x}_2 \quad (1.26)$$

To maintain on a sliding surface S=o; hence

$$ce_{x1} = -e_{x2} \quad (1.27)$$

$$ce_{x1} = -\dot{e}_{x1} \quad (1.28)$$

$$\dot{e}_{x1} = -ce_{x1} \quad (1.29)$$

$$e_{x1}(t) = e^{-ct} e_{x1}(0) \quad (1.30)$$

Now c governs the dynamics of the system which is user defined parameter not on system parameters. This c will decide how much fast it reaches to equilibrium or zero.

After selection of appropriate switching function, designing a sliding mode controller is done the proportional switching control is expressed as follows:

$$U = k_1 e_{x1} + k_2 e_{x2} \quad (1.31)$$

Where,

$$\kappa_1 = \begin{cases} \alpha_1, e_{x_1} s > 0, \\ \beta_1, e_{x_1} s < 0; \end{cases}$$
$$\kappa_2 = \begin{cases} \alpha_2, e_{x_2} s > 0, \\ \beta_2, e_{x_2} s < 0; \end{cases}$$

[18] [19] $\kappa_1, \kappa_2$is up to the conditions of the existence of the generalized sliding mode control. For existence of SMC to meet the following inequality:

$$s.\dot{s} < 0 \quad (1.32)$$

$$(c + a - b\kappa_2) s.\dot{e_{x_1}} + b\kappa_1 s.e_{x_1} < 0 \quad (1.33)$$

According to the equation 1.27 to 1.32, if the existences of sliding mode conditions are met, then we get following equations:

$$\alpha_1 < 0 < \beta 1 \quad (1.32)$$

$$\alpha_2 < \frac{c+a}{b} < \beta_2 \quad (1.33)$$

The mathematical model of the sliding mode controller is given by the equation 1.16 to 1.33.

Table 2. SMC Controller Parameter

Parameters	6/4 Configuration	8/6 Configuration
D	0.0183	0.004
J	0.0013	0.0016
$a = \frac{D}{J}$	14.0769	2.50
$b = \frac{1}{J\tau}$	769.2307	625
c	15	20
α_1	0.5	0.1
β_1	-0.5	-0.1
α_2	0.038	0.06
β_2	0.036	0.034

V. RESULTS AND PERFORMANCE COMPARISON

Different controller parameters considered for simulation are tabulated below.

Table 3. Values of Controller Parameter

	Parameters	6/4 Configuration
PI Controller	K_p	10
	K_i	10
SM Controller	c	15
	α_1	0.5
	β_1	-0.5
	α_2	0.038
	β_2	0.036

A. Simulation Results for 6/4 motors with No load:

Simulation are carried out on both controllers at a time and corresponding results are plotted.

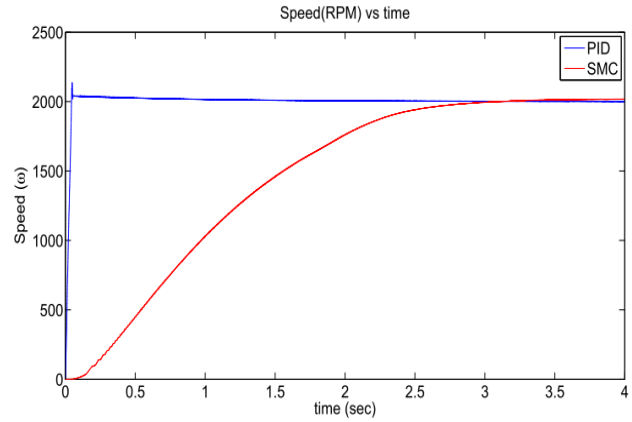

Fig. 7: Speed response of 6/4 Motor with No Load.

Below Table 5.2 shows the various measured output parameters for both controller.

Table 4. The 6/4 Speed performance of SRM with 0 Nm load.

Sr.No.	Parameters	PI controller	SM controller	Units
1	Rise Time	0.0349	1.8118	Sec
2	Settling Time	0.1584	2.7634	Sec
3	Settling Min	1800.6000	1815.1000	RPM
4	Settling Max	2137.0000	2018.2000	RPM
5	Overshoot	6.8279	0.0529	%
6	Undershoot	0.0000	0.0000	%
7	Peak	2137.0000	2018.2000	RPM
8	Peak Time	0.0483	3.9706	Sec

From the Figure 7its clear that speed response under no load condition is better for PI controller where as one spike appears at the starting which is again not desirable. On the other hand though rise time (table 5) is more for SMC, its reaching smoothly. From the Figure 8, we can easily recognize that with SMC we get very less torque ripple as compared to PI controller.

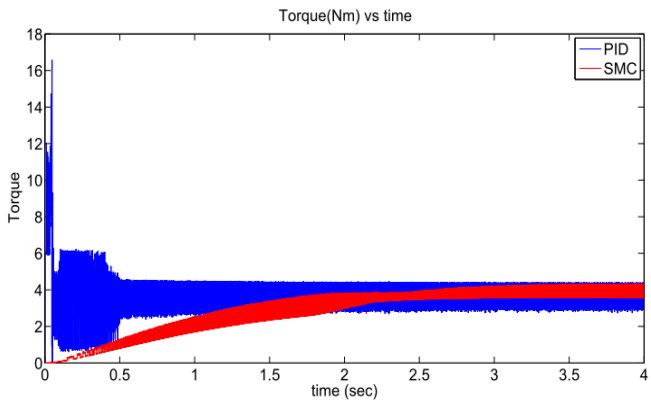

Fig. 8: Torque profile of 6/4 Motor with no load.

Table 5. The 6/4 torque perfromace of SRM with 0 Nm load.

Sr.No.	Parameters	PI controller	SM controller	Units
1	T_{av}	3.8986	2.8606	Nm
2	T_{min}	0	0	Nm
3	T_{max}	16.5663	4.3532	Nm
4	K_t	4.2493	1.5218	-

B. Simulation results of 6/4 motors with load of 2Nm:

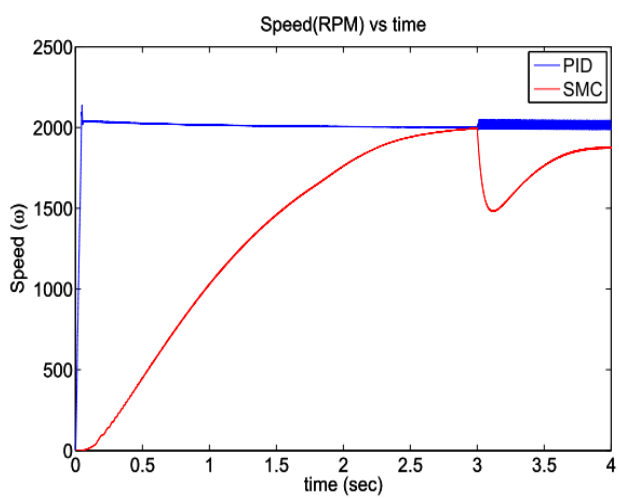

Fig. 9: Speed response of 6/4 motor with load of 2 Nm at 3s.

Table 6 The 6/4 Speed performance of SRM with 2 Nm load

Sr.No.	Parameters	PI controller	SM controller	Units
1	Rise Time	0.0349	1.5854	Sec
2	Settling Time	3.9948	3.6908	Sec
3	Settling Min	1798.3000	1479.8000	RPM
4	Settling Max	2137.0000	1995.5000	RPM
5	Overshoot	6.9707	6.2830	%
6	Undershoot	0.0000	0.0000	%
7	Peak	2137.0000	1995.5000	RPM
8	Peak Time	0.0483	2.9980	Sec

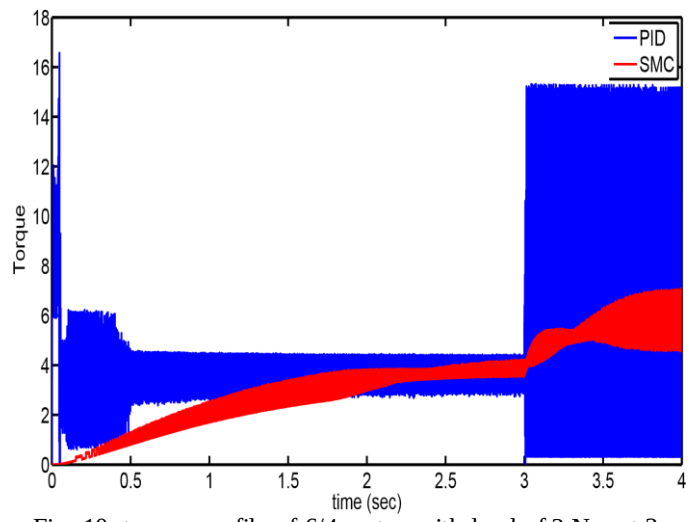

Fig. 10: torque profile of 6/4 motor with load of 2 Nm at 3s.

After loading machine with 2 Nm load both controllers adjust their gains to retain desired performance as shown in the fig.9. SMC though show dip at the instant when load is applied its reaching is smooth and also on application of load, torque ripple observed in Sliding Mode Controller is Low.

Table 7. The 6/4 Torque performance of SRM with 2 Nm load.

Sr.No.	Parameters	PI controller	SM controller	Units
1	T_{av}	4.3999	3.2222	Nm
2	T_{min}	0	0	Nm
3	T_{max}	16.5663	7.0914	Nm
4	K_t	3.7651	2.2008	-

VI. CONCLUSION

Sliding model variable structure control scheme for torque ripple minimization of SRM has been developed and describe in this paper. As the performance of traditional control strategies is not very satisfactory. Its complete mathematical analysis is described in the paper. It has been shown that sliding mode control is insensitive to plant parameter variations and that it provides rejection of inherent drive nonlinearities. The problem of torque chattering is overcome by adopting a cascaded integral operation in the torque control path between the sliding mode controller and the feed forward controller.

The controller is able to reduce the torque ripple up to the high electromagnetic property of switched reluctance motor. This control strategy is realized through the use of double closed-loop structure, which is able to produce smooth torque. Simulation results prove the feasibility of this method. The method proposed in this paper also has the characteristics of simple structure, easily to be implemented, strong suitability. Following are the conclusions,

- SRM dynamics is highly nonlinear and coupled.
- PI controller is good option for SRM only for fixed speed application.
- PI controller is highly sensitive to parameter variations and loading, hencecannot be used for variable speed rang.

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