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Torque Ripple Minimization of SRM for Electric Vehicle Applications

D.A. Shahakar, S.B. Warkad

Abstract: ***The shortage of energy and environmental pollution are considered as relevant problems due to the high amount of automotive vehicles with internal combustion engines. Electric vehicles (EV) are one of the solutions to localize the energy source and best choice for saving energy and provide zero emission vehicles. The key component of the Electric vehicles is the electric motor and, therefore, its choice is important. Many types of electric motors have been analyzed during last decades and evaluated for EVs. Switched reluctance motors (SRM) have a number of advantages in contrast with other electric motors due to their simple construction, flexibility of control, high efficiency, lower cost and robustness to run under failure conditions. The SRM rotor does not have any windings or permanent magnets, being suitable for very high speed drive application. The switched reluctance motors drives (SRDs) necessitate more advanced control technology than DC and AC motors drives. High torque ripple, acoustic noise and vibrations are the major drawbacks of the SRM. So to decrease the torque ripple and improve the electric efficiency is the main objective and can be achieved by optimization policy.***

Keywords **:** ***Electric Vehicle, Switched Reluctance Motor, , torque ripple, efficiency.***

I. INTRODUCTION

The Switched reluctance motors (SRMs) have become an admired resolution for the transportation, agriculture, mining, civil and tactical sectors. Moreover, SRMs are a perfect drive alternative for electric vehicles because of their low cost, high efficiency and have the capability to perform in difficult situations. However, they have several drawbacks, including high torque ripple, severe acoustic noise, and vibration. In addition, due to the SRM's dual salient structure and non-linear machine characteristics, smooth torque control is difficult to achieve [9]. In recent years, many studies have been conducted to reduce torque ripple, mostly via machine design optimization and high-performance control systems [10] [11]. Nowadays, Direct torque control (DTC) and indirect torque control (ITC) are the most common torque control technologies used in SRM in which the power converter's switching signal is directly generated in DTC by integrating the error between the command torque and the instantaneous torque of SRM with proper commutation logic [12-14]. Besides, DTC approaches such as direct instantaneous torque control, direct torque and flux control, and advanced DTC strategies, are proposed for SRM to solve the above drawbacks [15] [16]. In the domain of torque ripple reduction for SRM drives, instantaneous torque control (ITC) is gaining popularity because it distributes torque between motor phases using a torque sharing function (TSF) [17]. In [18], a direct instantaneous torque control (DITC) with wide operating range for SRMs was presented.

When compared with the existing DITC, the proposed DITC could reduce the torque ripple without the need for an additional switching angle optimization approach. Hence, the performance of the SRM drive system is affected by the inverter switching angles under various control approaches. Offline optimization and searching methods are more widely used because they are simple to implement in real time and more likely to find the global optimum point [19]. A Genetic Algorithm (GA) was used to find the best switching angles thereby increases the output voltage for a switched reluctance generator [20], however varied switching angles corresponding to different phases suggests low efficiency. In [21], based on the excitation angles, the torque ripples and copper losses are reduced by employing a two-group multi-objective optimization algorithm. Finally, the particle swarm optimization (PSO) algorithm is used to identify the optimal control parameters. Thus, the results reveal that the proposed control is feasible and effective over a wide speed range [22].

II. LITERATURE REVIEW

A. Related Works

In 2017, Xudong Gao et al. [1] have established a multi-objective optimization of Switched Reluctance Motor drive (SRD) for electric vehicles. Based on a nonlinear dynamic model, the effects of load torque, turn-on and turn-off angle on torque ripple and electric efficiency of the SRM can be analyzed. Then, a unique double-index synchronous optimization policy is developed to eliminate torque ripple and increases the electric efficiency. Thus, the simulation and experimental results shows the effectiveness and superiority of the proposed method. In 2021, Cunhe Li et al. [2] have developed a high-performance indirect torque control (HPITC) strategy for torque ripple minimization in SRM drive system. A unique torque sharing function is designed based on the nonlinear torque-angle characteristic of SRM to achieve the ideal current profiles such that the torque ripple is minimized.

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Then, a robust current controller is constructed to track current precisely and indirectly achieve high-performance torque control. Therefore, by using the pulse width modulation (PWM) method, the suggested controller not only addresses motor parameter modelling flaws, but also realizes fixed frequency current control. Finally, the presented schemes were examined in terms of torque ripple suppression, system efficiency, and anti disturbance.

In 2019, Pittam Krishna Reddy et al. [3] have introduced a new Direct Torque Control (DTC) strategy for controlling the SRM with enhanced dynamic performance and minimal torque ripple. Furthermore, by changing the sector partitioning and selecting the appropriate voltage vectors, this technique produces a greater source current by lowering the net torque per ampere ratio. Here, the adopted scheme enhances the performance in terms of efficiency and torque ripple under various operating conditions. In 2021, Mahmoud Hamouda et al. [4] have established an enhanced Direct Instantaneous Torque Control (DITC) strategy of SRMs for EVs. First of all, the turn-on angle was calculated analytically in order to give a wide range of operation and MTPA conditions. Second, an optimization-based method was utilized to determine the best turn-off angles for minimizing torque ripple, copper losses, and high efficiency. Thus, the results show that the proposed DITC can provide the lowest torque ripple, highest torque to current ratio, and the best efficiency over the low and medium speed ranges. In 2018, Hao Chen, et al. [5] have presented a novel multi-objective optimization design method for switched reluctance motor (SRM) on low speed electric vehicles. Six geometric parameters optimization objectives for SRM are offered, which are maximum speed, accelerate time, maximum climbing gradient, energy usage ratio, and torque ripple factor, based on the indexes of low speed EVs propulsion system and the huge torque ripple of SRM. Then, a Taguchi-Chicken Swarm Optimization (Taguchi-CSO) technique is used to do a multi-objective optimization design of the geometric parameters of SRM. Hence, the simulation result verifies the correctness of the finite element model and the accuracy of the multi-objective optimization. In 2017, He Cheng, et al. [6] have established a novel Adaptive Variable Angle Control (AVAC) control strategy which helps to avoid the switching chattering between the current chopping control and angle position control modes in SRM drives for EV applications. An EV model is developed in this study by combining the dynamic simulation model of SRM with the vehicle dynamic equations. The command torque of the motor drive system is given based on the accelerator pedal coefficient and motor operation areas. Finally, the simulation and experimental result shows the feasibility and effectiveness of the proposed control strategy. In 2021, Yuanfeng Lan et al. [7] have presented a review on Switched Reluctance Motor (SRM) and drive systems in electric vehicle (EV) powertrains. In order to eliminate torque ripples and to enhance the torque density and power factor, Multi-Stack Conventional SRM (MSCSRM) and Multi-Stack SRM with a Segmental Rotor (MSSRM-SR) are developed. In the end, the investigational outcomes have revealed the betterment of the adopted scheme. In 2019, Marcio Rodrigues da Cunha Reis et al. [8] have developed an improved technique for driving and controlling the SRM which helps to enhance the computational model, control response, and machine efficiency. The proposed identification technique based on a parametric regression model aids in determining the inductance profile of a switched reluctance motor with more precision and lower computational cost. Thus, the proposed technique ensures improvement in drive and control of SRM under conditions of speed variations, torque variations and cost reductions.

B. Problem Definition:

From the literature reviews on Switched Reluctance motor for EV applications, at first, Double-Index Synchronous optimization strategy was introduced in [1], which maximizes the electric efficiency, performance and offers minimum torque ripple. However, effective dynamic optimization of SRD is not possible. HPITC strategy was exploited in [2] that offer minimal torque ripple and it also provides improved system efficiency and anti-disturbance ability, but there occurs a major problem of uncertainty. DTC strategy was used in [3] that eradicate the negative torque and improves the efficiency and performance. However, it needs to concentrate mostly on traditional AC machines. Furthermore, DITC strategy was implemented in [4] which offer fast dynamic response and achieve high torque/current ratio with better efficiency; anyhow, a major drawback is the occurrence of high current peak. Taguchi-CSO technique was presented in [5] that offer fast convergence speed with better computational accuracy, but, optimization design index has to be concerned more. Moreover, AVAC control strategy was implemented in [6] that remove the switching chattering and provide highly feasible and accurate solutions. Nevertheless, adaptive control system stability is not considered here. In addition, MSCSRM + MSSRM-SR method was suggested in [7] which offer high torque density with improved power factor. However, it need consideration on MSCSRM with less number of switches and Control methods. Parametric Regression Model was introduced in [8] which is highly precise and offers less computational effort. However, Complex problems are not concerned. These restrictions must be taken into account so as to boost the performance of Switched Reluctance motor successfully in the current research.

III. SYSTEM MODEL OF THE PROPOSED OPTIMIZED ANGLE CONTROL METHODOLGY FOR SRM MOTOR

Fig. 1 depicts a block schematic of the proposed angle control of a SRM. The system comprises of speed and current control for which it uses PI controllers, a PWM full bridge converter and controller for commutation angle. The block commutation angle control determines the phase winding commutation period. The rotor position feedback's information is utilized to choose the angle at which the power switches are turned on (θ_{on}) and turn off (θ_{off}). A current hysteresis controller is deployed to manage the current in an activated phase winding.

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The rotor position, stator flux coupling, and excitation current all affect machine co-energy, which causes high torque ripple. Changes in rotor position and phase current cause the torque and flux linkage inductance to become nonlinear. Hence, ripples in torque can be reduced by adjusting the current profile and choosing the right angles to turn on and turn off. The angle control is presented in this work, together with optimal turn on and turns off angle, with torque ripple minimizing of SRM. The turn-on and turn-off angles were fixed for a certain reference speed, and then the reference current was modified until the needed reference speed was achieved. The method is then repeated for several sets of switching angles in order to find the one that delivers the most efficient operating at that speed during optimization process.

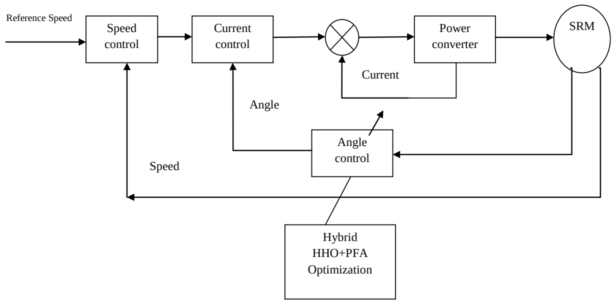

Fig.1: Block diagram of SRMD system

A. Mathematical Modelling of the SRMD [25]

The SRM is a singularly stimulated motor that has a dual significance. The switching reluctance motor's stator simply comprises excitation windings, while the rotor is made of steel laminations and does not contain a permanent magnet. For rotor movement, the phases are excited in order. The rotor moves due to its proclivity for acquiring a minimum reluctance position. The electrical equations for every phase and the equation guiding the mechanical systems make up the mathematical modeling that explains the dynamics of the 6/4, 60 KW SRM. The stator phase voltage is fed into the SRM model. Every phase's electrical circuit is made up of an inductance which is nonlinear and coupled to the converter. The stator phases are believed to have little mutual coupling.

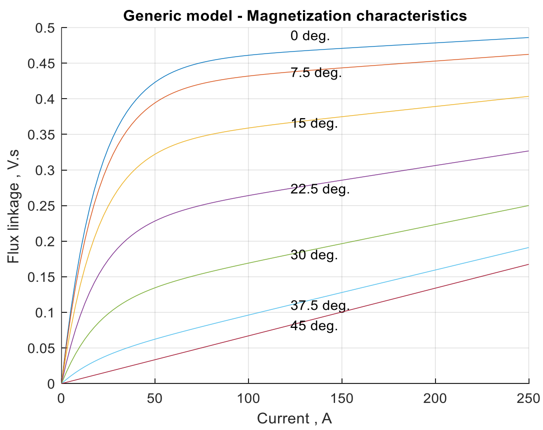

Fig.2 Magnetization characteristics of proposed SRMD

The stator current and rotor position affect the magnetic flux link in a nonlinear manner due to the nonlinear magnetic properties of Switched Reluctance Motor due to saturation and variable air gap with rotor position (θ).

The magnetic flux link can be calculated using the Eq. (1)

$$\psi_{fs}(t') = \psi_{fs}(i', \theta') \tag{1}$$

The phase voltage of stator is considered as the input voltage of the modeling. The integral time distinction betwixt phase voltage and voltage drop about the stator resistance is the stator phase voltage which is defined by Eq. (2).

$$\psi_{fs}(t') = \int_0^{t'} (V_{se} - R_{se} I_{se}) dt \tag{2}$$

Where, the flux linkage vector is denoted by $\psi_{fs}(t')$ V_{se} indicates the voltage of stator, R_{se} indicates the resistance of winding. The stator current is derived from the characteristic curve which is given in Fig.2. The rotor position θ is calculated from the different position of rotor during its revolution.

Let us consider the single phase of electromagnetic torque of SRM can be derived from its co-energy $E(i, \theta')$

$$T_{em}(i, \theta') = \frac{\partial}{\partial \theta'} E(i, \theta') \tag{3}$$

Where E can be calculated by Eq.(4).

$$E(i, \theta') = \int_0^{i'} \psi(i', \theta') di' \tag{4}$$

The electromagnetic torque T_{em} is created by SRM that is the summation of the torques created by seperate phase. The SRM's mechanical dynamics can be explained by the Eq. (5)

$$T_{em} = J' \frac{d\omega_{mv}}{dt'} + G\omega_{mv} + T_{L'} \tag{5}$$

here, $T_{L'}$ indicates load torque, J' indicates the moment of inertia ω_{mv} indicates angular velocity and G indicates coefficient of friction. In the aforementioned model, the following assumptions are made.

- There are no mutual inductances betwixt the phases.
- The motor operates within the linear range of its magnetic properties.

B. Modelling of Speed controller

The disparity among the reference speed with that of its feedback signals from the SRM is known as the speed error, and the current command is the speed controller's output. Generally, the integral gain (K'_{is}) reduces errors at steady state by integrator-based low-frequency compensation, while the proportional gain (K'_{ps}) through it's gain factor gives total control command proportionate to the error signal. The Eq. (6) and (7) is a general representation of the PI speed controller's transfer function.

$$G(s)_{TF} = K'_{ps}\left(1 + \frac{1}{T'_s S}\right) \tag{6}$$

$$G(s)_{TF} = \left(K'_{ps} + \frac{K'_{is}}{S}\right) \tag{7}$$

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here, T'_s is the time integral constant.

C. Modelling of Angle controller

The SRM's performance is ultimately enhanced and determined via the optimal control of switch-on and switch-off angles method. The selection of switch-on and switch-off angles affects the range of torque-speed, efficiency of motor, ripples in torque, and noise acoustic to certain limits. In addition to the PI control, the torque ripple is decreased via choosing the turn-on and turn-off angles ideally, that decreases the torque drop.

The phase commutation can be accelerated by increasing the turn-on and turn-off angles. Hence, to begin positive torque generation, the turn-on angle must be closer to the minimal position of inductance, and the turn-off angle must be close to the maximal position of inductance. The negative torque is avoided by allowing flux to dissipate prior to the rotor attains the point where negative torque is produced. It suggests that the supply is switched off in advance, yet if the turn-off is planned not with care, positive torque production may be lost. Here, Path Finder Insisted Harris-Hawk Optimization has been proposed to select the correct switch-on and switch-off angle via error reduction of the current controller to generate the control signal to the converter.

D. Modelling of current controller

The controller topology of every phase current control loop is similar, consisting of a PI current control and a PWM control. Now, the current controller's transfer function is defined by Eq. (8)

$$G(s)_{TF} = (K'_{pi} + \frac{K'_{ii}}{S}) \tag{8}$$

The current controller gets the command signal (reference current) from the speed controller and angle controller, then combines them and compares it with the measured phase current to minimize the current error. Finally, it produces the control signal to generate the duty cycle of the PWM generator.

IV. RESULT AND DISCUSSION

A. Simulation procedure

The proposed optimal angle control approach using the optimized angle controller for Switched Reluctance Motor was executed in MATLAB2021b Simulink environment and analysis was done in the same. The simulations for the optimal control under two cases of load torque patterns are carried out. For illustrating the supremacy of presented scheme, results are compared with many other optimization technique. The performance of these methods is analyzed concerning error analysis, convergence, speed stability, torque ripple reduction, and steady-state performance under uniform and non-uniform loading torque. Cases taken for analysis are,

Case 1: nonuniform load torque: 15 Nm and 75 Nm

Case 2: uniform load torque: 75 Nm

Speed Analysis

Fig.(4) and Fig.(5) gives the speed response of case A and B condition and its time domain performance parameters are given in Table 2 and 3.

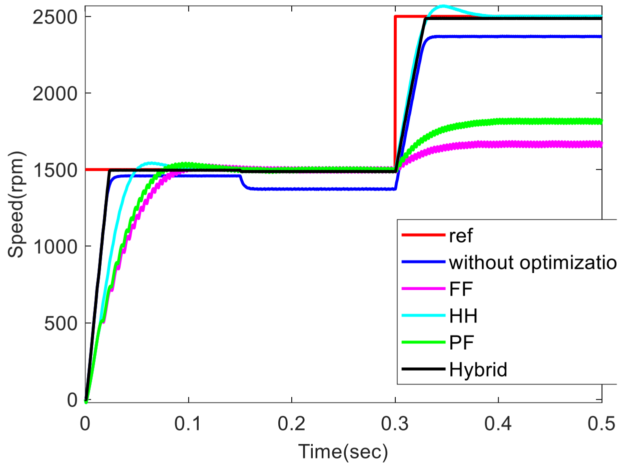

Fig.4 Speed response curve for case 1

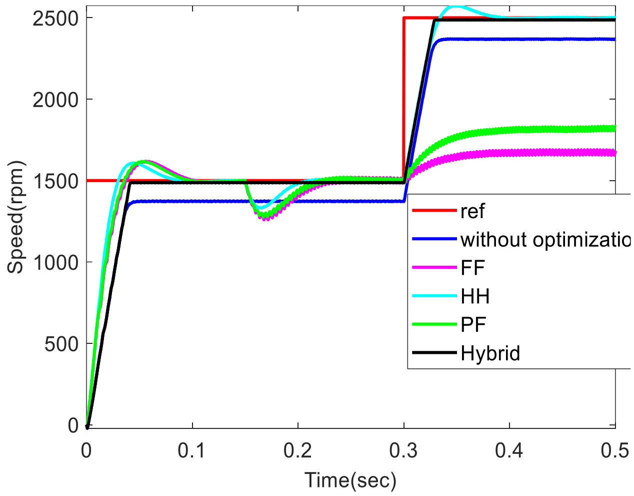

Fig.5 Speed response curve for case 2

Table 2: Stability Analysis for Speed curve for case 1

Parameters	WO	PO
Rise Time	0.31705	0.31685
Settling Time	0.32807	0.32741
Settling_min	2132.5	2237.6
Settling_max	2371.5	2488.4
Overshoot	0.1173	0.097381
Undershoot	0.11497	0.10955
Peak	2371.5	2488.4
Peak Time	0.40372	0.4845

Form this effectiveness of the proposed optimized angle control is described. In this case the set speed is varied from 1500 rpm to 2400rpm. From the speed response graph and time domain characteristics it is observed that the performance of proposed optimized controller attained the steady state without having very much overshoot and oscillations. The proposed controller for case 2 is settled in reference speed sooner at 0.32723s. The praposed optimized controller has negligible peak overshoot that is 0.05s than the conventional methods for case 2. Similarly the peak undershoot is also negligible for case 1 for the proposed controller that is 0.1s. The other parameters also proves that the effectiveness of the proposed hybrid controller.

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Table 3: Stability Analysis for Speed curve for case 2

Parameters	WO	PO
Rise Time	0.31351	0.31316
Settling Time	0.32807	0.32723
Settling_min	2133	2238
Settling_max	2371	2488
Overshoot	0.073601	0.058327
Undershoot	0.91571	0.87257
Peak	2371.5	2488.4
Peak Time	0.45348	0.44814

Torque Ripple Reduction

The Fig. (7) and (8) shows the phase current of SRM motor using for torque ripple reduction. For Analyzing and comparing the proposed PFI-HHO optimized controller with conventional optimized controller has very less torque ripples.

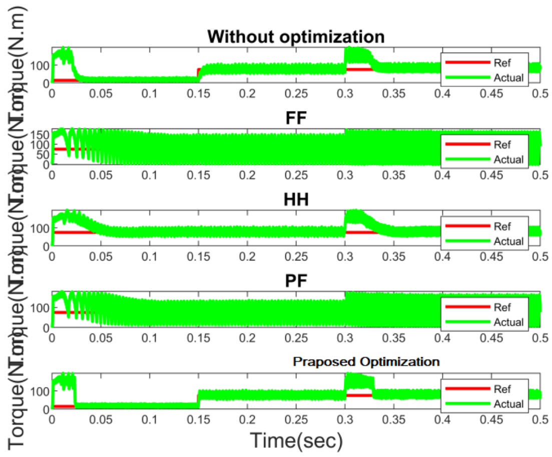

Fig.(7) Torque response of SRM motor for case 1

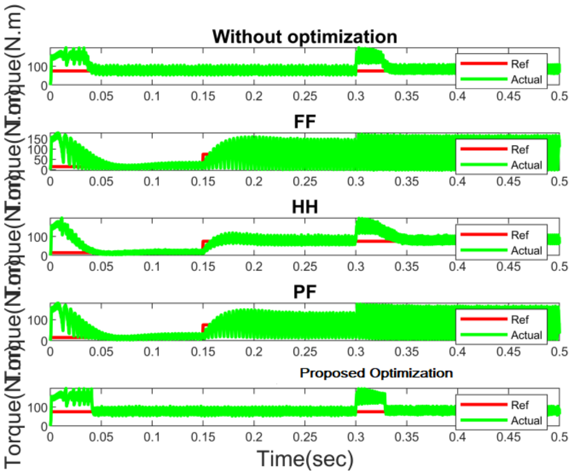

Fig.(8) Torque response of SRM motor for case 1

Table:4 Torque ripple coefficient of SRM Motor for case 1

Controller	Torque Ripple
Without Optimization	2.797523156
Proposed Optimization	1.052850741

Table :5 Torque ripple coefficient of SRM Motor for case 2

Controller	Torque Ripple
Without Optimization	2.241353571
Proposed Optimization	1.776802754

The torque ripple coefficient (T_r), given by Eq. (22), can be used to determine the amount of torque ripple. The values of T_r are given in Table 4 and 5.

$$T_r = \frac{T_{mx} - T_{mn}}{T_{mean}} \quad (22)$$

Where,

T_r is the torque ripple

T_{mx} is the maximum torque

T_{mn} is the minimum torque

T_{mean} is the mean torque value

From the Table (4) and (5) it is clear that the proposed optimized controller has less ripples of 1.05 for case 1 and 1.77 for case 2 than the conventional controllers which are having the torque ripple coefficient value more than 2. Its observed that the suggested optimized controller minimized the torque ripple very well than the conventional methods.

The optimal angles

The optimal angles obtained by the different methods are tabulated in Table 6 and 7 for the two cases. On observing both the cases, its clear that as the load torque increases the turn-on angle decreases from 43.017 to 42.627 for the proposed optimization scheme, whereas for all the other conventional methods it increases. This also accounts for the minimal torque ripples and optimal electric efficiency.

Table 6: The optimum turn-on angle for case 1 and case 2

Methods	Case1	Case2
Without Optimization	57.247	58.017
Proposed Optimization	43.017	42.627

Table7: The optimum turn-off angle for case 1 and case 2

Methods	Case1	Case2
Without Optimization	89.326	89.481
Proposed Optimization	82.481	85.400

Electric efficiency:

The torque smooth degree coefficient (TS) based on which the proportional co-efficient (K_{TSR}) for optimal electric efficiency [1] are defined as per Eq. (23) and Eq. (24).

$$TS = \sqrt{\frac{\pi}{3\int_0^{\frac{\pi}{3}} T_e^2(i,\theta)d\theta}} \quad (23)$$

$$K_{TSR} = \frac{TS}{TS_{\max}} \quad (24)$$

Table7: Proportional co-efficient for case 1 and case 2

Methods	Case1-K_{TSR}	Case2-K_{TSR}
Without Optimization	0.76982	0.82803
Proposed Optimization	0.80017	0.84102

Table 7 presents the proportional co-efficient values for the optimal electric efficiency of the proposed and the comparative methods.

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On observing both the cases the proposed method has a higher proportional co-efficient than that of the comparative techniques. Also, higher the value of TS and K_{TSR} , the torque ripple is least and electric efficiency is higher for the SRM applied to EV drive. To summarize the more effective the control or optimization strategy is the one that has the values of K_{TSR} closer to unity.

V. CONCLUSION

The proposed angle control for SRM accompanied by torque ripple minimization is described in this article by decreasing phase current inaccuracy. Also, the optimum values of switch on and switch off angles are discovered. For assessing the robustness of the performance, stability analysis for uniform and non-uniform load torques is considered. The proposed control has an optimal turn-off angle value of 85.400 which is less than conventional controllers which are having 89.481, 86.513, 91.477 and 86.392 for the torque variation as per case 2. From Table 4 and 5 it is clear that the proposed optimized controller has less ripples of 1.05 for case 1 and 1.77 for case 2 than the conventional controllers. The obtained results show that speed controllers provide improved performance for SRM drives by reducing torque ripple and settling times and providing a better current profile due to their robust exploitation capability.

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