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TORQUE RIPPLE RATE REDUCTION OF 6/4 SWITCHED RELUCTANCE MOTOR USING SLIDING MODE LEARNING CONTROLS

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ABSTRACT

This paper presents a sliding mode control for reducing the torque ripple of a 6/4 switched reluctance motor. Several types of sliding mode control based on the current variable are implemented: conventional sliding mode control, learning sliding mode control, and learning sliding mode control with PID. The research also includes the design of the controller and simulation results that demonstrate the effectiveness of the proposed method in reducing torque ripple. The learning sliding mode control with PID has a significant implication for reduction torque ripple rate improvement of about 70% compared to the conventional model. As well as controlling the speed response and settling time. This makes the control of switched reluctance motors a current and speed controller.

KEYWORDS

Torque ripple. 6/4 switched reluctance motor. SMLC, CSMC. Current controller. Speed controller.

1. INTRODUCTION

A switched reluctance motor (SRM) is an electrical motor that runs on reluctance torque. Power in SRM is delivered in the starter, unlike in other DC motors, where power is delivered in the rotor (Song and Liu, 2010). Switched reluctance motors are a focus for many researchers because of their advantages, such as simple construction, inexpensiveness, no permanent magnetic, no winding on the rotor, high-speed operation, high efficiency, and the ability to maintain high torque at low speed. On the other hand, the main disadvantages of SRM is a torque ripple that occurs due to the high nonlinearity characteristics and discrete nature of the torque production mechanism. Therefore, SRM suffer from high variation and acoustic noise. These drawbacks have a significant influence on overall performance and can make SRM unsuitable for smooth applications (Hilairet, Lubin and Tounzi, 2012), (Miller, 2002). For many years, researchers have proposed several methods to reduce these challenges: methods using electronic control, mechanical methods, which modify the structure and geometry of SRM, and the combination of electronics control and geometric techniques electronic control techniques can reduce the ripple, but they may limit the efficiency of the intrinsic structure of the motor, and the combination of electronics control and geometric techniques. In geometric techniques, there are several ways to optimize the shape of the SRM, which can reduce the torque ripple, such as designing the stator pole face with a non-uniform airgap, attaching the pole shoe to the lateral face of the rotor pole, or using skewed (Yang, Lim and Kim, 2013). Many papers used electronic control techniques to reduce torque ripple. In (Ro, Jeong and Lee, 2013), introduced a robust direct torque control based on sliding mode control, which has fast dynamic response characteristics and simple control. In (Marcsa and Kuczmann, 2017), torque ripple was reduced by geometry modification and using a control technique. The proposed method combined instantaneous torque control with a sinusoidal torque sharing function and a specially skewed rotor pole shape. A mix of analytical and adaptive neuro-fuzzy inference system methods was described in (Hashemi, Zohrabi and Mardaneh, 2019) as a way to get static characteristics and SRM modelling for use in a dynamic simulation method. (Tariq et al., 2020) proposed a controlling current and speed through an artificial neural network (AAN) by computing the desired output accuracy and offering speedy conversions in less computational time in comparison with a PI controller. In (Kotb et al., 2022a), presented two optimization techniques called local unimodal sampling (LUS) and spotted hyena algorithms (SHO) to optimally tune cascaded PID designs while controlling speed and reducing torque ripple. In (Razaq and Shehab Hadi, 2023) introduced turn-on and turn-off controllers to reduce the torque ripple rate by optimizing the current flow through the motor winding during the switch between phases. In recent years, there has been an increase in the use of sliding mode controls with several types of motors, such as DC motors (Hadi, Alamili and Abbas, 2023), actuators (Al-Ghanimi, Shehab and Alamili, 2021), switched reluctance motors, and etc. This is because the SMC ensured stability and robustness against uncertainties, loads, and disturbances. This paper proposes a technique of sliding mode controller coupled with a recursive learning control algorithm to improve controller adaptability and performance in systems with uncertainty and disturbance are all embedded in the so-called Lipschitz-like condition and thus, no prior information on the upper and/or lower bounds of the uncertainties is required for the controller design.

This research is organized as follows: In Section 2, analyze the dynamic model of SRM. Propose several types of sliding mode control in Section 3. Then, Section 4 discusses the simulation result. Section 5 illustrates the comparison between the proposed controls and previous researches. Finally, give the conclusion.

2. DYNAMIC MODEL OF SWITCHED RELUCTANCE MOTOR

The simplest design of SRM is a double salient pole on the stator and rotor without winding on the rotor. Therefore, due to this double salient, SRM has a non-linear magnetic characteristic. The flux linkage $\lambda(i,\theta)$ and inductance $L(i,\theta)$ are depend on the magnitude of current (i) and the rotor position (θ) (Hamouda and Szamel, 2018). The electrical and mechanical differential equations for the dynamic modelling of SRM are (Namazi et al., 2016):

$$u = ri + \frac{d\lambda(i,\theta)}{dt} \tag{1}$$

u represent the applied voltage, and r is a phase resistance.

$$J\dot{\omega} = T_e(i,\theta) - T_L - B\omega \tag{2}$$

J is the inertia of the motor, ω denotes a rotor speed, $T_e(i,\theta)$ is a phase torque, T_L represent the load torque, and B is a friction motor.

$$\lambda(i,\theta) = L(i,\theta)i, \quad \omega = \frac{d\theta}{dt}$$

$$u = ri + L(i,\theta)\frac{di}{dt} + i\frac{dL(i,\theta)}{d\theta}\omega \tag{3}$$

The phase torque is a function of derivative phase inductance and current, which is given in the following:

$$T_e = \frac{1}{2}\, i^2 \frac{dL}{d\theta} \tag{4}$$

The dynamics equations can be written from (2) and (3) (Sahoo et al., 2012):

$$\frac{dT_e(i,\theta)}{dt} = \frac{\partial T_e(i,\theta)}{\partial i}\frac{di}{dt} + \frac{\partial T_e(i,\theta)}{\partial \theta}\frac{d\theta}{dt} \tag{5}$$

$$\frac{di}{dt} = \left(\frac{\partial \lambda(i,\theta)}{\partial i}\right)^{-1}\left(u - ri - \frac{\partial \lambda(i,\theta)}{\partial \theta}\omega\right) \tag{6}$$

Substituting (6) in (5), obtain:

$$\frac{dT_e}{dt} = \frac{\partial T_e}{\partial i}\left(\frac{\partial \lambda}{\partial i}\right)^{-1}\left(u - ri - \frac{\partial \lambda}{\partial \theta}\omega\right) + \frac{\partial T_e}{\partial \theta}\omega \tag{7}$$

3. METHODOLOGY

Sliding mode control is one of the most robust and nonlinear controllers. It is a type of variable structure control based on the concept of changing the structure of control according to the current state of the system, forcing the system to move according to the sliding surface. Theoretically able to reject uncertainty and provide robust control under disturbances. This ability makes the control have a fast response to parameter changes and disturbances. Therefore, SMC is a successful control in the nonlinear method (Sun et al., 2021, Utkin, 1977). This research will focus on conventional sliding mode controllers and learning sliding mode controllers. Generally, it suffers from a high-frequency oscillation of the sliding variable around the sliding surface called the chattering phenomenon (Utkin and Lee, 2006). This chattering can be reduced by adding the switch function to the control law, such as the saturation function (sat(s)), (Eker, 2012).

3.1. Conventional sliding mode control (CSMC)

In SRM, the CSMC is designed for the system with a relative degree of one, which means that the control signal appears after the first derivative of the sliding surface (Furat and Eker, 2012). The control law consists of two distinct terms: switching control, which enforces the error toward the desired value of the sliding surface, and equivalent control, which is found to make the derivative of the sliding surface equal to zero (Utkin, 1977). The design procedure can be followed by the following steps:

Step 1: Find the sliding surface.

$$\mathrm{s(t)} = \mathrm{c_1 e(t)} + \mathrm{\dot{e}(t)} + \int e(t)dt \tag{8}$$

the c_1 is a tuning parameter that determines the slope of the sliding surface and is equal to 10000. It's chosen by trial and error to obtain lower torque ripple and robustness against uncertainties.

the tracking error e(t) is:

$$e(t) = i - i^* \tag{9}$$

and the first derivative of the tracking error is:

$$\mathrm{\dot{e}(t)} = \frac{\mathrm{di}}{\mathrm{dt}} = \left(\frac{\partial \lambda(i,\theta)}{\partial i}\right)^{-1}\left(u - ri - \frac{\partial \lambda(i,\theta)}{\partial \theta}\omega\right) \tag{10}$$

Step 2: Choose the appropriate switch function. This research proposes the following equation:

$$u_{sw}(t) = ksat(s(t)) \tag{11}$$

sat () is a saturation function, and k is a positive constant chosen to suppress all matching uncertainties at 300.

Step 3: Calculate the control law from the first derivative of the sliding surface, which is equal to zero.

$$\dot{s}(t) = (c_1 + \frac{d}{dt})\dot{e}(t) + e(t) = 0 \tag{12}$$

substituting (10) in (12) and rewriting in the term u, control law is given in the following:

$$u = \frac{1}{\left(c_1+\frac{d}{dt}\right)\left(\frac{\partial\lambda}{\partial i}\right)^{-1}}\left[-e(t) - k\,sat(s(t)) - \left(c_1 + \frac{d}{dt}\right)\left(\frac{\partial\lambda}{\partial i}\right)^{-1}\left(-ri - \frac{\partial\lambda(i,\theta)}{\partial\theta}\omega\right)\right] \tag{13}$$

Step 4: Improve the stability using the Lyapunov function.

Lyapunov function: $v(s) = \frac{1}{2}s^2(t)$ and $\dot{v}(s) = \dot{s}s$

To improve stability, the proposed SMC should satisfy the following conditions:

- $v(s) > 0 \rightarrow v(s) = \frac{1}{2}s^2 \quad then \quad v(s) > 0$
- $v(0) = 0 \rightarrow v(0) = \frac{1}{2}(0) \quad then \quad v(0) = 0$
- $\dot{v}(0) = 0 \rightarrow \dot{v}(0) = \dot{s}(0) \quad then \quad \dot{v}(0) = 0$
- $\dot{v}(s) < 0$

Substituting (10) and (12) in the $\dot{v}(s) = \dot{s}s$. So, we have:

$$\dot{v}(s) = s\left[\left(c_1 + \frac{d}{dt}\right)\left(\frac{\partial\lambda(i,\theta)}{\partial i}\right)^{-1}\left(u - ri - \frac{\partial\lambda(i,\theta)}{\partial\theta}\omega\right)\right] \tag{14}$$

substituting (13) in (14) to obtain: $\dot{v}(s) = s\big(-k\ sat(s)\big) < 0$, k > 0. So, the stability of design is improved.

3.2. Learning Sliding Mode Control (LSMC)

A recursive learning technique is integrated with SMC to ensure that the tracking error and sliding variable approximately converge to zero (Hadi, Alamili and Abbas, 2023). The proposed method consists of a recent control signal and a learning term. The learning term proposed is to search for stability in the sliding manifold and adjust the stability and convergence of the system. When the closed-loop system is unstable, the learning term adjusts the control signal. As a result, this method with both chattering-free characteristics and zero error convergence is achieved (Tuan et al., 2012).

The starting tracking error is defined in (9). And the sliding surface is given in (8). The first derivative sliding surface is expressed by:

$$\dot{s}(\mathrm{t}) = \phi + |c_3|u \tag{15}$$

$$\phi = \left(c_2 + \frac{d}{dt}\right)\left[\left(\frac{\partial\lambda}{\partial i}\right)^{-1}\left(-ri - \frac{\partial\lambda}{\partial\theta}\omega\right)\right] \tag{16}$$

$$c_3 = \left(c_2 + \frac{d}{dt}\right)\left[\left(\frac{\partial\lambda}{\partial i}\right)^{-1}\right] \tag{17}$$

The control law is proposed as (Tuan et al., 2012):

$$u(t) = u(t-\tau) - \Delta u(t) \tag{18}$$

$\Delta u(t)$ is the iterative learning part defined as:

$$\Delta u(t) = \begin{cases} \frac{1}{c_3 s(t)}\left(\eta_1 \hat{\dot{v}}\,(t-\tau) + \eta_2\left|\hat{\dot{v}}\,(t-\tau)\right|\right) & ,s \neq 0 \\ 0 & ,s = 0 \end{cases} \tag{19}$$

time delay is denoted as $\tau = 1e - 06$. $\eta_1 = 0.6, \eta_2 = 0.02$ represents the control design to be controlled. c_2, and c_3 are the parameters of sliding surface where c_2=100, c_3 take the absolute value of the average of (17). $\dot{v}(t)$ is the candidate Lyapunov function defined as: $v(t) = \frac{1}{2}\sigma^2$.

Meanwhile, $\hat{\dot{v}}\,(t-\tau) = \frac{v(t)-v(t-\tau)}{\tau}$ is the delayed and estimated of $\hat{\dot{v}}\,(t)$.

Remark 1: From (18) and (19), the control signal will be continuous due to the learning part when $\sigma \neq 0$. But when $\sigma = 0$ the only previous signal $u(t-\tau)$ is in charge, this technique led to a continuous control effort, which then led to free chattering.

In order to improve the overall performance LSMC. Adding gain to the sliding surfaces, which could be expressed in the formula (Furat and Eker, 2012):

$$s(t) = k_p e(t) + k_d \dot{e}(t) + k_i \int e(t) \tag{20}$$

the gains of PID parameter choice depend on trial and error as $k_p = 100, k_d = 1, k_i = 0.9$.

4. RESULTS

Drives and controllers are implemented using MATLAB\Simulink in the 6/4 SRM, 60Kw, 240V, and 200A models. Various conditions have been discussed in this section, which begin as follows: CSMC, LSMC, and LSMC with PID gains. All cases will be implemented under uncertainties that are represented by a random function with load and no-load. Then compare the results of torque ripple and speed response with previous papers.

First: CSMC

As shown in Fig. 1, the minimum torque value reaches zero for no load and load cases. The torque ripple is high and approximately comparable to the conventional model of SRM. At load, the current variable model can add a maximum load value equal to 10 N.m. Meanwhile, average torque values are relatively low, which has a negative effect on torque ripple rate depending on the following formula:

$$torque\ ripple = \frac{T_{maximum} - T_{minimum}}{T_{average}} \tag{21}$$

as a result, using a CSMC with SRM is not good, and the reasons of these drawbacks can be summarized as follows:

- Nonlinearity characteristics: SRM has strong nonlinear torque characteristics, especially at low speed. So, the CSMC might not handle this nonlinearity, leading to suboptimal torque ripple reduction.
- Lack of adaptation: CSMC doesn't combine with other adaptation techniques, which may lead to the inability to modify time-varying dynamics. As a result, it limited the ability to reduce torque ripple.

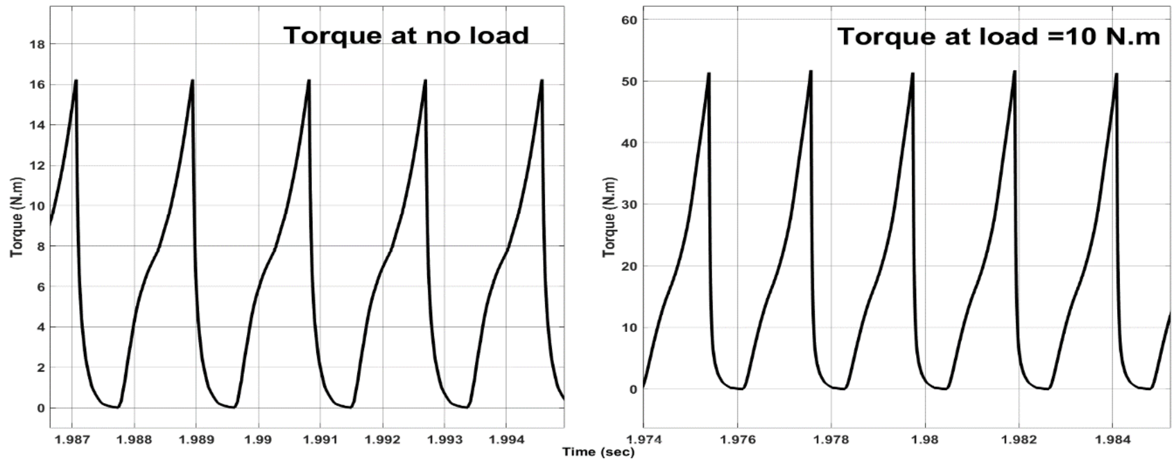

Fig.1. Torque of CSMC

Second: LSMC

In the case of no load, from Table 1 it appears that the value of average torque is higher than CSMC, with a huge reduction in torque ripple compared with CSMC. Also, torque minimum has a relatively high value and doesn't reach zero as CSMC with a minimum value of $\Delta T = (T_{maximum} - T_{minimum})$. All these factors have an excellent effect on reducing the torque ripple rate in the case of no load. LSMC can be implemented with higher load values (25, 50, and 100 N.m.), while 10 N.m. for CSMC. As shown in Table 1, we may not be able to apply the same turn-on and turn-off at various values of load. This is because of the adaptive property of the SMC, which adjusts the control parameter to compensate for the effect of the torque load on the rotor. This adaptivity effect affects the overlapping between adjacent phases, therefore decreasing the torque ripple rate. Also, we can notice that the torque ripple rates have approximate values with a great reduction in torque ripple compared to CSMC. Torque for all conditions is shown in Fig. 2.

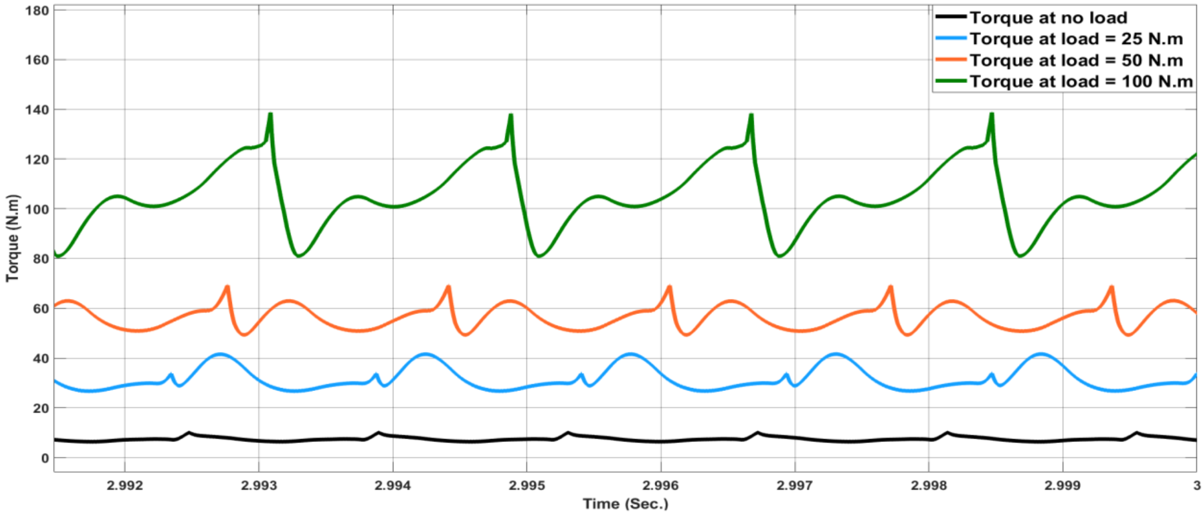

Fig.2. Torque of SMLC

Third: LSMC with PID gains

From Table 1, can notice that average torque values have slightly higher values than LSMC without PID gains, with relatively the same values ΔT as LSMC without PID gains. Also, maximum and minimum torque values are approximately same. Finally, the torque ripple rates are relatively constant when changing the load values and less than the torque ripple rates in the case of without PID gains, which means the proposed method has robustness with changing loads. Torque for all conditions is shown in Fig. 3. We can notice that SMC need to change turn-on and turn-off angles for variable loads. While, in the case of LSMC with PID gains, constant turn-off angles.

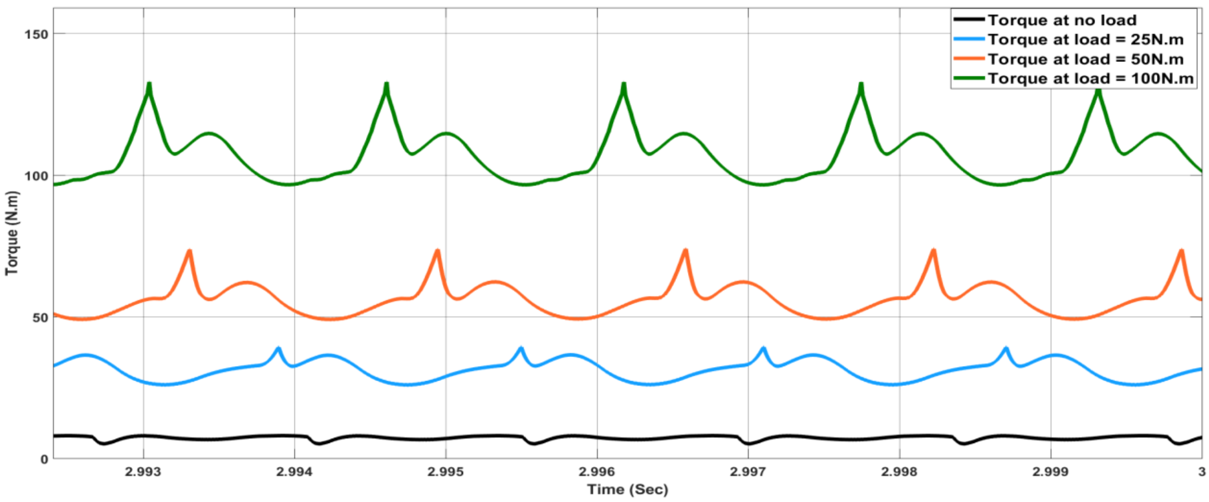

Fig.3. Torque of LSMC with PID gains

Fourth: Speed

The speeds of CSMC, LSMC, and LSMC with PID gains are shown in Figs 4, 5, and 6, respectively. The best speed performance was achieved in LSMC with PID gains. It has the same range of speed under no load and loads. From Table 1, the speed response settling time of no-load cases is approximately the same for all the proposed methods. In the case of loads 25 N.m. and 50 N.m the speed response settling time the LSMC with PID gains has the fastest speed response. Finally, in the case of 100 N.m. it appears that both methods (LSMC and LSMC with PID gains) have an approximately fast response. In the case of LSMC with PID gains, we can notice a speed of 100 N.m. faster than 25 and 50 N.m. due to the motor's characteristics, which influence its performance under different load conditions. SRM may appear more efficient or better suited to handle the 100 N.m. load, resulting in higher speed compared to other load values. Also, LSMC with PID is optimized or tuned to perform better under the 100 N.m. load, resulting in faster speeds compared to the other loads.

Remark 2: All turn-on and turn-off choices are made through trial and error.

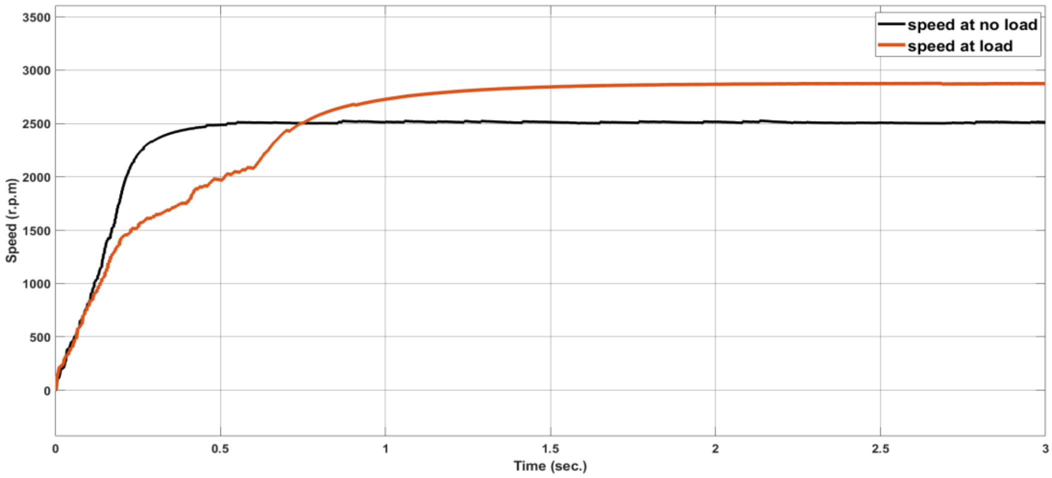

Fig. 4. Speed at CSMC

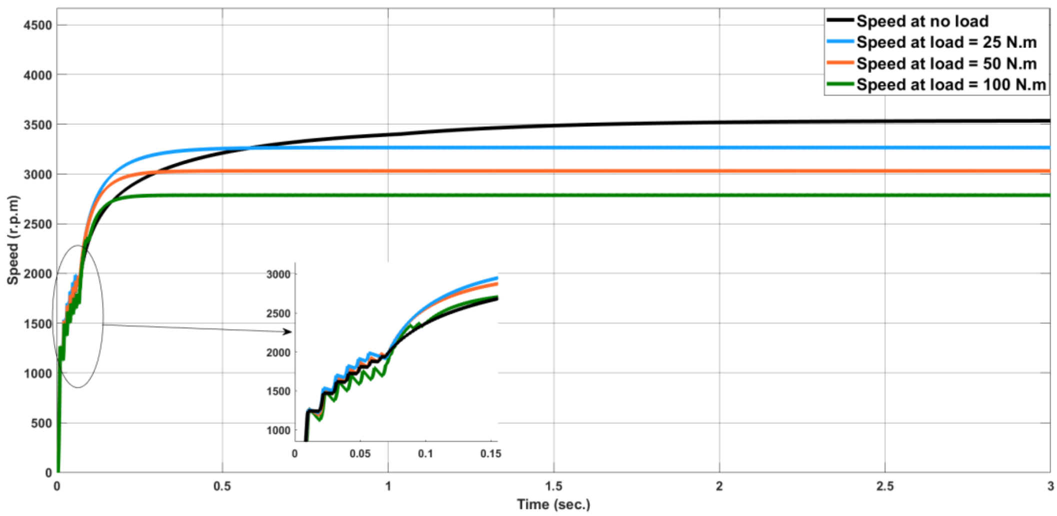

Fig.5. speed at LSMC

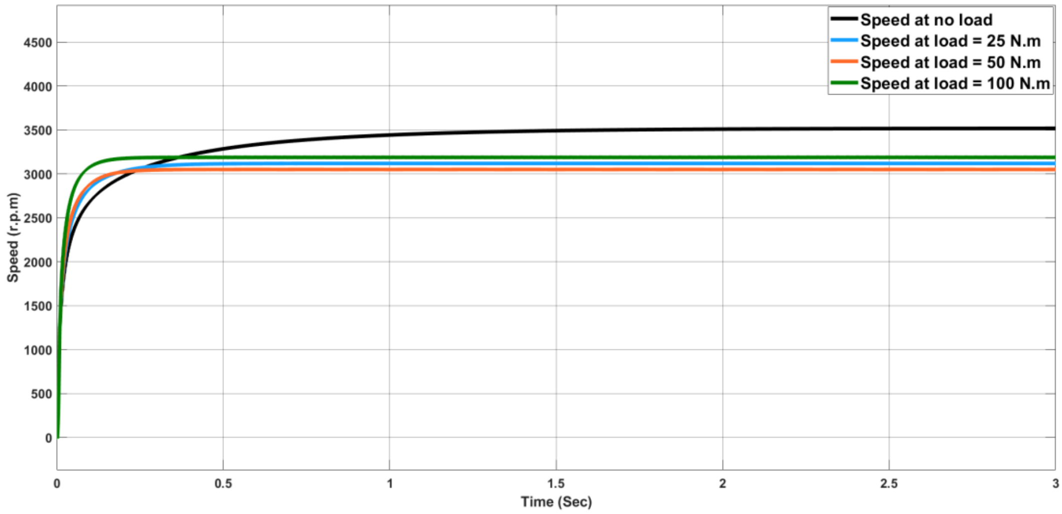

Fig.6.speed at LSMC with PID gain

Table 1. torque values under all conditions

Technique	**Load (N.m)**	**Maximum torque (N.m)**	**Minimum torque (N.m)**	**Average torque (N.m)**	**Torque ripple rate**	**Settling time (Sec.)**
Conventional model						
$\theta_{on} = 45$ $\theta_{off} = 70$	No load	23.5	1.2	9.627	2.31	1.54
	25	53.5	2.5	32.23	1.58	1.25
	50	90	4	56	1.58	1.26
$\theta_{on} = 50$ $\theta_{off} = 85$	100	142.1	46	100.2	0.959	1.523
Conventional sliding mode controller						
$\theta_{on} = 50$ $\theta_{off} = 72$	No load	16	0	5.759	2.77	1.3524
$\theta_{on} = 50$ $\theta_{off} = 72$	10	52	0	17.52	2.968	1.2659
Learning sliding mode controller						
$\theta_{on} = 50$ $\theta_{off} = 78$	No load	10	6.74	7	0.4657	1.33
$\theta_{on} = 46$ $\theta_{off} = 79$	25	41.5	26.6	29.87	0.49	0.3047
$\theta_{on} = 45$ $\theta_{off} = 79$	50	70	49.2	62.9	0.33	0.2077
$\theta_{on} = 43$ $\theta_{off} = 78$	100	138.1	81	101.4	0.563	0.1695
Sliding mode learning controller with PID gains						
$\boldsymbol{\theta_{on} = 50}$ $\boldsymbol{\theta_{off} = 80}$	No load	8.3	5.3	8.026	0.37	1.0364
$\boldsymbol{\theta_{on} = 47}$ $\boldsymbol{\theta_{off} = 80}$	25	39.6	26	35.53	0.382	0.2303
$\boldsymbol{\theta_{on} = 45}$ $\boldsymbol{\theta_{off} = 80}$	50	74	49.2	61.63	0.402	0.1540
$\boldsymbol{\theta_{on} = 40}$ $\boldsymbol{\theta_{off} = 80}$	100	138	96.5	117.9	0.309	0.1231

Fifth: chattering

From Figs. 1, 2, and 3, the SMC enjoys chatter-free characteristics. This occurs because the SMLC has strong robustness with respect to uncertainties.

Sixth: control signal

Figs 7 and 8 presented the control law of SMLC and SMLC with PID gain respectively, which illustrate chattering free control law. Also, these figures show that in the case of SMLC with PID gain has less control and better control signal response compare with SMLC without PID gains. This mean that SMLC with PID more suitable to use.

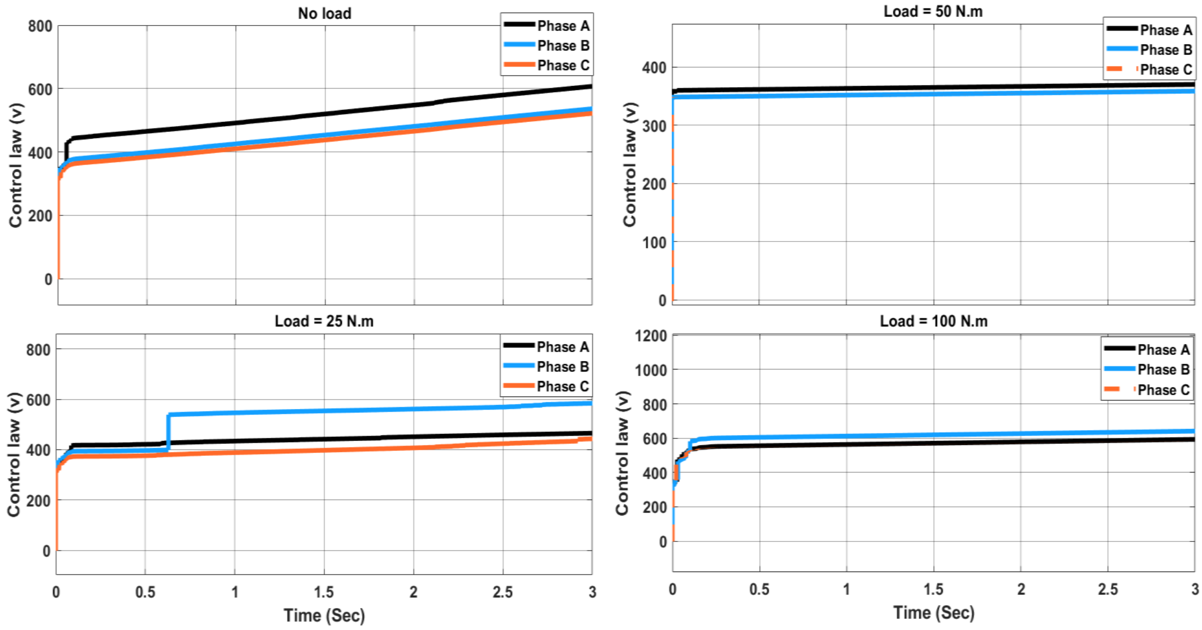

Fig. 7. Control signal of SMLC

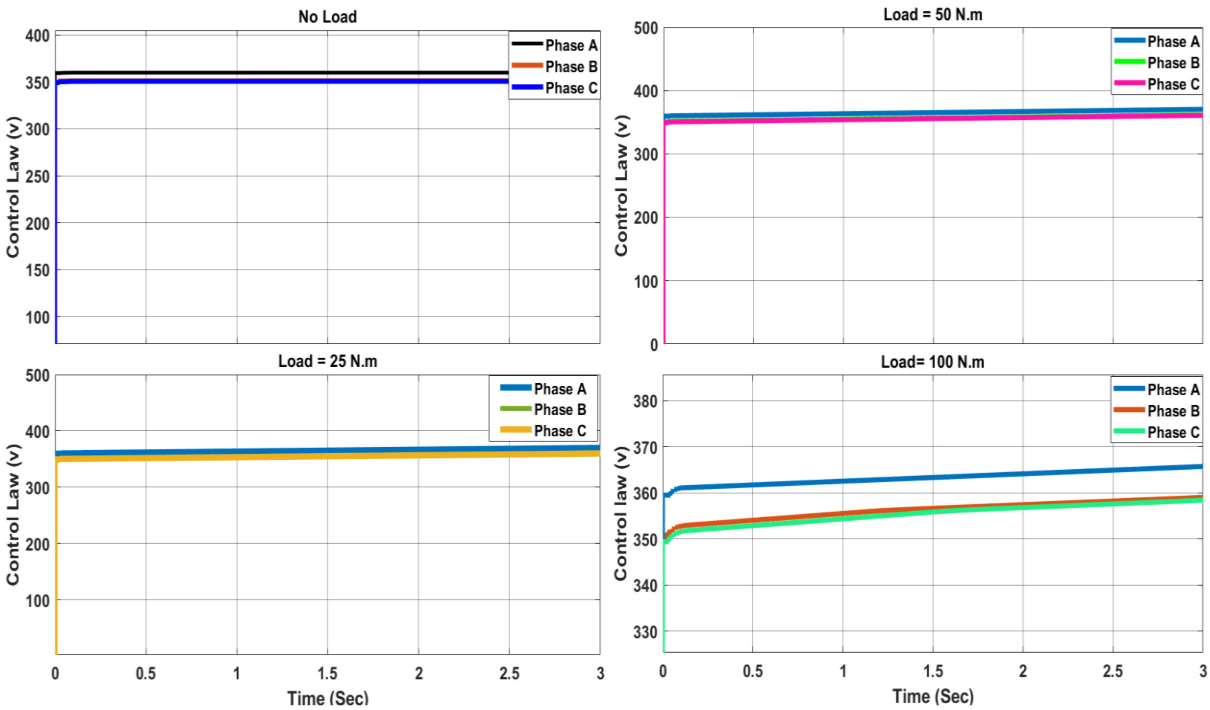

Fig.8. Control signal of SMLC with PID gains

Seventh: Step load

Fig. 9, illustrate the response of applying step load on SMLC which load change from 100 N.m to 50 N.m at time 1.5 sec. the speed response settling time is 1.684. For SMLC with PID gains, applying step load at time 1.5 sec for load changes from 50 N.m to 100N.m show in Fig.10. Speed response settling time is 1.624. This mean is the SMLC with both cases have adaptively feature with suddenly change in load with settling time approximately equal to 0.1 sec.

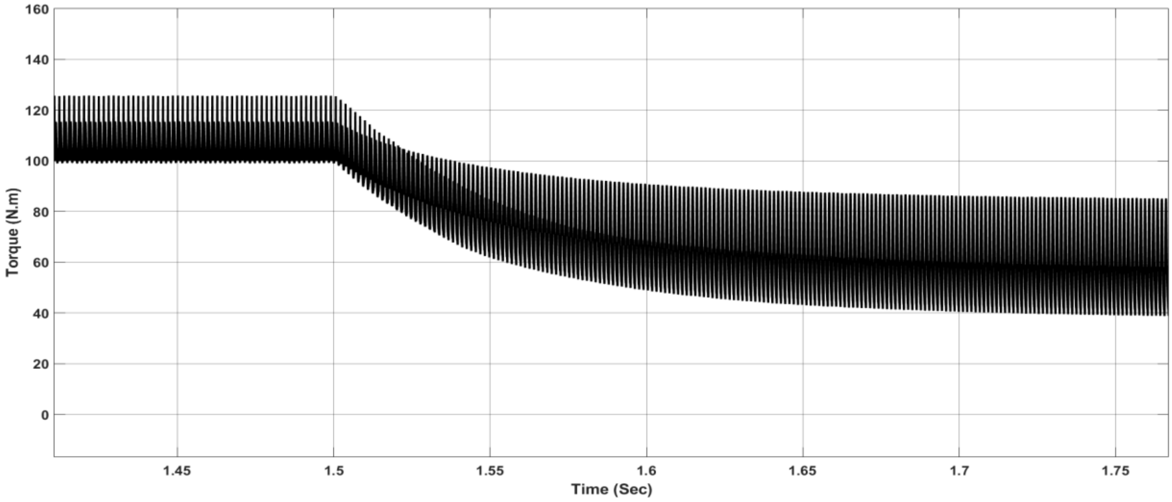

Fig. 9. step load at SMLC

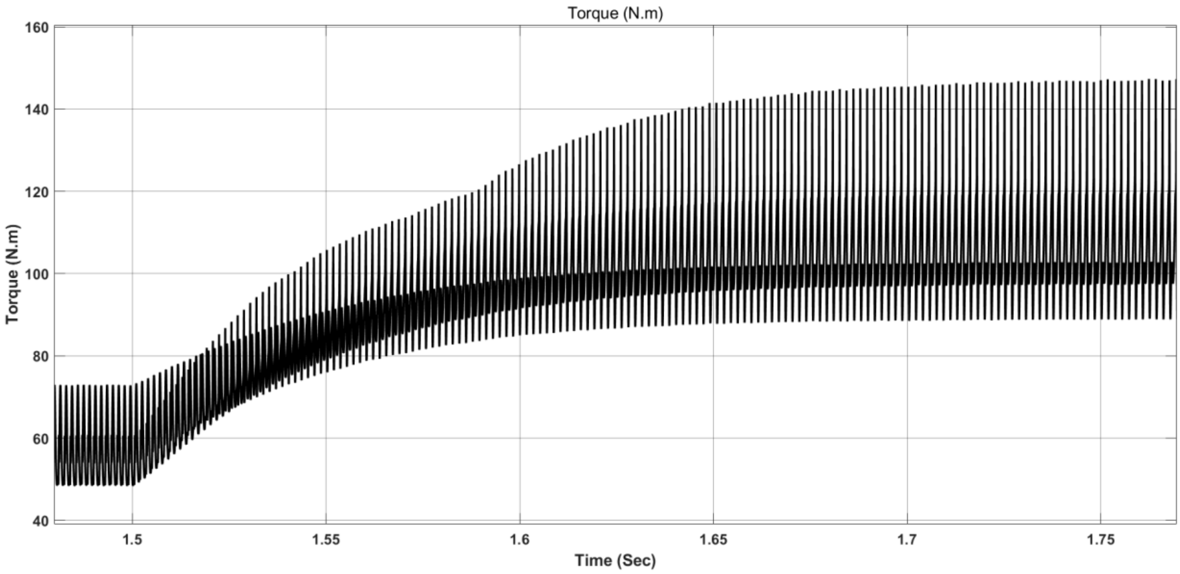

Fig. 10. step load of SMLC with PID gains

5. COMPARISON BETWEEN TECHNIQUE

In comparison with previous papers (Shehab, 2013), (Tariq et al., 2020), (Kotb et al., 2022b), and (Razaq and Shehab Hadi, 2023), with proposed methods which results shown in the Table 1 and Figs from 1 to 6. The comparison can be summarized as follows:

- Torque ripple rate: the learning sliding mode controller with PID gains rely on torque and current variables appears to have the lowest torque ripple rate for all studied cases of loads.

- In the case of load, LSMC with PID gains has a faster speed response settling time, which approximately has the same settling time. The proposed technique has approximately the same speed response as SHO-PID in the case of (load =100 N.m)(Kotb et al., 2022b).
- In the case of no load, SHO-PID has the fastest speed response settling time over all the techniques introduced in this thesis, (Tariq et al., 2020), and (Kotb et al., 2022b) which is equal to 0.1sec.
- The speed of SRM under all load values is approximately in the same range as the rotor speed in the case of LSMC with PID gain based on the current and torque variables as well as SHO-PID. This made these techniques suitable for applications that required constant speed with varying loads.
- Adding PID gains to the sliding surface has a noticeable effect on reducing torque ripple and enhancing the motor speed for all cases of loads and no load.
- In the case of no load, LSMC with PID gains based on the current variable has the lowest ΔT among the comparative techniques.
- For all load values, LSMC with PID gains based on the torque variable has the lowest value of ΔT among the comparative techniques.
- The improvement percentage in Table 2 point out that SMLC with PID have greatly influence in reduction torque ripple when compared with conventional model without controller. In the case of 100 N.m load, cannot apply on conventional model, so its compared relative to changing turn-on and turn-off angles.
- the result of adding uncertainties to proposed methods shows that all types of SMC have excellent dealing with it.
- Applied step load for all methods appear that SMLC with PID gains have faster response.

Table 2. improvement percentage compared with conventional model

Method	Load (N.m)	Torque ripple	percentage
Conventional model	0	2.31	
	25	1.58	
	50	1.58	
	100	0.959	
LSMC	0	0.4657	**80 %**
	25	0.49	**70 %**
	50	0.33	**79 %**
	100	0.563	**42 %**
LSMC based on currei Variable with PID gains	0	0.37	**84 %**
	25	0.38	**76 %**
	50	0.40	**75 %**
	100	0.309	**68 %**

6. CONCLUSION

In this paper, we propose various models of sliding mode controls to reduce the torque ripple of the 6/4 switched reluctance motor. The results show that SMLC with PID gains models have excellent improvement in reduction torque ripple in percentages of about (84%, 76%, 75%, and 68%) for (no-load, 25, 50 N.m) loads when compared with conventional models. Also, improved average torque, chatter-free, and speed response. Also, when compared with previous papers that were based on speed controllers, the LSMC with PID controlled speed in addition to torque ripple reduction. So, LSMC with PID work as speed controller and torque ripple reduction at the same time.

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