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Power Efficient Higher Order Sliding Mode Control of SR Motor for Speed Control Applications

Muhammad Rafiq[1], Saeed-ur-Rehman[2], Fazal-ur-Rehman[1], Qarab Raza[2]

[1]Muhammad Ali Jinnah University,
Islamabad, Pakistan.

[2]Centre for Advanced Studies in Engineering (CASE),
Islamabad, Pakistan.

Abstract.

This paper presents a novel scheme for speed regulation/tracking of Switched Reluctance (SR) motors based on Higher-Order Sliding-Mode technique. In particular, a Second-Order Sliding-Mode Controller (SOSMC) based on Super Twisting algorithm is developed. Owing to the peculiar structural properties of SRM, torque produced by each motor phase is a function of phase current as well as rotor position. More importantly, unlike many other motors the polarity of the phase torque in SR motors is solely determined by the rotor position and is independent of the polarity of the applied voltage or phase current. The proposed controller takes advantage of this property and incorporates a commutation scheme which, at any time instant, selects only those motor phases for the computation of control law, which can contribute torque of the desired polarity at that instant. This feature helps in achieving the desired speed regulation/tracking objective in a power efficient manner as control efforts are applied through selective phases and counterproductive phases are left un-energized. This approach also minimizes the power loss in the motor windings thus reducing the heat generation within the motor. In order to highlight the advantages of Higher-Order Sliding-Mode controllers, a classical First-Order Sliding-Mode controller (FOSMC) is also developed and applied to the same system. The comparison of the two schemes shows much reduced chattering in case of SOSMC. The performance of the proposed SOSMC controller for speed regulation is also compared with that of another sliding mode speed controller published in the literature.

Keywords— *SR motor, sliding mode control, higher order sliding mode control, commutation, speed regulation/tracking control*

1. Introduction

Switched reluctance motors have received considerable attention among the researchers due to its simple construction, rugged mechanical structure, and low cost driver electronics. Because of the absence of any windings on the rotor, SR motor is very suitable for operations at high speed and/or at high temperatures [2]. SR motor is doubly salient machine, i.e. both stator and rotor have salient poles on their laminations. Torque is developed in the motor when rotor poles align with the excited stator poles. Due to this particular nature of torque production, the phase torque is independent of the polarity of phase current and depends only upon the relative position of the rotor poles with respect to the excited phase poles. For this reason, low cost unipolar power converters are used to drive SR motors. This fact also leads to a very important feature peculiar to this motor, i.e. unlike most of the other types of electrical motors, not all the phases of SR motor can produce the torque of the same polarity at any given rotor position. For example, in a 3-phase SR motor, there are certain rotor positions where only one phase can contribute the torque of the desired polarity whereas the torques produced by the other two phases are of opposite polarity. Thus energizing all 3-phases would lead to reduction in the net motor torque because of the cancellation among the phase torques.

SR motors are usually operated in magnetic saturation to increase its output torque. Magnetic saturation and mechanical saliencies in SR motors make phase torque a highly non-linear function of phase current and rotor position. Due to advancements in control theory, many nonlinear control techniques such as artificial neural network, feedback linearization, sliding mode, back stepping, fuzzy logic, etc. have been explored in the literature for the control of SR motors. Hajatipour and Farrokhi [3] developed an adaptive intelligent control based on Lyapunov functions. The proposed technique consists of two components; the first one approximates the load-torque, error in the moment of inertia and the coefficient of friction, the second component drives the system output to track the desired value. The speed controller does not require exact motor parameters and is shown to be robust against disturbances and uncertainties. Neural network torque estimator is used as a second controller in the proposed technique for torque ripple reduction. In [4], artificial neural network technique was also adopted in designing the speed controller of SR motor for regulation problem. The performance of the proposed controller was shown better than fuzzy logic and fuzzy logic PI controllers.

Sliding-Mode control has been gaining popularity in control application due to its simple structure, inherent robustness and capability to control nonlinear systems [5]. John and Eastham [6], and Forrai et al [7] have used sliding-mode control for SR motor to control speed but their research did not account for magnetic saturation of the motor. Sahoo et al. [8] has applied sliding-mode technique for direct torque control of SR motor. Nihat Inanc and Veysel Ozbular [9] proposed sliding mode control to minimize torque ripples in SR motor. The proposed controller was then used for speed regulation problem and its performance was compared with conventional PI and fuzzy controllers. It was shown that the proposed controller works well for reduction of low frequency oscillations. Dynamic sliding mode controller (DSMC) has also been developed for SR motors [10]. The performance of DSMC has been compared with the conventional sliding mode controller. Both these controllers were shown to be robust against parameter and load torque variations; DSMC, however, had the advantage of reduced chattering. Chiag et al. [11] has applied sliding-mode control on synchronous reluctance motor for speed regulation problem. Tahour et al. [12] used the same technique for SR motor and compared its performance with conventional PI controller. It was shown that the proposed controller outperformed the conventional one. This performance was further improved in [13] by introducing fuzzy sliding mode control in order to remove chattering. The proposed scheme provides good transient response. Chen et al. [14] used the idea of Gaussian radial basis function neural network and developed sliding mode controller for synchronous reluctance motor. The proposed technique was based on Lyapunov approach and steepest descent rule. With this technique, the chattering problem can be reduced.

The conventional sliding mode technique has a chattering problem that can be evaded by introducing higher order sliding mode (HOSM) control [15]. HOSM has been successfully applied for various engineering problems (see [16]-[19]; for example). Rain et al. [20] developed and implemented a novel current controller for SR motor using HOSM technique for position control problem. The proposed algorithm shows good dynamic response in handling parametric uncertainties and external disturbance. A similar work was also reported in ([21]-[22]) for stepper motor. To compensate uncertainties and modeling inaccuracies, an integral term was also augmented in the proposed scheme that was shown to be robust against unknown disturbances and parametric variations. Rashed et al. [23] applied HOSM on induction motor to achieve chattering free and decoupled control over motor speed and flux by incorporating stator phase resistance, rotor speed and load torque estimators. To see the performance of HOSM controller clearly, a test was conducted in [1] with conventional sliding mode and PI controller on SR motor at different system parameters and unknown disturbances. It was found that HOSM has outperformed the conventional controllers with respect to chattering reduction and robustness.

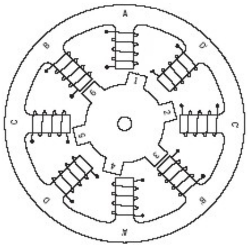

Fig. 1 Four-Phase SR motor with 8-Stator and 6-Rotor poles.

Two sliding-mode controllers are developed here for speed control applications, which incorporate a commutation scheme for selectively energizing motor phases in order to achieve power efficiency. The proposed designs use less power as compared to the conventional schemes where all phases are energized. Comparison of power losses is carried out with [24] and [8].

The paper is organized as follows: Section -2 represents the dynamic model of the system, Section-3 discusses HOSM technique, Section-4 describes the important steps in controller design for regulation and tracking speed problems and Section-5 introduces the commutation scheme used in the proposed designs. Simulation results are addressed in Section-6 and finally Section-7 concludes this paper.

2. Mathematical model of the system

Before describing the details of controller design, the electro-mechanical model of an SR motor is described in a form suitable for the purpose. Although the proposed controllers can be developed for any SR motor with arbitrary number of phases (a four phase motor schematic is shown in Fig. 1), for clarity of presentation and subsequent simulations we consider a specific 3-phase commercial SR motor whose parameters are listed in Table-1 and its dynamic model is given by the following set of equations (see [1], [24] for a detailed explanation and derivation of the model):

$$\frac{d\theta}{dt} = \omega \tag{1}$$

$$\frac{d\omega}{dt} = \frac{1}{J}\left(T_e - B\,\omega - T_L\right) \tag{2}$$

$$\frac{di_j}{dt} = \left(\frac{\partial\lambda_j(\theta,i_j)}{\partial i_j}\right)^{-1}\left(u_j - R_j i_j - \omega\,\frac{\partial\lambda_j(\theta,i_j)}{\partial\theta}\right) \quad (3)$$

$$j = 1,2,3$$

where

θ	Rotor position
ω	Angular velocity of rotor
J	Moment of inertia (rotor)
T_e	Total electromagnetic torque
B	Coefficient of friction
T_L	Load torque
i_j	Current in the jth phase
λ_j	Flux linkages in jth phase
u_j	Voltages of jth phase.
R_j	Resistance to the jth phase

3. Higher Order Sliding Mode (HOSM)

The basic idea behind sliding-mode control is to define an observable function of the system states, also called switching surface, and then to design a controller in such a way that trajectories in the state space are directed towards the switching surface or the hyper plane. Once the system states reach the hyper plane, it slides along the surface towards the equilibrium point. In this technique the system's behavior remains robust to certain parameter variations and unknown disturbances [25].

The higher-order sliding-mode (HOSM) technique extends the basic idea of sliding-mode by incorporating higher order derivatives of the sliding variable. The addition of higher-order derivatives leads to a reduction in the undesirable chattering issue inherent in the sliding-mode technique while keeping the same robustness and performance as that of traditional sliding mode [26]. HOSM technique attains this quality due to the knowledge of the higher-order derivative terms of sliding variable. For example, for an nth order SMC; $s, \dot{s}, \ddot{s} \ldots s^{(n-1)}$ should be known to make $s = 0$. To get the information about all these variables is a problem. However, this problem can be resolved with the help of super twisting algorithm.

Super-Twisting algorithm has been used for chattering reduction with systems having relative degree one. This algorithm does not demand any extra information about sliding variable and ensures that system trajectories twist around the origin in the phase portrait as shown in Fig. 2. This property makes it prominent to the other algorithms.

Super twisting algorithm has been successfully applied and implemented on various engineering applications. Derafa et al. [27] used super twisting algorithm for altitude tracking of four rotors helicopter. The simulation results show that the proposed scheme performs well for stabilization, robustness and tracking, in addition of chattering reduction. In [28] super twisting algorithm was employed for fault detection and isolation problem of three tank system. It is verified through simulation results that the proposed algorithm can significantly reduce the estimation error as well as chattering. In [29], the performance of super twisting algorithm was tested with other algorithm, so called twisting algorithm on dc drive under uncertain parameters and load conditions. It was claimed that super twisting algorithm, is best suited for real experiments subject to certain conditions. The super twisting algorithm based sliding mode observer was also investigated in [30] for sensorless speed control of permanent magnate synchronous motor. The simulation results show that the proposed scheme behaves well at low speed and is robust. The further detail of super twisting algorithm design is given in [1].

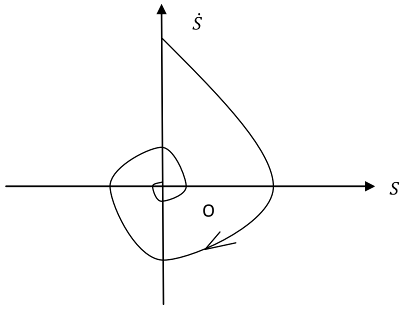

Fig. 2 Evolution of Switching Surface during the super twisting controller action; minimizing the error between reference signal and desired output signal.

4. Controllers Design

A speed controller is designed to minimize the speed error, i.e.

$$e(t) = \omega(t) - \omega_{ref}(t) \quad (4)$$

where $\omega_{ref}(t)$ is the desired speed. In this section, we develop speed controllers based on sliding-mode technique. The starting point is to define a sliding surface, which in our case is taken to be

$$s = \dot{e} + \lambda e \quad (5)$$

An appropriate candidate for Lyapunov function is taken as $V = \frac{1}{2}s^2$ which would yield $\dot{V} = s\dot{s}$ on differentiation where

$$\dot{s} = \ddot{e} + \lambda\dot{e} \quad (6)$$

$$\dot{s} = \ddot{\omega}(t) + \lambda\dot{\omega}(t) - \left(\ddot{\omega}_{ref}(t) + \lambda\dot{\omega}_{ref}(t)\right) \quad (7)$$

$$\dot{V} = s\left(\ddot{\omega}(t) + \lambda\dot{\omega}(t) - \left(\ddot{\omega}_{ref}(t) + \lambda\dot{\omega}_{ref}(t)\right)\right) \quad (8)$$

In order to find conditions which would guarantee $\dot{V} < 0$, we begin by differentiating Eq. (2)

$$\ddot{\omega} = \frac{1}{J}\left(\frac{dT_e}{dt} - B\,\frac{d\omega}{dt} - \frac{dT_L}{dt}\right) \quad (9)$$

$$\ddot{\omega} = \frac{1}{J}\left(\sum_{j=1}^{3}\frac{dT_j(\theta,i_j)}{dt} - B\,\dot{\omega} - \frac{dT_L}{dt}\right) \quad (10)$$

$$\ddot{\omega} = \frac{1}{J}\left(\sum_{j=1}^{3}\frac{\partial T_j(\theta,i_j)}{\partial i_j}\frac{di_j}{dt} + \omega\sum_{j=1}^{3}\frac{\partial T_j(\theta,i_j)}{\partial\theta} - B\dot{\omega} - \frac{dT_L}{dt}\right) \quad (11)$$

Substituting (3) into (11) leads to:

$$\ddot{\omega} = \frac{1}{J}\left(\sum_{j=1}^{3}\frac{\partial T_j(\theta,i_j)}{\partial i_j}\left(\frac{\partial\lambda_j(\theta,i_j)}{\partial i_j}\right)^{-1}\left(u_j - R_j i_j - \omega\,\frac{\partial\lambda_j(\theta,i_j)}{\partial\theta}\right) + \omega\sum_{j=1}^{3}\frac{\partial T_j(\theta,i_j)}{\partial\theta} - B\,\dot{\omega} - \frac{dT_L}{dt}\right) \quad (12)$$

Which can be written in the following form suitable for the design of our proposed controllers discussed in the following sections:

$$\ddot{\omega} = \left(\sum_{j=1}^{N}\frac{\partial T_j(\theta,i_j)}{\partial i_j}\left(\frac{\partial\lambda_j(\theta,i_j)}{\partial i_j}\right)^{-1}\left(-R_j i_j - \omega\,\frac{\partial\lambda_j(\theta,i_j)}{\partial\theta}\right) + \omega\sum_{j=1}^{N}\frac{\partial T_j(\theta,i_j)}{\partial\theta} - B\,\dot{\omega} - \frac{dT_L}{dt}\right) + \frac{1}{J}\left(\left(\sum_{j=1}^{N}\frac{\partial T_j(\theta,i_j)}{\partial i_j}\left(\frac{\partial\lambda_j(\theta,i_j)}{\partial i_j}\right)^{-1}\right)u_j\right) \quad (13)$$

Which can simply be written in a compact form as:

$$\ddot{\omega} = f(\theta,\omega,i,B,T_L) + g(\theta,i,)u \quad (14)$$

where *u* represents the input vector comprising of *N* phase voltages, *N* represents the number of phases which are being energized at a particular instant to produce net torque and will be determined through the commutation scheme described in the next section. The scalar function *f* and vector function *g* are defined as:

$$f = \frac{1}{J}\left(\sum_{j=1}^{3}\frac{\partial T_j(\theta,i_j)}{\partial i_j}\left(\frac{\partial\lambda_j(\theta,i_j)}{\partial i_j}\right)^{-1}\left(-R_j i_j - \omega\,\frac{\partial\lambda_j(\theta,i_j)}{\partial\theta}\right) + \omega\sum_{j=1}^{3}\frac{\partial T_j(\theta,i_j)}{\partial\theta} - B\,\dot{\omega} - \frac{dT_L}{dt}\right) \quad (15)$$

and $g = \frac{1}{J}\sum_{j=1}^{3}\frac{\partial T_j(\theta,i_j)}{\partial i_j}\left(\frac{\partial\lambda_j(\theta,i_j)}{\partial i_j}\right)^{-1}$ (16)

For simplicity, the explicit dependence of *u* on time *t* and *f* & *g* vectors on θ,ω,i,B,T_L will be omitted in the following sections. Now we consider the speed regulation and tracking problem one by one for the design of FOSMC.

4.1 Case-1: Regulation Problem

The objective of the regulation problem is to stabilize the motor speed at a desired constant value. i.e. $\omega_{ref}(t) = \omega_{ref}$ and $\dot{\omega}_{ref}(t) = 0$. For proving that the proposed control law guarantees the constant speed requirement, first consider the Lemma 1.

Lemma 1: The following control law will stabilize the motor speed to its desired value when $t \to \infty$.

$$u = -\frac{1}{g}\left(f + \lambda\dot{\omega} + Ksign(s)\right) \quad (17)$$

Proof: Substituting Eq. (14) in Eq. (8), the following expression is obtained.

$$\dot{V} = s(f + gu + \lambda\,\dot{\omega}) \quad (18)$$

Now plugging in Eq. (17) in Eq. (18), we get

$$\dot{V} = s(f - f - \lambda\dot{\omega} - Ksign(s) + \lambda\,\dot{\omega}) \quad (19)$$

Then $\dot{V} = -K\,s\,sign(s) < 0$ (20)

As it is clear from Eq. (20) that $\dot{V} = 0$ only when $s = 0$. This ensures that the control law as defined in Eq. (17) would guarantee that $\omega(t) \to \omega_{ref}$ when $t \to \infty$

4.2 Case-2: Tracking Problem

The aim of tracking problem is to follow the time varying reference signal minimizing the tracking error. To prove that the proposed control law will track the reference signal, consider the Lemma 2.

Lemma 2: The following control law will ensure that the speed will follow a time varying reference signal as $t \to \infty$.

$$u = -\frac{1}{g}(f + \lambda\dot{\omega}(t) + Ksign(s) - (\ddot{\omega}_{ref}(t) + \lambda\dot{\omega}_{ref}(t)) \quad (21)$$

Proof: Combining Eq. (8) and Eq. (14), the following is obtained.

$$\dot{V} = s(f + gu + \lambda\,\dot{\omega}(t) - (\ddot{\omega}_{ref}(t) + \lambda\dot{\omega}_{ref}(t))) \quad (22)$$

Substituting Eq. (21) in Eq. (22) yields

$$\dot{V} = -K\,s\,sign(s) < 0 \quad (23)$$

From Eq. (23), it is obvious that,$\dot{V} = 0$ would be zero only when $s = 0$. This ensures that the control law defined in Eq. (21) would guarantee that the motor speed follows the time-varying reference signal in the limit. In both the above cases, it is shown that the Lyapunov function *V* is positive definite and its time derivative $\dot{V}$ is negative definite, hence decaying and therefore the control law *u* will guarantee that $\omega(t) \to \omega_{ref}(t)$ as$t \to \infty$.

Now we proceed with the design of SOSMC based on supertwisting algorithm as discussed in section-3. Finally, the control law after incorporating the super-twisting algorithm takes the following form for speed regulation case:

$$u = -\frac{1}{g}\left(f + \lambda\dot{\omega}(t) + K|s|^{0.5}sign(s)\right) + u_a \quad (24)$$

$$\dot{u}_a = -Ksign(s) \quad (25)$$

and for speed tracking, it becomes

$$u = -\frac{1}{g}\left(f + \lambda\dot{\omega}(t) + K|s|^{0.5}sign(s) - \left(\ddot{\omega}_{ref}(t) + \lambda\dot{\omega}_{ref}(t)\right)\right) + u_a \quad (26)$$

$$\dot{u}_a = -Ksign(s) \quad (27)$$

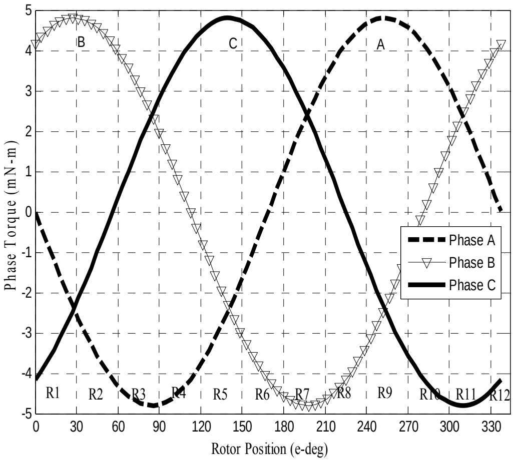

Fig. 3 Division of one electrical cycle into 12 distinct regions for commutation purposes.

5. Commutation Scheme

While applying Eq. (17), and Eq. (21) for FOSMC and Eq. (24), Eq. (25) and Eq. (26), Eq. (27) for SOSMC in order to compute the control laws at each instant, in terms of phase voltages, the elements of control vector u will be selected so as to engage only those phases which can contribute torque of the desired polarity. The selection of the appropriate motor phases at each instant depends upon the rotor position and the sign of the speed error at that instant. The commutation scheme which does this phase selection is now being explained and also shown in Fig. 3.

Although the phase torque of SR motor is a complex nonlinear function of rotor position and phase current as explained earlier, for ease in explaining the commutation scheme we would refer to Fig. 3 which shows the phase torques of a 3-phase SR motor at a specific value of phase currents, ignoring the effects of magnetic saturation and spatial harmonics. The figure shows the variation of phase torques as a function of rotor position within one electrical cycle. The complete electrical cycle is divided into 12 distinct regions R1-R12 such that in each region, specific phase(s) can only produce positive torque whereas the remaining phase(s) can contribute only negative torque. For example, in region R1, positive torque is only produced via phase B, while phase C and phase A when energized provide only negative torques. Similarly in region R3, phases B and C provide positive torque while negative torque can only be produced by energizing phase A.

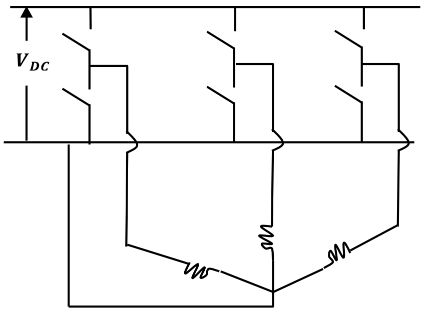

Fig. 4 Driver circuit used for energizing motor phases.

Thus if the rotor position lies in R3 at a specific time instant and positive torque is required to reduce the speed error, only phases B and C should be used to compute the control law using Eq. (24)-Eq. (27). This would lead to achieving the desired net torque using lower voltage levels and with reduced copper losses in the motor windings. Had we energized all the motor phases, not only that phase A would have generated counterproductive torque, other phases would had to produce higher than the required values of torques to cancel the opposing torque produced by phase A. This would have lead to applying higher phase voltages and an increase in copper losses too. On the other hand, if negative torque is required in this region to reduce the speed error, then only phase A should be energized. There is no need to energize phases B and C because they can only produce positive torques in this region, which would be counterproductive.

A similar approach is adopted in all these regions, which suggests that for a 3-phase SR motor, only one or at the most two phases can produce the desired polarity torque at any instant depending upon the current rotor position. Thus a judicious choice of the phases to be used in computing the control law as in Eq. (17), Eq. (21) and Eq. (24)-(27) would result in saving net power leading to increased system efficiency.

6. Simulation Results and Discussion

The effectiveness of the proposed controllers is evaluated by simulations carried out using MATLAB/SIMULINK software. The parameters of SR motor used for simulations are given as:

No of phases=3, No. of stator poles= 6,
No. of rotor poles=8, Rotor inertia (J) =0.1 $N.ms^2$
Phase Resistance =4.7 Ω DC Voltage Supply =250 V
Coefficient of friction (B) =0.1 $N.ms$

A schematic of driver electronics used to drive the motor phases is shown in Fig. 4, which uses only one leg of the H-bridge as our proposed controllers require only positive phase voltage. The FOSMC and SOSMC designed in Section-4 along with the commutation scheme developed in Section-5 are applied for speed regulation as well as speed tracking problems.

For comparison purposes, the sliding-mode controller of [10] is also implemented. Simulation results are presented in Fig 5 to Fig. 16. A number of advantageous features of FOSMC and SOSMC with the designed commutation scheme are elaborated and compared to the conventional control; the latter can also be seen in [10] and [23].

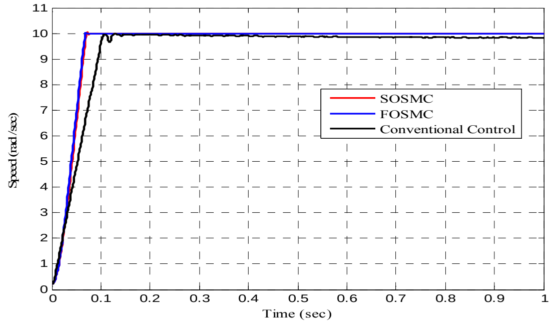

Figure 5: Speed Response of FOSMC and SOSMC to a step command.

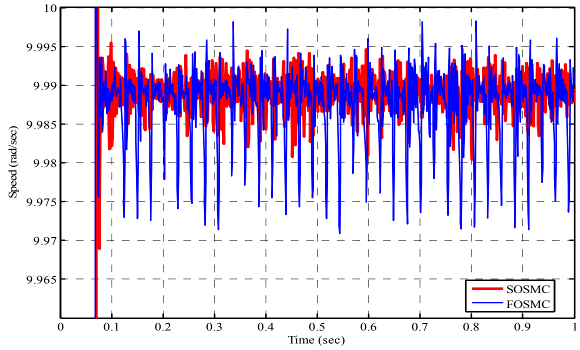

Fig 6: A Close-up View of Response of both FOSMC and SOSMC to a step command. The high magnitude of chattering signal of FOSMC is clearly noticeable.

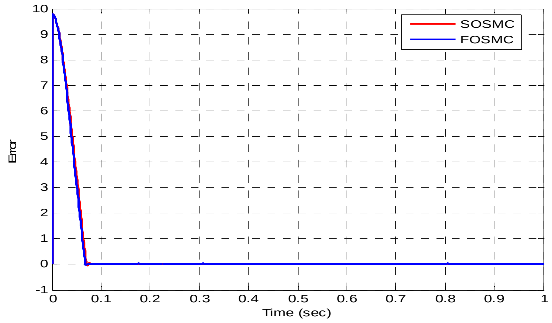

Fig 7: Error plot of Speed Response of FOSMC and SOSMC to a step command

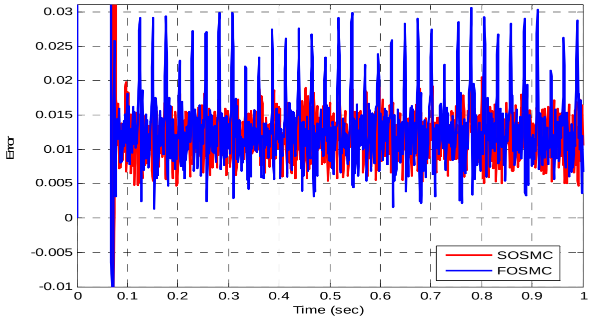

Fig 8: A Close-up View of Error plot of Speed Response for FOSMC and SOSMC to a step command. The reduced amount of error magnitude is clearly visible

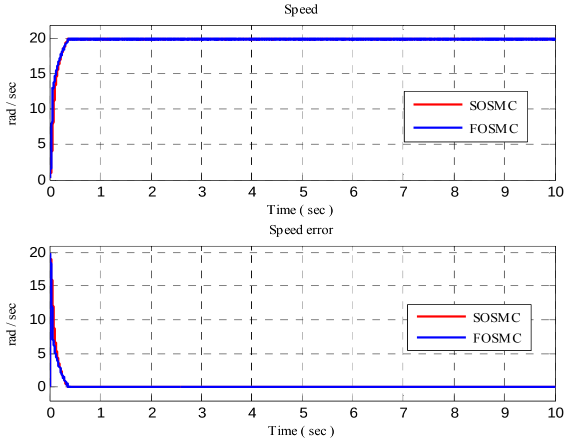

Fig 9: Speed Response and error plot of FOSMC and SOSMC to a step command for a reference speed of 20 rad/s.

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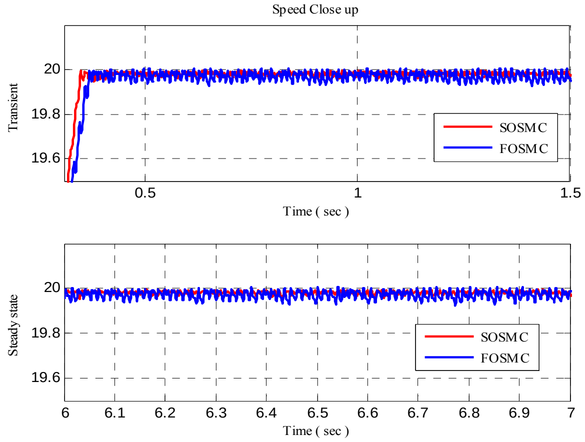

Fig 10**:** A Close-up View of Response of both FOSMC and SOSMC to a step command in the starting and steady state regions.. The high magnitude of chattering signal of FOSMC is clearly noticeable.

Fig. 5 and Fig. 6 compare the outputs of FOSM & SOSM controllers developed in this paper with that of another sliding mode controller reported in [10] for the case when motor is commanded to move at 10 rad/s from rest. As it is clear, the commutation based controllers converge the motor speed more quickly to the desired value. Fig. 7 and Fig. 8 show a performance test for FOSMC and SOSMC for a reference speed of 10 rad/s. It can be visualized that FOSMC shows higher magnitude of chattering than SOSMC. The same results are verified for a motor speed of 20 rad/s in next simulation tests shown in Fig. 9 and Fig 10.

A comparison of power loss in motor phases during operation is shown in Fig. 11. Power loss in conventional design is about 85 kW whereas even the FOSMC which suffers from the same level of chattering has much reduced power loss, i.e. only 19 KW.

This power saving can be mainly attributed to the commutation scheme employed in FOSMC. SOSMC with its reduced level of chattering reduces the power loss further to 15 kW which confirms the effectiveness of the proposed design. Fig. 12 and Fig. 13 highlight the main reason behind this power savings (area under the curve, which is less for SOSMC).

Fig. 12 shows the three phase voltages during initial stage of steady state operation. It is well clear from these figures that in commutation based controllers; only one or two motor phases are selected for generation of control efforts at any given instant of time. The conventional design, on the other hand, energizes all the three phases simultaneously and applies bipolar voltages to motor phases. A closer focus on the time interval 0.44 - 0.45 sec is of particular interest. It shows that even in those cases where apparently only two of the three phases are being energized by the conventional sliding-mode controller, the controller has selected wrong phases for the generation of control efforts. Despite that maximum voltages are being applied to the two phases resulting in large phase currents, the torques produced by the two phases are cancelling each other. This results in much reduced net motor torque as compared to the torques produced by each phase independently. This amounts to wastage of efforts and also results in increased power loss in motor windings.

The commutation based FOSMC and SOSMC use only unipolar voltages with reduced voltage levels thus resulting in lower phase currents. As a result, proposed controllers (FOSMC and HOSMC) produce lesser individual torques of the same polarities which add up to give a higher net torque. The torques produced by three individual phases and net torque are shown in Fig. 14 which verify this.

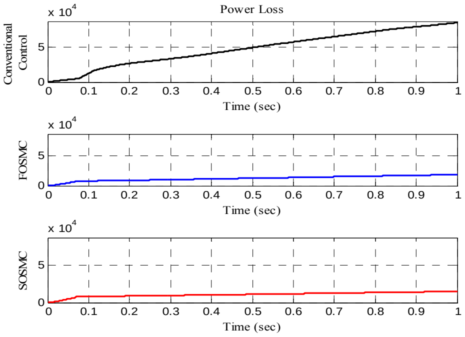

Figure 11: Power loss in Conventional Design is about 85 kW. Using FOSMC it is about 19 KW. Using SOSMC it even lowers to about 15 kW.

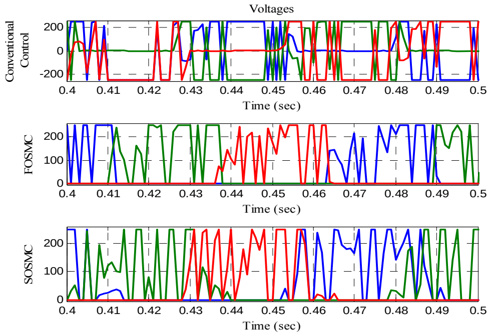

Figure 12: 3-phase voltages during initial stage of steady state response.

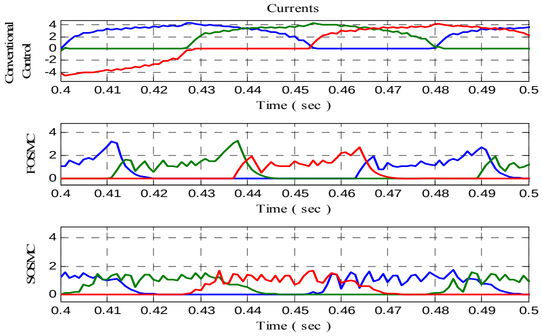

Figure 13: 3-phase currents during initial stage of steady state response.

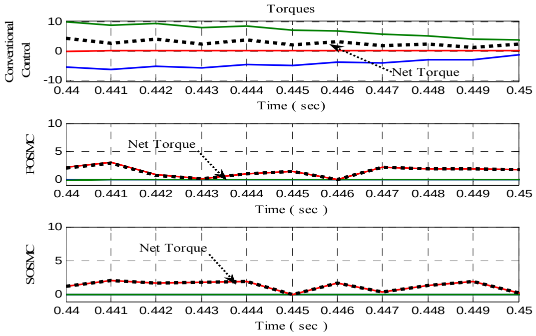

Fig. 14 Torques during initial stage of steady state response.

Tracking performance of FOSMC and SOSMC can be reflected from Fig. 15 where sinusoidal signal is selected for comparison test. It can be seen that SOSMC is exhibiting less amount of chattering and smaller spikes than FOSMC. Another good performance of SOSMC can be shown from Fig. 16 when SR motor experiences a sudden change in external load driven by the motor. The external load varies from 0 to 1.5 Nm, 0 to 2 Nm and 0 to 2.5 Nm during the intervals t=3 to t=3.1 second, t=5 to t=5.1 second and t=7 to t=7.1 second respectively. It can be seen that despite a sudden change in external load, the SOSMC does not allow a bigger dip and keeps the motor closer to its desired speed. The results of these simulations clearly indicate that commutation scheme based sliding-mode controllers developed in this paper show promising results. These results are good enough to establish the fidelity of both designs in tracking as well as regulation applications. A selection out of these two schemes would depend upon a number of factors, some of which are highlighted below:

- The magnitude of error a designer can safely tolerate.
- The effect of chattering on the actuator action.
- The actuator safety while dealing with chattering in the actuation signal.
- The natural frequency of actuator and the frequency and magnitude of chattering, etc.

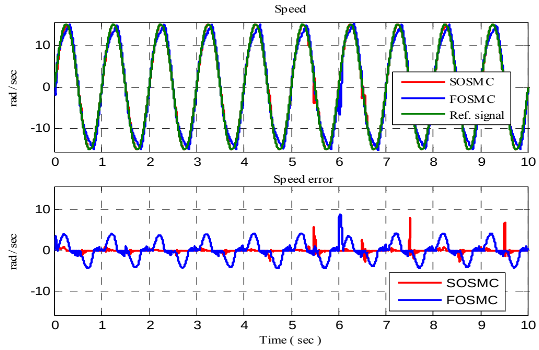

Fig. 15 Speed response of proposed controllers while tracking a reference signal given by $\omega_{ref}(t) = 15\ \sin 2\pi t$. The lower plot shows a close up to elaborate the performance of both controllers.

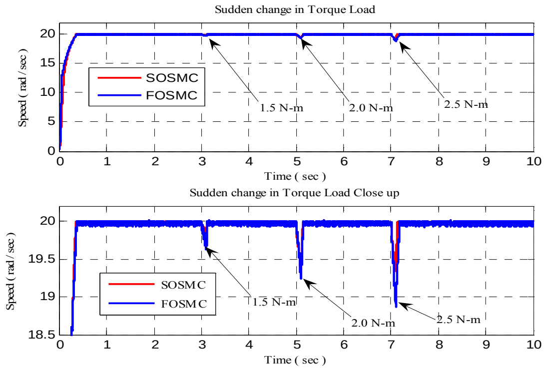

Fig. 16 Speed response of proposed controllers against sudden change in torque load.

7. Conclusion

First-order and Second-order sliding-mode controllers have been developed for speed (regulation/tracking) control of SR motors. Contrary to the conventional sliding-mode controllers developed for SR motors , the proposed controllers use a designed commutation scheme which uses only those motor phases for the computation of control law, at any given instant, which can produce torque of the desired polarity. Second-order sliding-mode controller (SOSMC) is shown to be more effective in terms of accuracy and reduced amount of chattering than First-order sliding-mode controller (FOSMC). Both the controllers are shown to be power efficient and also result in reduced power loss in motor windings leading to reduced heat generation.

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Muhammad Rafiq Mufti received M.Sc. degree in computer science from Bahauddin Zakariya University, Multan, Pakistan and M .Sc. degree in computer engineering from Centre for Advanced Studies in Engineering (CASE) Islamabad in 1994 and 2007, respectively. Currently, he is working towards his PhD degree from Mohammad Ali Jinnah University (MAJU) Islamabad. His research interests include sliding mode control, fractional control, and neural network.

Dr. Saeed-ur-Rehman got his PhD from GA. Tech. Atlanta, Georgia, USA. He specializes in digital control systems and power electronics. Dr. Rehman has more than 15 years of industrial and academic experience. Currently he is a professor at Centre for Advanced Studies in Engineering (CASE) Pakistan. He is also associated with CARE from where he has developed several embedded systems for ruggedized industrial/military applications. He has authored several papers and holds a US patent on sensorless motor control.

Dr. Fazal-ur-Rehman received his M. Sc. & M. Phil. degrees in Mathematics from B. Z. University Multan. Pakistan in 1986 and 1990, and M. Eng. & Ph.D. degrees in Control Systems from Department of Electrical Engineering, McGill University, Montreal, Canada in 1993 and 1997 respectively. He joined the Faculty of Electronic Engineering, GIK Institute of Engineering, Pakistan as an Assistant Professor in January 1998 and worked there as an Assistant Professor 1998-2002 and Associate Professor 2003-2005. Presently he is working as a Professor in Department of Electronic Engineering, Mohammad Ali Jinnah University (MAJU), Islamabad, Pakistan. Dr. Fazal's research interests are primarily in a particular area of Nonlinear Control Systems, called Nonholonomic Control Systems. He has also interest in Optimal Control and Digital Signal Processing.

Qarab Raza got his Bachelor's degree in Mechanical Engineering from University College of Engineering, Taxila in 1989. He received a post graduate diploma in computer system software and hardware in 1990 from Computer Training Center, Islamabad. Since 1990, he has been working in industry as an installation, fabrication and design engineer for nearly sixteen years. He got his Masters Degree in Control Engineering from Center for Advanced Studies in Engineering, Islamabad in 2004. He is first author and co-author of 10 Conference and 4 journal publications. He is currently a PhD candidate at Center for Advanced Studies in Engineering, Islamabad. His research interests are sliding mode control, fractional control, mathematical modeling of dynamic systems for control and fault diagnosis.