

Torque Ripple Minimization of an Innovative Non-Permanent Magnet Hybrid Excited Switched Reluctance Motor for Electric Vehicle Applications

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Abstract—This paper presents a novel hybrid excitation topology for a switched reluctance motor (SRM) that enhances torque performance and minimizes torque ripple in electric vehicle (EV) applications. It has novel hybrid SRM (HESRM) excitation features without using permanent magnet (PM) excitations inside the machine core. By injecting a separate direct current (DC) through the designated auxiliary poles, the same flux path as standard SRMs can be provided. Thus, the variable current in the various pole phases contributes more magnetic flux to the active region, leading to a more substantial electromagnetic torque. To examine the electromagnetic properties of the machine, the 2D finite element method (FEM) is employed using the Ansys/Maxwell software. The torque, efficiency, ripple, and power performance are evaluated and compared between the conventional SRM and the proposed HESRM at the same ratings. Experimental results confirm the integrity of the simulated results and demonstrate that the new HESRM tends to increase torque performance over the conventional machine with minimal torque ripple and reduced consumption of rare earth elements. The proposed machine has advantages over conventional and magnet-assisted HESRM motors due to its superior control, in-dependability, redundancy, and suitability for electric vehicles.

Index Terms—Switched reluctance motor (SRM), hybrid excitation of switched reluctance motor (HESRM), permanent magnet (PM), electromagnetic torque, torque ripple minimization, electric vehicle (EV).

I. INTRODUCTION

THE usage of PMs for electric motors can create a crisis for various industrial and commercial applications, especially for electric vehicles (EVs), which are getting popular to decarbonize the transportation sector [1], [2]. The main requirement of EV motors is to provide high torque/power at high and wide speed ranges in the constant power region.

The inclusion of permanent magnets (PM) in electric machines contributes to enhancing traditional machine performances. The permanent magnet synchronous machine (PMSM), brushless DC machines (BLDC), induction machines (IM), and switched reluctance machines are the leading electric vehicle motors [3]. Apart from PM motors, SRM is a potential candidate for EV applications due to its rigid structure, low production cost, the absence of a permanent magnet or winding in the rotor, and excellent power-speed characteristics with high reliability and robustness. However, the SRM motors also suffer disadvantages such as low power and torque densities, high torque ripple, and acoustic noise compared to other PM machines [4].

An effective way to improve the torque and power densities is to use the PM inside the motor core to increase the flux density in the active region. Numerous kinds of research are currently going on to enhance the torque performance of SRMs, focusing mainly on the controller circuits, the stator and rotor segmentation, and hybrid excitation using permanent magnets. The switching of the stator of the SRM can be controlled to produce maximum torque using advanced controller circuits [5]. The power electronics converters can be configured according to the advanced winding typologies. Even the torque ripples the motor produces can be significantly regulated with this precise switching technique [6]. The segmentation technique cuts and arranges the stator and rotor poles along the flux paths to conduct the entire flux line. The multiple stator segments of the drive circuits also produce higher torque and power density and can be applied for both low-speed and high-speed applications [7]–[11]. This method increases the torque output but reduces the machine's structural integrity.

The hybrid excitation method introduced a new revolution in SRMs to enhance electromagnetic torque generation [10]. However, in this method, the machine structure is impregnated with PM to improve the performance of the motor. This excitation method employs permanent magnets, which are impregnated into the stator or rotor cores to increase the available flux in the air gap and thus improve the resultant flux [12], [13]. In this methodology, flux passes through the PM, adding the flux density for the active region, thereby increasing the average torque [14], [15]. Due to its manufacturing complexity, this PM-inserted system creates cogging torque and increases costs. The mutual flux coupling happens inside the core, which may reduce the motor's overall efficiency. Moreover, enhancing the average torque with ripple causes the system to become inactive [16], thereby reducing the torque ripple, which is necessary.

The primary goal of this paper is to improve the torque performance of SRM using hybrid excitation without the use of PMs, as well as to reduce torque ripple while maintaining torque performance. Leading companies' SRM innovations incorporate PMs into their designs to achieve the required performance. PMs are made of rare earth metals, which are becoming scarce and depleted. A requirement for cheap and efficient motors will arise in the coming era of electric vehicles. However, PMs' high demand and unavailability will spike the manufacturing cost of machines carrying them. In such a

scenario, the proposed method of hybrid excitation without PMs plays a vital role in the future of SRMs. This topology analysis result reduces the torque ripple and increases the torque capability. This torque ripple minimization technique's achieved by using the phase advancing method.

This paper is structured as follows: Section II describes the structure and fundamental operation of the proposed machine topology. In Section III, results and discussion include both the outcomes from the software, hardware and performance comparisons. In Section IV, experimental validation and results are discussed. Section V compares the proposed HESRM and the conventional SRM at the same power rating regarding torque ripple, efficiency, and input power. Section VI concludes the paper.

II. STRUCTURAL ANALYSIS

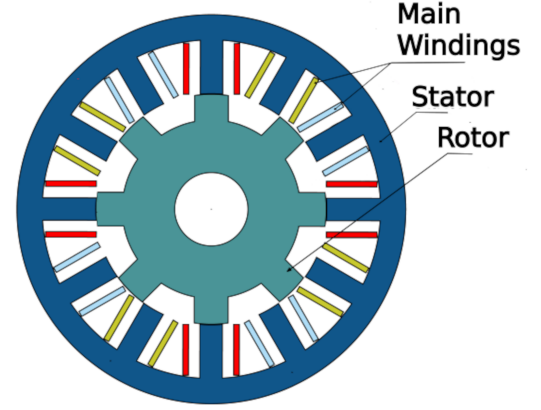
The structure of the proposed HESRM machine and the conventional SRM is shown in Fig. 1. The machine topologies of the ratings are 12/8 poles, 1.2 kW, 2 N-m, and 2500 rpm. In Table. I shows that both SRMs have the same stator and rotor pole configuration, which features four poles per phase without any PM in the machine core.

In the conventional SRM, the three-phase switching circuit, the motor consists of 12 stator poles and 6 rotor poles. Hence, each phase has 4 concentrically connected poles for contributing flux in the active region. For newly designed HESRM with non-PM, the windings are assigned for the different excitations, namely the main winding and the auxiliary windings. Therefore, half of the total active poles are electrically and mechanically equally separated and allocated as the switching provided to the main winding [17], [18]. The rest of the poles were given to the auxiliary poles, which use separate injecting of the DC with the help of an independent controller. For this purpose, both windings have a carrying capacity of different currents for each switching phase. As a result, of the symmetric nature of the pole alignment of the proposed HESRM, the flux path is similar to that of conventional; the only difference is the intensity of the flux carried in the active region. Subsequently, using two separate windings for each phase influences more electromagnetic torque than the conventional motor.

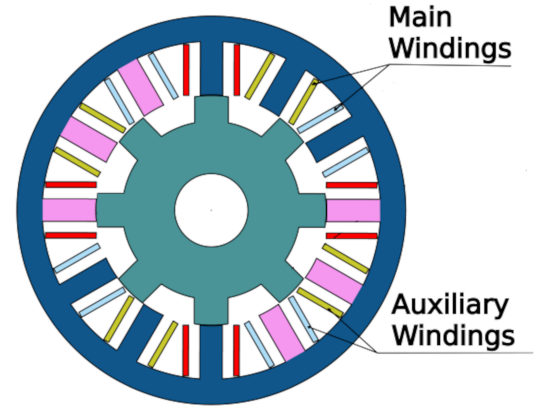
TABLE I: Specification of the two SRMs

Dimensions	Conventional SRM	HESRM
Number of phases	3	3
Number of stator poles	12	6-6 (12)
Number of rotor poles	8	8
Diameter (mm)	300	300
Rated Power	1.2kW	1.2kW
Stack length (mm)	70	70
Core	M15_26G	M15_26G

The optimum turn-on angle is selected to manage the excitation angle such that the phase current at the turn-off time of the preceding phase should meet the maximum current of the incoming phase (θ_k). The ripple minimization excitation scheme will be switched as A-AB-B-BC-C-CA in



(a) Conventional SRM



(b) Proposed HESRM

Fig. 1: The structural diagram of 12/8, three-phase conventional SRM and proposed HESRM.

the proposed HESRM. The graphical representation of the torque ripple minimization for the phases is shown in Fig. 2.

$$T_x(\theta, i_x) = T_{MC_x}(\theta, i_M) + T_{AC_x}(\theta, i_A) \quad (1)$$

T_x is the electromagnetic torque provided by one phase that can be obtained from the total energy of that phase. $T_{MC_x}(\theta, i_M)$ is the torque to the main winding excitation, and the $T_{AC_x}(\theta, i_A)$ is the torque due to the auxiliary.

III. RESULT AND DISCUSSION

1) *Magnetic flux linkage*: The rotor position dependence of the flux linkage properties of the conventional and the proposed 12/8 SRMs is shown in Fig. 3. In general, the area enclosed between the aligned and the unaligned curves gives the co-energy for fixed MMF, which is the torque

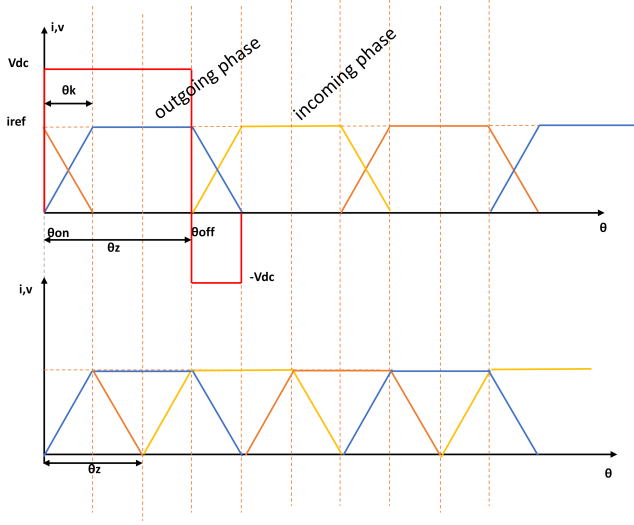


Fig. 2: The graphical representation of torque ripple minimization.

corresponding to a single energy stroke. In Fig. 3, the proposed HESRM achieves more prominent flux linkage in all the rotor positions concerning the aligned and unaligned positions. With the same position, the conventional SRM generates a feasible flux compared to the proposed one. The new method portrays the same characteristics as the conventional SRM but with an extended amplitude with a maximum of 0.27 Weber. In other words, the proposed HESRM generates more torque at the same rotor position due to the doubly excited current injection in the auxiliary windings.

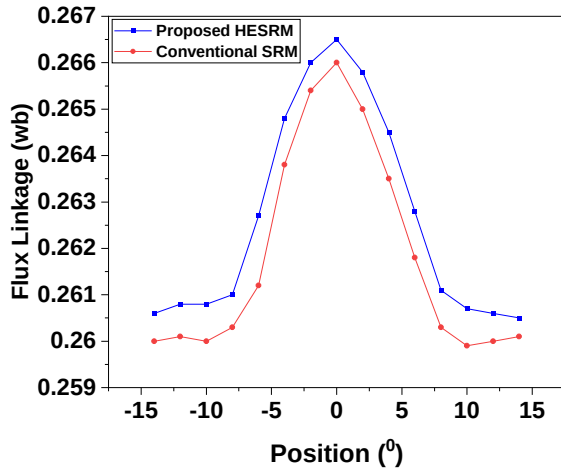
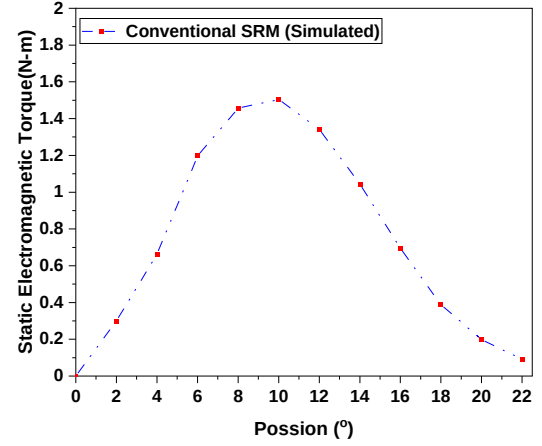


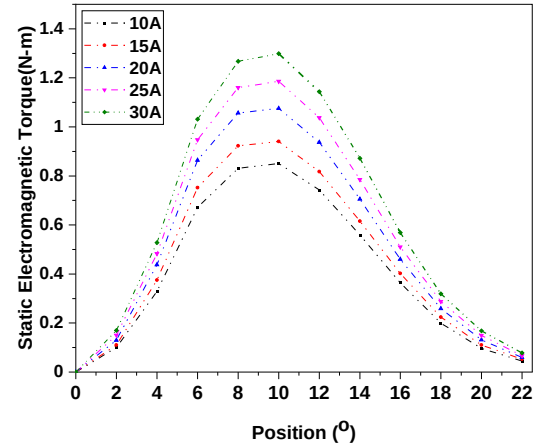
Fig. 3: The magnetic flux linkage characteristics of both SRMs.

2) *Static electromagnetic torque*: Torque analyzed during individual rotor position is measured using software analysis. The static electromagnetic characteristics of two SRMs with phase excitation are shown in Fig. 4a. In the conventional SRM, a current of 15 A is used to excite each phase from aligned to unaligned. The static electromagnetic torque

is shown to vary concerning the angle to reach its most outstanding torque of 1.5 N-m at the aligned position. The static electromagnetic torque in Fig. 4b changes according to the various excitations produced by the auxiliary winding in the new topology. The suggested machine exhibits various electromagnetic patterns depending on the current injection rate, which ranges from a minimum current of zero to a maximum current of 30 A. As the direct auxiliary gradually changes, the static flux pattern increases.



(a) Conventional SRM



(b) Proposed HESRM

Fig. 4: The static electromagnetic torque characteristics of both SRMs with phase excitations.

3) *Torque ripple characteristics*: From the average torque characteristics, it is clear that the motor lacks of smooth torque profile. The maximum and minimum torque produced by the conventional SRM and the proposed HESRM varies, and the difference in these values creates torque ripple. High torque ripple diminishes the advantages of the newly designed motors; hence, reducing ripple is mandatory for the specified applications.

The torque ripple can be calculated as,

$$T_{ripple} = (T_{max} - T_{min})/T_{avg} \times 100\% \quad (2)$$

where T_{ripple} is the torque ripple, and T_{max} , T_{min} , T_{avg} are the maximum, minimum and average torque, respectively.

The comparison of the output torque ripple characteristics with and without enabling phase advancing is shown in Fig. 5. The bottom graph shows the results of phase advancement, and the top graph shows the content of ripples in the torque waveforms of conventional and hybrid SRM. The SRM is a three-phased excited motor employed in this experiment, and the A, B, and C phases are all stimulated at the respective interval of time—the resulting current and voltage adjustment cause a ripple in the output torque. The ripples can be decreased by shortening the time between switching. However, if the switching is too close together, the current will exceed itself by superimposing on itself. Phase advancing is a method in which the preceding phase is activated quickly to minimize the ripple. A control mechanism that prevents the current from overshooting alters the limit of this shift from the outside.

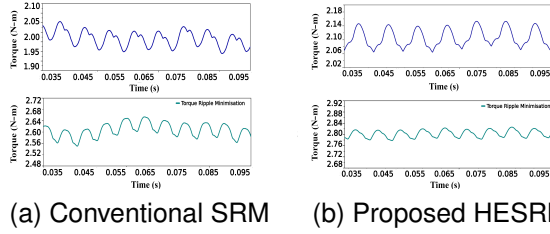


Fig. 5: Experimental results of an implementation of torque ripple minimization in 12/8 conventional SRM and the proposed HESRM without PM (a) Conventional SRM and (b) Proposed HESRM.

A. Comparison of Performance using Hardware and Software Solutions

IV. EXPERIMENTAL VALIDATION

A 12/8 SRM prototype is designed, made, and tested to check the proposed HESRM's concept proof. A permanent magnet synchronous motor (PMSM) is electrically connected back-to-back on the load side. A torque sensor is connected to the motor's center to acquire instantaneous data. A WAVECT Controller with FPGA architecture is used for real-time control prototyping. Using inverters and the PWMs generated by this controller, the SRM is switched. As shown in Fig. 6, the SRM was loaded with the back-emf generated by the PMSM using rheostats. The experimental setup for executing the controller is shown in Fig. 7. The suggested HESRM topology is followed while rewinding the stator terminals. Secondary excitation executes and implements dual excitation without a permanent magnet. Because of this excitation, the secondary controller can carry different currents to produce more torque. Consequently, the experimental setup consists of two inverter stacks and an FPGA-based wavect controller.

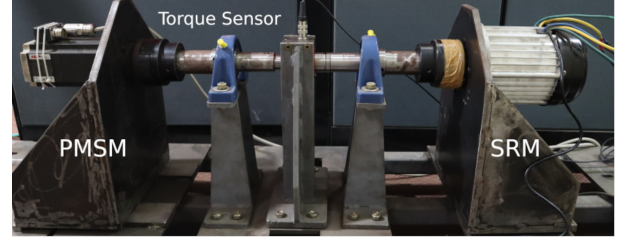


Fig. 6: Back-to-back set up for experimentation.

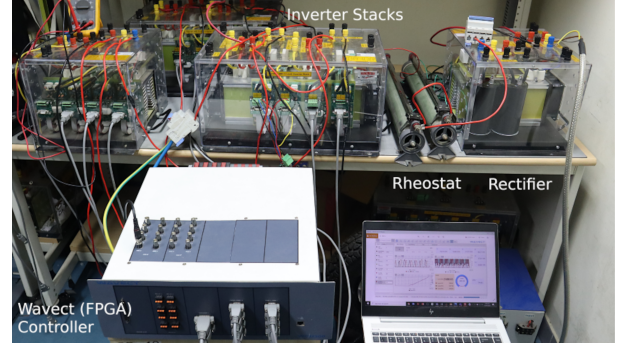


Fig. 7: Experimental platform for the proposed HESRM.

A. Experimental Validation of Torque Ripple

The simulation results of the proposed system and the torque measurements were taken with the help of hardware implementation. The experimental results of the Wavect controller, which displays the torque measurement, are shown in Fig. 8. This window creates the result after enabling excitation switching; it includes torque sensor output concerning the time, the angle of rotor position theta, speed, input power, output power, and efficiency. Furthermore, the results are in rms and cover the average, maximum, and minimum values. The results were executed with a rated current of 1500 rpm and a maximum and minimum torque of 2.59 N-m and 2.50 N-m, respectively. And with an average torque of 2.54 N-m, the resultant torque ripple is 3.54%.

V. COMPARISON OF PROPOSED HESRM WITH CONVENTIONAL SRM

A. Torque Ripple

The torque ripple of the proposed HESRM is compared with conventional SRM, and ideally, it should be lower than the conventional SRM. The suggested HESRM method's performance analyses are compared with traditional SRM. Fig. 9 compares the torque ripple responses over the variable speed range and displays the average torque produced by the newly developed machines. The conventional SRM torque ripple increases from 500 to 2500 rpm. In addition, the recommended HESRM achieves a lower torque ripple than the conventional SRM in each speed range. Consequently, torque ripple reduction using phase advance reduces the amount of ripple by 58% compared to conventional SRM and by 33%

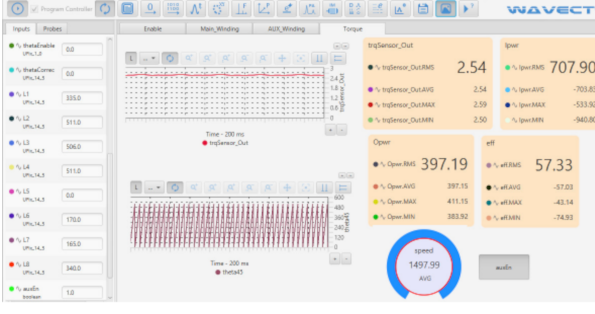


Fig. 8: Experimental results of wavec controller outcomes with torque measurement.

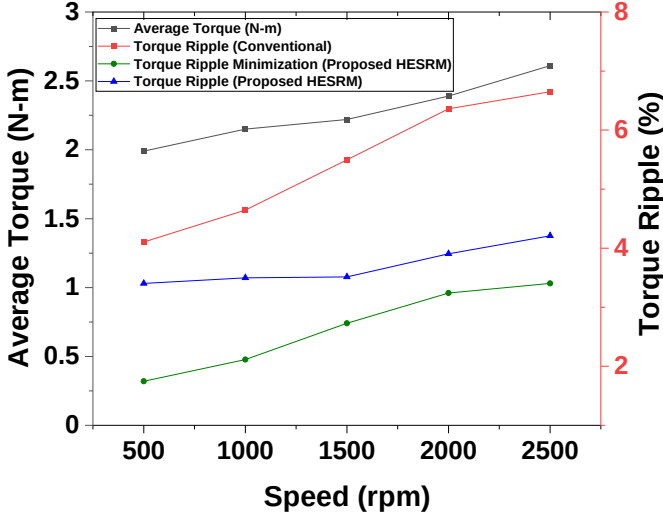


Fig. 9: Torque ripple comparison of the conventional and proposed SRMs.

TABLE II: Comparison of torque ripple minimization.

Sl.No	Speed (rpm)	Torque-Ripple (%)	Torque-Ripple Minimization (%)	Percentage of Decrease (%)
1	500	6.35	3.35	47.20%
2	1000	4.65	1.96	57.84%
3	1500	4.18	1.53	63.51%
4	2000	3.55	1.26	64.67%
5	2500	1.79	1.00	44.06%

VI. CONCLUSION

A novel 12/8 hybrid excitation SRM was proposed for EV applications in this paper. The structure and operating principle were shown graphically. The experimental analysis is compared to the conventional SRM for the identical application to verify the validity. The comparison result demonstrates that the proposed HESRM generates greater average torque than the conventional SRM. In addition, because of its switching characteristics, it tends to generate torque ripple. However, the performance of the phase advance method implemented in the proposed method is superior to previous results. In II comparing the results, prove that the proposed minimization technique reduces the torque ripple 40-50% of the proposed topology. In addition, it reduced torque ripple to produce a smooth high-value torque. Due to the dual winding controller, this proposed method has the advantages of feasible control,

improved redundancy, and high efficiency. Consequently, this HESRM methodology is ideally suited for electric vehicle applications. The future aim of this research is to optimize the machine parameters to improve its performance.

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