Fuzzy Controller Based DTC of SRM Drive Fed by Common High Side Asymmetric Switch Converter

Original Scientific Paper

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Abstract – *The switched reluctance motor (SRM) is recently gaining huge popularity in electric vehicle (EV) applications due to its control flexibility, simple structure, lower cost and high efficiency than the synchronous and induction motors. Among all the controllers, the direct torque control (DTC) is the most preferred due to its higher efficiency, lower losses and superior control characteristics. In this paper, a 6/4 pole SRM with fuzzy logic based DTC has been proposed for the EV application along with a converter with reduced switch counts to reduce the torque ripples and enhance the performance of the system under steady and transient state conditions. The proposed system is tested and validated under various scenarios that include load torque and speed variations and compared with the vector control method. From, the investigation it has been found that the proposed technique reduces ripples from the system during all the scenarios with a resultant flux of less than 0.5pu.*

Keywords: *Switched Reluctance Motor, high side switch asymmetric converter, direct torque control, fuzzy logic controller*

1. INTRODUCTION

Switched reluctance motor (SRM) has gained popularity among the industries for various inherent characteristics such as low cost, simple design, a wider range of speed, flexible control, higher starting torque and fault tolerance [1,2]. The advancement of power electronics converters and their control algorithms has additionally improved the performance of SRM [3]. The growing industrialization has led to the application of the SRM in various sectors like aviation, textile factories, robotics and electric vehicles [4-6]. However, the SRM encounters reliability and safety issues due to presence of doubly salient and switching power properties that added several demerits of higher torque ripples generation, noise and non-linear magnetic characteristics [7-9]. Also, nowadays, more research is going to design new control strategies to enhance the performance of the SRM as traditional techniques lag in terms of accuracy [10-15].

The most complex control strategies proposed in the wide range of literature include direct torque control (DTC), torque sharing function (TSF), advance torque control (ATC) and feedback control that can reduce the ripples in the SRM drives [16-19]. The torque ripples suppression of 12/8 SRM along with an investigation of the response of speed and load torque has been done by using both the TSF and DTC techniques in the literature [16]. Additionally, a predictive DTC strategy for torque and speed response improvement of SRM has been proposed and proved to be more effective than the conventional DTC in the literature [17]. An ATC-based control technique that maintains desired torque of the motor at the desired speed of the SRM has been proposed in [18] which is further improved by using the control parameters based on multi-objective optimization [19]. The low-frequency oscillations of the output torque in SRM torque have been compensated using a sliding mode control strategy in the literature [20]. Another technique based on the optimal commutation has been proposed for the SRM to reduce the torque ripple and enhance the torque-producing capacity of the motor [21]. A state-of-the-art literature review on various advanced control, current regulation and torque control strategies of the SRM drives has been conducted in [22].

Various research based on the utilization of simple PID controllers with optimization techniques has been conducted recently to meet the optimal torque and speed response of the SRM [23-25]. Some examples of optimization based PID controller technique includes ant colony optimization [23] and genetic algorithm [24] that have been applied to the 8/6 pole SRM that enhanced the speed regulation by tracking the set points in a faster way. Similarly, another particle swarm optimization based optimal PID controller has been proposed that achieved a minimum integral quadratic error of the speed by tuning the parameters [25]. Also, the torque and speed profile enhancement of a 6/4 SRM has been done by using ant lion optimization in a fractional order PID controller [26]. In [27], the performance of the speed and torque has been improved by using an optimal design for the parameters of the SRM. Also, the performance of SRM has been enhanced in [28] by replacing the material of the core with a soft magnetic composite.

Over the past few years, the current regulation of SRM has been carried out through numerous control strategies as investigated in [29] among which the current chopping control technique [30] has gained importance due to its independence in model and faster dynamic response. Moreover, as an alternative to the hysteresis controller, a controller with intelligence based on iterative learning has been proposed [31, 32]. Also, various complex control strategies has been proposed that include model prediction [33, 34], sliding mode [35, 36], dead-beat [37, 38] and adaptive [39] control strategies. However, the mentioned strategies have various vulnerabilities in terms of complexity, cost, slow response, sensitivity, higher ripples in current, etc. Recently, a PID controller based on the adaptive fuzzy concept has been proposed but, the system shows poor performance in terms of torque and speed regulation [40].

Hence, in this paper, a fuzzy logic based direct torque control (DTC) strategy for the SRM has been proposed that can reduce the torque ripples and enhance the performance and efficiency of the system during any scenario. The strategy has been applied to a 6/4 pole SRM along with a converter topology with a reduced number of switches that minimizes the cost and losses in the system. The performance of the proposed technique has been compared to the system with vector control DTC using various scenarios such as load and speed variation. The proposed work has been successfully implemented using MATLAB simulation environment. Further in addition, the same technique can also be implemented in real-time scenario as a future contribution of article.

The rest of the paper includes the description of the system modelling in section 2, the proposed control strategy in section 3, followed by the results and discussion in section 4 and the conclusion in section 5.

2. SYSTEM MODELLING

The proposed system has been shown in Fig.1 which comprises a novel converter configuration with only four switches, a 6/4 pole SRM, and an appropriate controller. The SRM is a doubly salient machine which has variable reluctance in the stator as well as the rotor. The following equations have been used to model the motor.

$$V = \frac{(\lambda_a - \lambda_u)i}{\lambda_u} \frac{(L^s{}_a - L_u) \times i}{t} \tag{1}$$

Where $t = \frac{\beta_s}{\omega_r}$

$$\sigma_s = \frac{T^s{}_a}{L_a} \quad \text{and} \quad \sigma_u = \frac{T^s{}_u}{Lu}$$

$$V = \frac{\omega_r}{\beta_s} L^s{}_a i \left(1 - \frac{1}{\sigma_s \sigma_u}\right) \tag{2}$$

$$L^s{}_a i = \phi T_{ph} = B \times A_{sp} \times T_{ph} = B \times D \times L \times \beta_s \times T_{ph} / 2 \tag{3}$$

$$A_s = \frac{2T_{ph} im}{\pi D} \tag{4}$$

$$P_d = k_a k_d V_{in} \tag{5}$$

$$k_d = \frac{\theta_i q P_r}{360} \tag{6}$$

In the case of 6/4 SRM having short pitch winding, a phase is mainly formed from the series connection of coils with physically opposing poles. Hence, to avoid negative torque components, only one phase of the SRM is excited as a result, there is a simultaneous operation of the two phases during the commutation period. This cause the current of the ongoing phase to zero four which there is an increase in the current of the next incoming current. Hence, the developed power during one phase conduction (P_d) has been calculated as

$$P_d = k^d k_e \left(\frac{\pi^2}{120}\right)\left(1 - \frac{1}{\sigma_s \sigma_u}\right) B A_s D^2 L N_r$$

$$T = k_d k_e k_3 k_2 (B A_s) D^2 L$$

with $k_2 = 1 - \frac{1}{\sigma_s \sigma_u}$ and $k_3 = \frac{\pi}{4}$

$L^s{}_a$: per phase aligned inductance

L_u: unaligned inductance

t: time required by the rotor to turn from aligned to unaligned

$L^u{}_a$: unaligned unsaturated inductance

β_s: arc of stator pole

φ: aligned flux

A_{sp}: stator pole area

D: bore diameter
L: length of stator pole inductance
B: flux density of stator pole
T_{ph}: number of turns per pole per phase
m: active number of phases
k_d: duty cycle
q: number of stator phases i.e. Ps/2
θ_i: current conducting per phase
P_d: power developed by the SRM (as only one phase conducts at a time)
P_s: number of poles in the stator
P_r: number of poles in the rotor

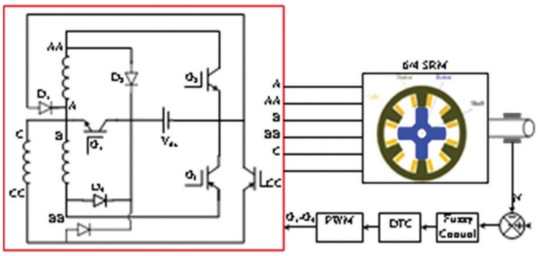

Fig. 1. Speed control of SRM

Also, it can be viewed from Fig.1 that one DC supply, four PWM-based switches and four diodes have been used and applied to the three phases of the SRM. The proposed system is less expensive and can be easily implemented in SRM as compared to the conventional converters. Also, due to lesser switch counts involved in the power conversion, the ripples from the system get reduced.

3. CONTROL STRATEGY

Direct torque control (DTC) is a strategy that controls the PWM converter fed drives by controlling the torque and flux of the SRM without requiring any complicated algorithms like vector control. Also, it requires only the stator resistance in which torque and flux components can directly regulate within the limits so that it can regulate torque under less ripples compared to vector control. The block diagram of DTC for the proposed system has been represented in Fig.2. The Fuzzy controller generates the reference torque signal by using Fuzzy memberships and the Fuzzy block diagram has been represented in Fig.3.

Also, the fuzzy rule base table used in the proposed concept has been tabularized in Table 1.

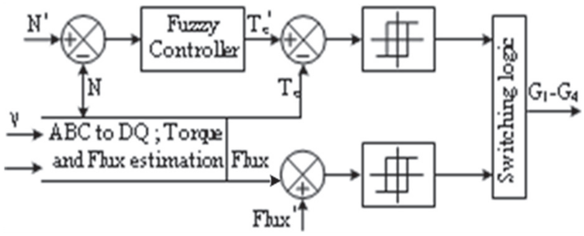

Fig. 2. Direct torque control (DTC) for the proposed system

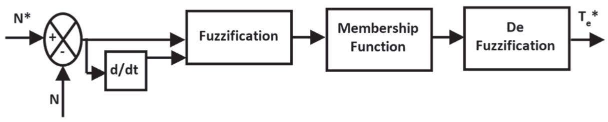

Fig. 3. Block representation of the fuzzy controller

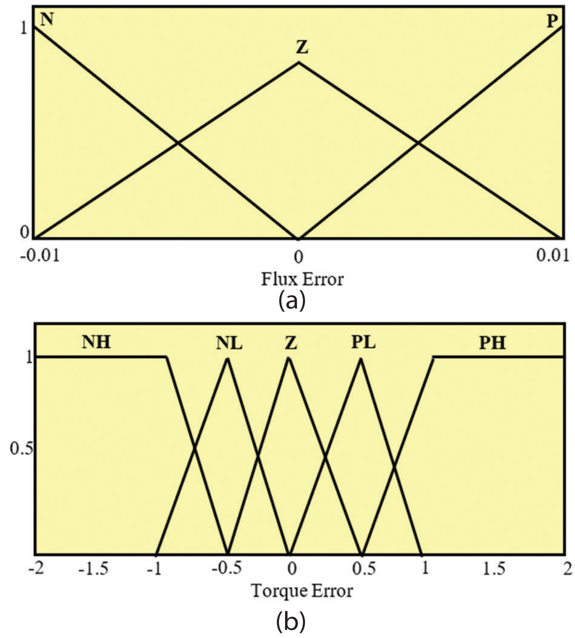

Fig. 4. Membership function of (a) flux, and (b) torque

The trapezoidal membership function has been used in this work for Fuzzification. Based on two inputs and a single output, three membership function groups with each group having many subsets have been used. The torque error (T_e) and stator flux error (F_e) are considered the inputs of the fuzzy system. The Te has five categories whereas the Fe has three. From the fuzzy rule base table given in Table 1, three linguistic variables i.e. positive (*P*), negative (*N*) and zero (*Z*) has been used to represent the error in the stator flux. Similarly, five linguistic variables i.e. positive high (PH), positive low (PL), negative high (*NH*), negative low (*NH*) and zero has been used to represent the torque error. The membership function of flux and torque have been represented in Fig.4 (a) and (b) respectively. The actions that will be decided by the fuzzy controller include torque and flux increase (*TIFI*), torque increase and flux decrease (*TIFD*), torque hold (*TH*), torque decrease and flux increase (*TDFI*) and torque decrease flux decrease (*TDFD*). In this work, the maximum method of fuzzification has been considered to achieve smooth control and switching where the membership functions are distributed to the entire range of fuzzy range through the crossing.

Table 1. Fuzzy rule base table

T_e / F_e	NH	NL	Z	PL	PH
N	TDFD	TDFD	TH	TIFD	TIFD
Z	TDFI	TH	TH	TIFD	TIFD
P	TDFI	TDFI	TH	TIFI	TIFI

Table 2. Switching sequence of the converter

G1	G2	G3	G4	Torque	Flux
On	On	On	On	High	High
On	On	On	Off	High	Low
On	On	Off	Off	Low	Low
On	Off	Off	Off	Zero	High

The switching sequence of the proposed converter to torque and flux has been given in Table 2. The reference torque is compared with the estimated torque and the error signal is sent to torque controller. Similarly, the reference flux is compared with the estimated value and the respective signal is fed to the flux controller. The d-q reference frame representation of the torque and flux has been given below.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos2\theta & \cos\left(2\theta - \frac{2\pi}{3}\right) & \cos\left(2\theta + \frac{2\pi}{3}\right) \\ -sin2\theta & -\sin\left(2\theta - \frac{2\pi}{3}\right) & -\sin\left(2\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + \begin{bmatrix} L_{dc} + \frac{L_{ac}}{2}\cos 6\theta & -\frac{L_{ac}}{2}\sin 6\theta & L_{ac}/\sqrt{2} \\ -\frac{L_{ac}}{2}\sin 6\theta & L_{dc} + \frac{L_{ac}}{2}\cos 6\theta & 0 \\ L_{ac}/\sqrt{2} & 0 & L_{ac} \end{bmatrix} \quad (10)$$

The torque created is proportional to the current in the q-axis and given as

$$T_e = k_t i_q \quad (11)$$

where $k_t = \sqrt{2} P L_{ac} i_d$

The d-q reference components have been used to design the direct torque controller. The pulse generator generates four pulses for each of the four switches. The specification of the SRM considered in the study has been given in Table 2.

The switching logic block will generate only 4 pulses which are required for the proposed converter to drive the 6/4 pole SRM. The fuzzy logic controllers will help to generate smooth reference signals to make less ripples in the electromagnetic torque of the SRM.

Table 2. Specification of the SRM

Parameter	Ratings
Stator resistance	3.1Ω
Inertia	0.0089 N^{-m}
Friction coefficient	0.01
Unaligned inductance	5.9 e^{-3}
Aligned inductance	23.6e^{-3}
Saturated aligned inductance	0.15e^{-3}

4. RESULTS AND DISCUSSIONS

The performance of the proposed system has been evaluated in the MATLAB/Simulink environment and tested under various scenarios such as load torque and speed variation. Also, the ripples generation of the proposed technique has been compared with the artificial neural network vector control DTC technique.

4.1. TORQUE RIPPLES COMPARISON

The performance of the proposed system has been validated by comparing it with the ANN-based vector control technique in terms of torque ripples generation. The graph represented in Fig.5 represents the torque ripples generated by the SRM with ANN vector control and the proposed control technique and it can be observed that the ripples are less in the case of the proposed fuzzy-based converter compared to the ANN vector control technique. Due to the direct control of torque and flux, the torque gets stabilizes quickly with a very less ripple content and this type of response is very important in case of electric vehicle application.

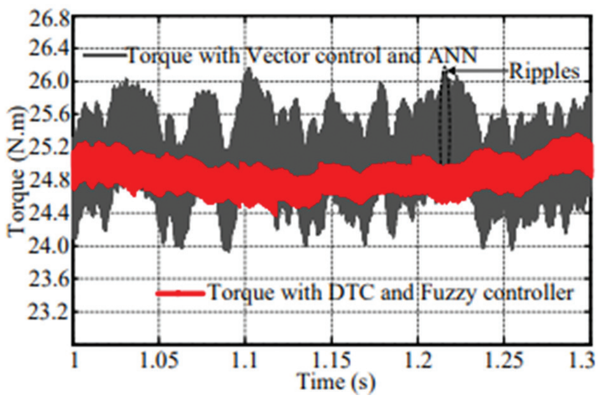

Fig. 5. Response of torque in vector control, ANN and proposed fuzzy based DTC

The load torque considered in this study is of value 25Nm and it can be visualised from the graph that the proposed technique controller can stabilize the electromagnetic torque with reduced ripples in the system. Also, the reduced count of switches in the converter provides a smooth power conversion between the batteries and motor windings.

4.2. SPEED VARIATION

In this study, the proposed controller is tested under a speed variation scenario in which the speed of the motor has been increased at time t=3s from 1000rpm to 1500rpm. During this case, the proposed controller attempts to raise the reference torque of the system. As the speed of the SRM depends on the generated electromagnetic torque hence, the controller enhances the torque of the motor to increase the speed and maintain it to the reference value.

The response of speed of the SRM during this case has been depicted in Fig. 6 in which it is visible that the proposed controller stabilizes the speed to the set reference value. The response of the electromagnetic torque has been shown in Fig.7 from which it can be seen that the torque increases temporarily before stabilizing at its usual value which is equal to the load torque.

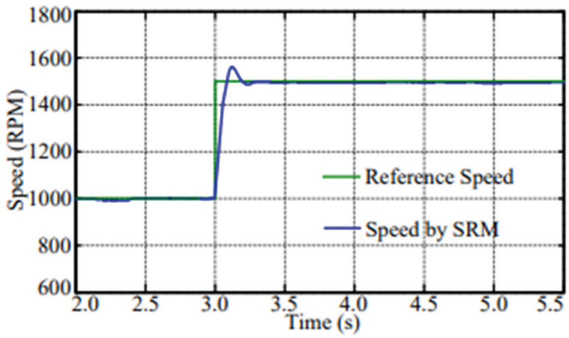

Fig. 6. Response of speed

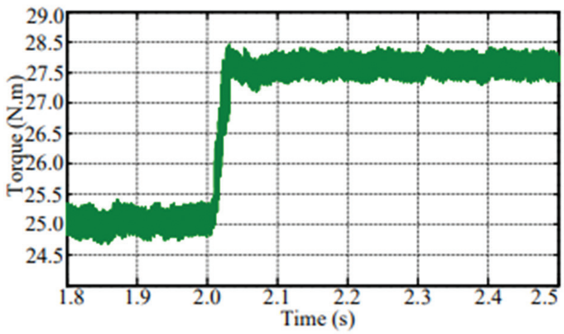

Fig. 7. Response of electromagnetic torque

4.3. LOAD TORQUE VARIATION

The performance of the proposed fuzzy logic based controller has been tested under load torque variation. In this scenario, the load torque has been increased from 25Nm to 27Nm at time t=2s. During this scenario, it has been observed that there is a reduction in the speed of the SRM due to increased load torque. The proposed fuzzy controller then increases the reference electromagnetic torque to increase the speed of the motor. This operation is carried out by the controller that sends the required signal to the switches of the converter to increase electromagnetic torque of motor. The response of electromagnetic torque and speed of the system during this scenario has been recorded in Fig.8 and Fig.9 respectively in which it can be observed that when electromagnetic torque reached near the reference value, the speed of the SRM reduced temporarily which has been managed by the proposed controller.

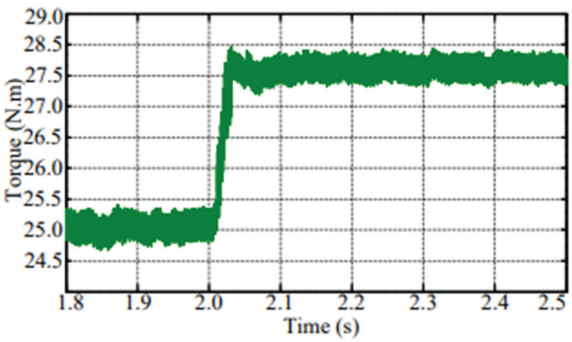

Fig. 8. Response of electromagnetic torque under load torque variation

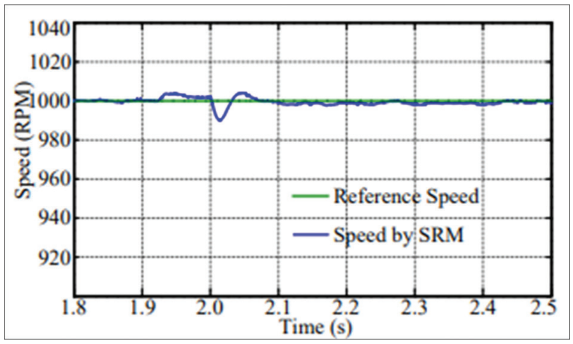

Fig. 9. Response of speed under load torque variation

4.4. RAPID REFERENCE SPEED VARIATION

The rapid speed variation is one of the common case noticed among the SRM applications such as electric vehicles. Hence, to study the efficacy of the controller, a scenario where the reference speed of the motor has been varied from time t=1s to 2.2s. The response of the reference speed with the variation has been shown in Fig.10 in which it can be observed that the controller can track the changing reference value effectively and allows the motor to run according to the reference speed. This scenario is most useful for the case of electric vehicles in which the reference speed varies continuously. The controller is capable of tracking all types of reference speed variation in the system.

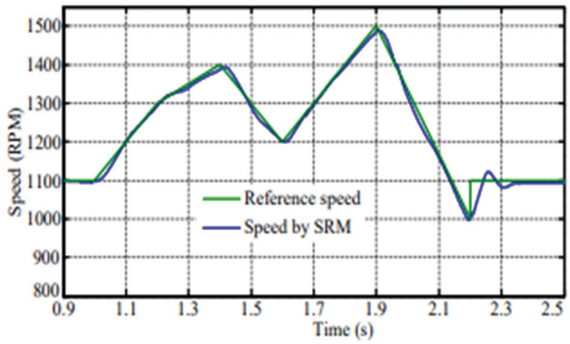

Fig. 10. Response of speed of SRM with rapid reference speed variation

4.5. FLUX TRAJECTORY

The trajectory between the flux of the direct axis and quadrature axis is very important to analyzing the flux status under the operation of the motor. This trajectory can examine both flux weakening and saturation mode of the core. The response of trajectory has been shown in Fig.11 for changing the speed and torque. From the graph, it can be observed that the resultant flux is less than 0.5 per unit (pu), hence the flux is under the limit to avoid saturation mode.

Hence, from the results, it can be concluded that the proposed fuzzy logic based DTC technique for SRM works effectively by smoothing the system's operation along with reducing the ripples. The main advantage of the proposed technique is the requirement of less switches in the converter and higher toque reduction capability than vector control methods and simple structure. But, the demerit lies in switching frequency variation and the dependence on the flux of the stator along with the hysteresis ban comparator.

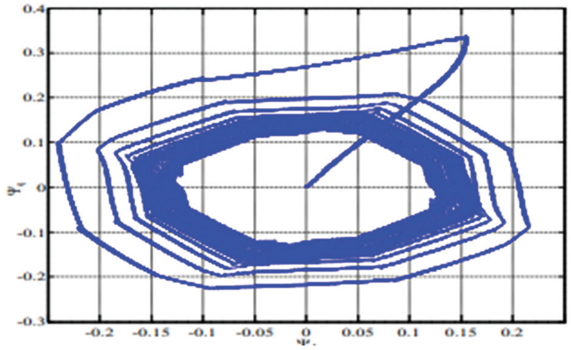

Fig. 11. Response of flux trajectory in pu

5. CONCLUSION

In this paper, a fuzzy logic based direct torque control for the 6/4 poles switched reluctance motor has been proposed that can be used in the electric vehicle application. Also, a new converter with reduced switch counts has been designed to reduce the associated cost and losses from the system. The proposed technique has been tested under various steady-state and transient state scenarios that include load torque variation and speed variation of SRM and compared with the vector control technique. The results clearly state that the proposed technique is capable of reducing the torque ripple and increasing efficiency. Also, it has been noted that during load torque and speed variation scenarios, the proposed technique can stabilize the system with very less generated ripples. Also, during speed variation of the motor, the fuzzy logic-based controller can enhance the speed and maintain it to the reference value. From the conducted analysis, it has been established that the proposed system has a resultant flux of less than 0.5pu. The main advantages of using the proposed control technique lie in its efficient torque reduction, simple structure and reliability. Also, the proposed advanced technique does not generate negative torques like conventional DTC resulting in no reduction of the torque-ampere ratio of the motor. The future scope of this work can be the implementation of the proposed technique in the four-phase and five-phase SRM along with applying the concept in sliding mode control. The same can also be implemented in a real-time scenario with development of hardware prototype as a future scope of the article.

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