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Torque ripple minimization and performance enhancement of switched reluctance motor for electric vehicle application

Yogesh B. Mandake[1], Deepak S. Bankar[1], Amit L. Nehete[2]
[1]Department of Electrical Engineering, Bharati Vidyapaeeth (Deemed to be) University, College of Engineering, Pune, India
[2]Department of Electrical and Electronics Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, India

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ABSTRACT

Switched reluctance motors (SRMs) are an attractive choice for electric vehicle (EV) applications but suffer from certain limitations, such as high torque ripple and acoustic noise. This paper presents ongoing research and development activity details to enhance the performance of SRMs for EV applications. The poor performance of a conventional SRM which is available in market with a rating of 8/6 poles, 48 V, 500 W, and 2,000 rpm is tested. A motor model of the same rating is developed using ANSYS Maxwell software. Motor performance parameters important for EV applications, such as efficiency, rated torque and torque ripple are compared with the conventional motor. One novel technique to reduce the torque ripple of SRM is discussed along with the results. Torque ripple of developed software model is reduced by 24.52% without a reduction in the efficiency and rated torque of the motor. The performance of the developed SRM software model is better compared to conventional SRMs available in the market. 2D and 3D models of SRM were presented using ANSYS Maxwell software.

Corresponding Author:

Yogesh B. Mandake
Department of Electrical Engineering, Bharati Vidyapeeth (Deemed to be) University
College of Engineering
Pune, 411043, Maharashtra, India
Email: yogesh.mandake@bvucoep.edu.in

1. INTRODUCTION

Motor is a major part of the electric vehicle (EV) drive system. Nowadays, we are using different motors for EV applications, such as brushless direct current (BLDC) motors, permanent magnet synchronous motor (PMSM) motors, universal motors, switched reluctance motors (SRMs). The increase in demand for motors in the future necessitates the development of motors with good performance and minimal or no use of rare earth magnets. SRMs have good fault tolerance capability [1]. SRM offer good performance characteristic for EV applications and do not require rare earth magnets [2]. However, SRMs have some limitations, such as higher torque ripple which results in increased vibration and acoustic noise in EV applications [3], [4]. Efficiency, rated torque, speed and torque ripple are major technical parameters considered for EV applications. SRMs currently available in the market have poor performance, highlighting the need of reenhancement in SRM performance. More research work is needed to successfully use SRMs for EV applications [5]. Performance of SRM for EV application can be improved by increasing efficiency, torque, and reducing torque ripple.

Various techniques have been explored in the literature [6]-[18] to reduce torque ripple problem in SRM. Researchers have discussed different methods to reduce torque ripple in SRMs and have highlighted the advantages and limitations of each method. Torque ripple can be reduced by proper selection of stator and rotor pole arcs. The researchers [6], [7] an electronic control approach is proposed in [8], [9]. The selection of instantaneous torque control (ITC) technique is explored in [8], [10], while excitation angle optimization used in [11]. A technique involving an increased number of phases is discussed in [12], and the use of notched rotor hole in each rotor pole is proposed in [11], [13]. The average torque control (ATC) strategy is discussed in [11], [14], and a torque sharing function (TSF)-based control technique is used in [11], [15]. Intelligent control techniques are discussed in [16], and different converter topologies for reducing SRM torque ripple are discussed in [17]. Torque ripple with different converter configurations for SRM have been evaluated in [18]. As per literature review, conventional torque ripple reduction techniques aim to improve the performance of the SRMs by enhancing the design of the drive circuit, motor, converter circuit, controller circuit, and other components. Conventional torque ripple reduction techniques do not discuss the study and selection of stator and rotor materials for reducing torque ripple in SRMs. There is a need for more research to reduce torque ripple in SRM through a detailed study and proper selection of stator and rotor materials.

This paper proposes a torque ripple reduction technique for conventional SRM by suggesting constructional and material changes in the motor. The recommended hybrid approach modifies in rotor pole embrace along with the appropriate selection of materials for stator and rotor. Figure 1 presents the methodology of the research work.

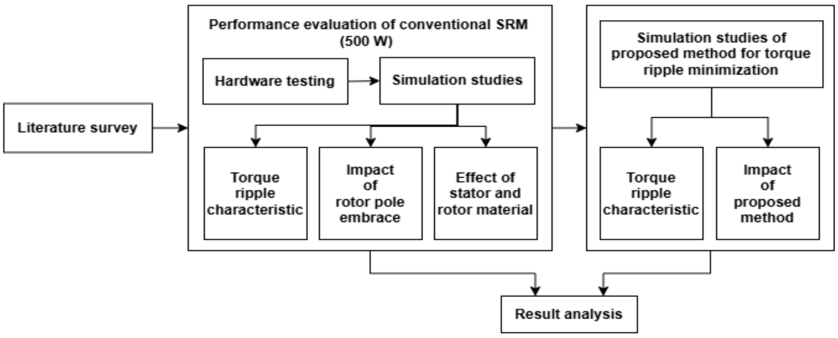
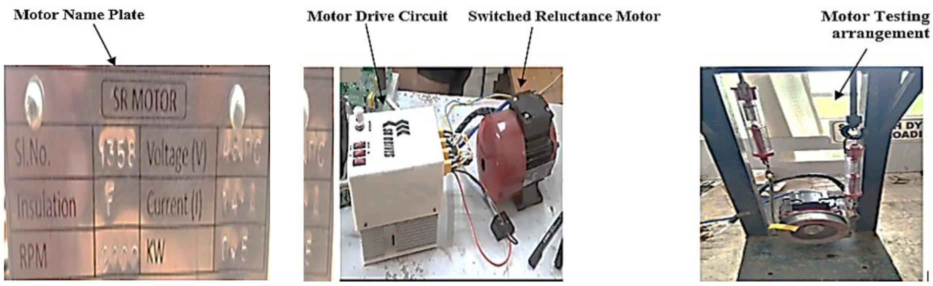


Figure 1. Methodology of the research work

This paper is organized into six sections. Section 1 introduces the topic of the research paper; section 2 evaluates the performance of the hardware of conventional SRM available in the market; section 3 presents the simulation studies of the SRM model developed using ANSYS Maxwell software; section 4 explains the proposed method to reduce the torque ripple of the simulated SRM; section 5 presents the result and discussions and summarizes the simulation results. Finally, section 6 provides the conclusion and outlines the future scope of this research work.

2. PERFORMANCE TESTING OF A CONVENTIONAL SRM HARDWARE

Figure 2 shows the conventional hardware model of SRM with the drive circuit and testing arrangement. The specifications of the tested SRM are 4-phase, 500 W, 48 V, 14 A, 2,000 rpm. Figure 2(a) shows the motor name plate, Figure 2(b) shows the motor drive circuit, and Figure 2(c) shows the SRM motor testing arrangement.



(a) (b) (c)

Figure 2. Hardware model and performance testing of 500 W SRM; (a) motor specifications, (b) motor with drive circuit, and (c) motor testing

Figure 3 shows the speed v/s torque characteristics of the SRM available in the market. The graph shows that an output torque of 2.05 N-m is obtained at the rated speed of 2,000 rpm. Table 1 presents the performance of the SRM. It is observed that the performance of SRM available in market is poor and no information on torque ripple is available. We have to develop a motor with increased efficiency, increased torque, and reduced torque ripple for EV applications.

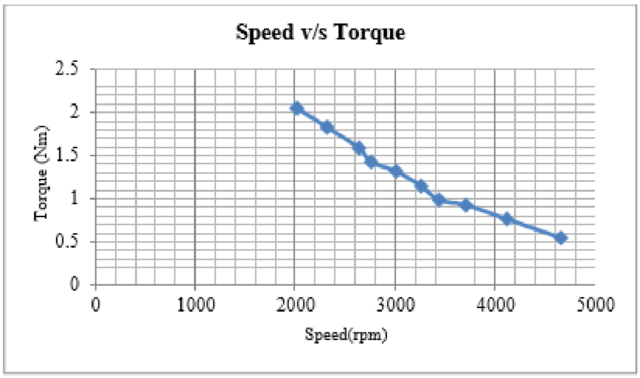


Figure3. Speed v/s torque characteristic of SRM

Table 1. The performance of SRM available in the market

Performance parameter	Rated torque (N-m)	Efficiency (%)	Speed (rpm)
Conventional motor performance	2.05	60	2,010

3. SIMULATION STUDIES OF CONVENTIONAL SRM USING ANSYS MAXWELL

The simulation model of 4-phase 8/6, 48 V, 500 W, 14 A, 2,000 rpm SRM have been developed using ANSYS Maxwell software (RMXprt tool). The stator has 8 poles and the rotor has 6 poles. Multiple simulations were carried out by using the same drive circuit (control type: DC and circuit type: full voltage). An asymmetric bridge converter was used in the developed model. Motor performance was tested with a constant power load, considering EV applications, and was checked at a temperature of 75 °C (environmental boundary condition). Magnetic vector potential boundary conditions are considered. A transient simulation was carried out with a stop time of 0.012 seconds and a time step of 6e-05 seconds. A total diode voltage drop of 0.5 V have been assumed. Steel 1008 (bulk conductivity: 2,000,000 S/m, thermal conductivity: 45 W/m·K, mass density: 7,875 kg/m³, specific heat: 481 J/kg·K) and steel 1010 (bulk conductivity: 2,000,000 S/m, thermal conductivity: 45 W/m·K, mass density: 7,872 kg/m³, specific heat: 448 J/kg·K) were selected for the simulation work.

Motor performance was improved by changing motor constructional parameters. Multiple simulations were carried out by changing the geometrical parameters of following parts of motor:

a) Stator: i) outer diameter, ii) inner diameter, iii) length, iv) stacking factor, v) steel material type, vi) number of poles, and vii) embrace.
b) Rotor: i) outer diameter, ii) inner diameter, iii) length, iv) steel material type, v) stacking factor, vi) number of poles, vii) embrace, and viii) yoke thickness.
c) Winding: i) insulation thickness, ii) end adjustment, iii) parallel branches, iv) turns per pole, v) number of strands, vi) wire wrap, and vii) wire size.

In the analysis of the simulated SRM model, three key aspects have been examined: initially, torque ripple characteristics are assessed; subsequently, the impact of rotor pole embrace on performance is evaluated; and finally, the influence of different materials used in the stator and rotor on the motor's overall performance is investigated.

3.1. Torque ripple characteristic

After multiple simulations, the final model, referred to as the simulated model, has an efficiency of 77.27% and a rated torque of 2.355 N-m at a rated speed of 2,017 rpm. Figure 4 shows the variation of moving torque with time. The efficiency of SRM is the ratio of its output power to its input power. Torque ripple is calculated in (1) using standard formula [19].

$$Torque\ ripple\ (\Delta T)\ = \frac{T_{max} - T_{min}}{T_{ave}} \times 100 = \frac{3.4558 - 1.8338}{2.2361} \times 100 = 72.537\% \quad (1)$$

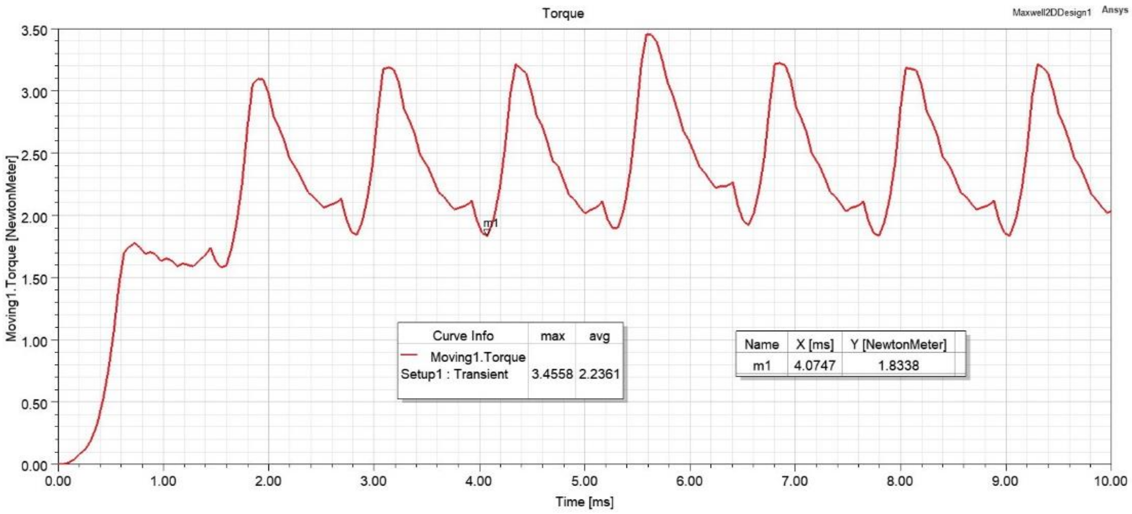


Figure 4. Torque ripple in simulated conventional SRM model

Table 2 represents the comparison of conventional motor performance with the developed model. The developed model demonstrates better performance i.e., higher efficiency and improved torque at nearly the same rated speed. The conventional motor lacks torque ripple data, while the simulated SRM model has a torque ripple of 72.537%. High torque ripple is a major drawback of SRM causing increased acoustic noise and vibrations in EV applications. Torque ripple is reduced using the proposed novel method discussed in sections 4 and 5 of this paper.

Table 2. Comparison of conventional motor performance with developed SRM

Performance parameter	Speed (rpm)	Efficiency (%)	Torque (N-m)	Torque ripple (%)
Conventional motor performance	2,010	60	2.05	Not available
Simulated motor performance	2,017	77.27	2.355	72.537

3.2. Evaluation of the impact of rotor pole embrace

Pole embrace is the ratio of actual pole arc to pole pitch [20]. A change in rotor pole geometry changes inductance, which affects current, input power and therefore efficiency [21]. When the rotor embrace is increased, smoother interaction and increased overlap between stator and rotor poles, along with reduced cogging torque, decrease torque ripple in SRMs. However, an increase in rotor pole embraces results in higher iron losses, increased core losses and higher inductance, which reduce the motor efficiency. On the other hand, increased rotor embrace also raises the rated torque of the motor due to better magnetic coupling between the stator and rotor [22]-[24]. The performance of the simulated SRM model, a 4-phase, 48 V, 500 W, 8/6 Pole motor operating at 2,000 rpm is checked with different rotor pole embraces. Table 3 shows the performance of the simulated SRM model at different values of rotor pole embrace. From this table, it is observed that with an increase in rotor embrace, torque ripple decreases; however, it also decreases efficiency and increases the rated torque of the motor. This method individually fails to decrease torque ripple without affecting the efficiency and rated torque of the motor.

Table 3. Effect of increasing rotor pole embrace on performance of simulated SRM

Rotor pole embrace	Efficiency	Rated torque	Torque ripple
0.4	77.27%	2.355 N-m	72.537%
0.445	76.08%	2.766 N-m	56.2835%
0.5	73.19%	3.367 N-m	41.34%
0.6	58.4592%	4.936 N-m	30.17%

3.3. Investigation of the materials used for stator and rotor

Performance of the simulated SRM model (4-phase, 48 V, 500 W, 8/6 Pole, 2,000 rpm) is checked with different materials for the stator and rotor. Steel 1008 and steel 1010 are used for the stator and rotor of the SRM. Steel 1008 has low carbon content compared to steel 1010, resulting in low hysteresis losses, high permeability, and better magnetic performance. Steel 1008 has moderate magnetic permeability, good magnetic properties, and low electrical conductivity, which helps in reducing eddy currents and core losses. Steel 1010 has slightly higher carbon content than steel 1008, providing high mechanical strength and the ability to handle high magnetic flux densities.

Steel 1010 also has higher magnetic permeability, which offers slightly better performance, and its low electrical conductivity helps reduce eddy current losses. Using steel 1008 for the stator and steel 1010 for the rotor in an SRM leads to a reduction in torque ripple due to smoother flux distribution and good magnetic interaction. This combination also slightly increases efficiency due to reduced core losses in the stator and efficient magnetic coupling with the rotor. Additionally, using steel 1008 for the stator and steel 1010 for the rotor increases the rated torque of motor because better flux management in this combination enhances the ability to handle higher flux densities and mechanical stress [10], [25]-[27]. The performance of the simulated SRM model, a 4-phase, 48 V, 500 W, 8/6 Pole motor operating at 2,000 rpm is checked with different stator and rotor material combinations (steel 1008 and steel 1010).

Table 4 presents the performance of the simulated SRM using various combinations of stator and rotor materials. It is evident from Table 4 that employing steel 1008 for the stator and steel 1010 for the rotor leads to a reduction in torque ripple, although this reduction is less significant compared to the approach of increasing rotor pole embrace. Additionally, this material combination results in a modest improvement in both efficiency and rated torque. However, this method does not effectively reduce torque ripple without impacting the motor's efficiency and rated torque. Further, Table 5 represents a comparative analysis of torque ripple reduction techniques using rotor pole embrace and stator and rotor materials.

Table 4. Effect of changing stator and rotor material on performance of simulated SRM model

Sr. No.	Stator material	Rotor material	Efficiency (%)	Rated torque (N-m)	Torque ripple (%)
1	Steel_1010	Steel_1010	77.27	2.335	71.81
2	Steel_1008	Steel_1008	78.59	2.335	69.62
3	Steel_1010	Steel_1008	77.47	2.353	69.27
4	Steel_1008	Steel_1010	78.3929	2.337	69.58

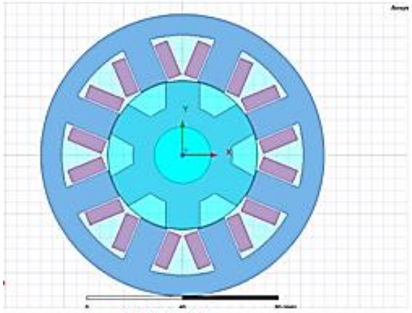
Table 5. Comparison of torque ripple reduction techniques

Technique	Advantages	Disadvantages	Effectiveness	Implementation complexity	Cost implications
Increase in rotor pole embrace	Significant reduction in torque ripple; increases torque	May reduce efficiency; increases core losses	High	High	Moderate
Stator and rotor material selection	Reduces torque ripple and core losses; slight efficiency gain	Material availability and processing can be challenging	Moderate to high	Moderate	Moderate to high

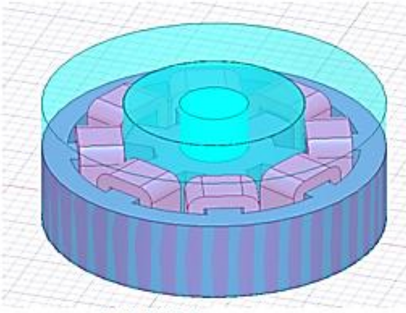
4. PROPOSED METHOD

The method of increasing rotor pole embraces alone failed to reduce torque ripple without a decrease in efficiency and rated torque. Similarly, the method of different stator and rotor material alone was not sufficient to reduce torque ripple without reducing efficiency and rated torque. Based on this analysis, in this paper, we have proposed a novel hybrid approach that suggests an increase in rotor pole embrace along with different material used for stator and rotor. The method proposed in this paper recommends enhancing rotor pole embrace and utilizing steel 1008 for the stator alongside steel 1010 for the rotor in a conventional.

This method focuses on the potential of selecting appropriate materials for the stator and rotor to reduce torque ripple in SRM, a topic that was not addressed in conventional torque ripple reduction techniques. The main advantage of this method is that it can significantly reduce torque ripple in SRM (by nearly 24.52%) without compromising the efficiency or rated torque of the motor. Figure 5 shows the 2D and 3D model of proposed SRM software model. Figure 5(a) shows 2D model and Figure 5(b) shows 3D model of the proposed SRM software model.



(a)



(b)

Figure 5. Simulation of proposed SRM model with improved performance (a) 2D model and (b) 3D model

5. RESULTS AND DISCUSSION

The proposed novel method for reducing torque ripple combines the effect of increase in the rotor pole embrace and use of steel 1008 for the stator and steel 1010 for the rotor to overcome the limitations of each individual case as investigated in subsections 3.2 and 3.3. Figure 6 shows the variation of moving torque with time. Here in (2), torque ripple after the implementation of proposed method is calculated using standard formula.

$$Torque\ ripple\ (\Delta T) = \frac{T_{max} - T_{min}}{T_{ave}} \times 100 = \frac{3.8472 - 2.3919}{2.6580} \times 100 = 54.75\% \quad (2)$$

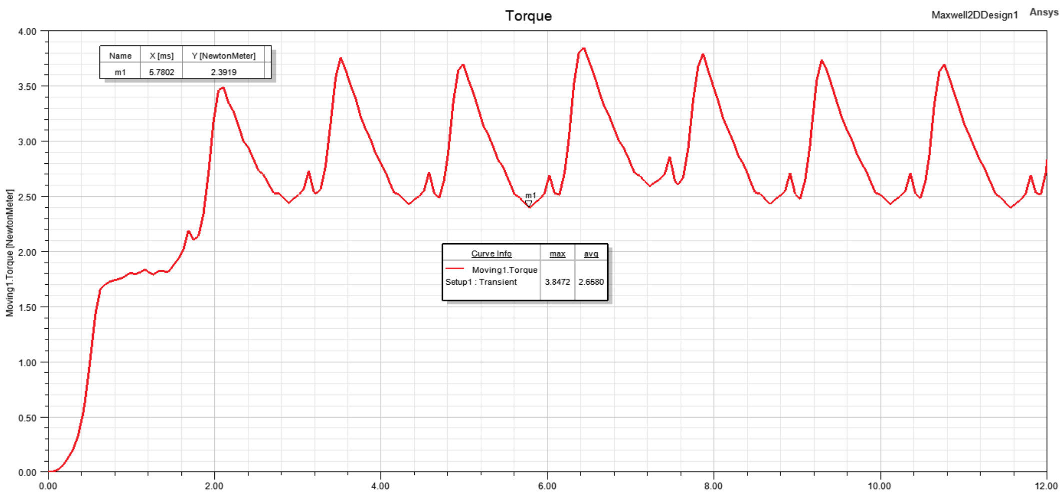


Figure 6. Torque ripple in simulated SRM after implementation of novel torque ripple reduction technique

Table 6 shows the performance of simulated SRM model after implementing proposed method of reducing torque ripple. Torque ripple of simulated SRM model get reduced with nearly same efficiency and torque of motor. Torque ripple of simulated motor get reduced from 72.537% to 54.75%.

Table 6. Performance of simulated SRM model after implanting proposed torque ripple reduction technique

Condition	Stator material	Rotor material	Rotor pole embrace	Efficiency (%)	Rated torque (N-m)	Torque ripple (%)
Simulated SRM performance after implementing novel hybrid technique (Increase in rotor pole embrace and change in stator and rotor material)	Steel_1008	Steel _1010	0.445	77.37	2.7487	54.75

The performance of the simulated SRM under various configurations is summarized in Table 7, highlighting the impact of rotor pole embrace adjustments and material choices for the stator and rotor. Initially, the SRM in its unmodified state (using steel 1010 for both the stator and rotor with a rotor pole embrace of 0.4) exhibited an efficiency of 77.28%, a rated torque of 2.36 N-m, and a torque ripple of 72.54%. The first modification involved solely increasing the rotor pole embrace to 0.445 while keeping the stator and rotor materials as steel 1010. This adjustment led to an efficiency of 76.08% and a rated torque of 2.77 N-m. Notably, torque ripple was significantly reduced to 56.28%, demonstrating that increasing rotor pole embrace can effectively reduce torque ripple, albeit with a minor decrease in efficiency.

Table 7. Performance of simulated SRM model at different conditions

Condition	Stator material	Rotor material	Rotor pole embrace	Efficiency (%)	Rated torque (N-m)	Torque ripple (%)
Before modification	Steel_1010	Steel_1010	0.4	77.2781	2.35519	72.537
With only increase in rotor pole embrace	Steel_1010	Steel_1010	0.445	76.08	2.766	56.2835
With only change in stator and rotor material	Steel_1008	Steel_1010	0.4	78.3929	2.337	69.58
After implementing a novel hybrid technique (Increase in rotor pole embrace and change in stator and rotor material)	Steel_1008	Steel_1010	0.445	77.37	2.7487	54.75

In the second configuration, only the stator material was changed to steel 1008 while maintaining steel 1010 for the rotor and a pole embrace of 0.4. This modification resulted in a slight improvement in efficiency to 78.39% but only modestly affected rated torque, which stood at 2.34 N-m. The torque ripple, however, decreased to 69.58%, suggesting that material selection alone provides a moderate impact on torque ripple.

The novel hybrid technique, simultaneously combining both the increased rotor pole embrace (0.445) and the material change for the stator (steel 1008) and rotor (steel 1010), achieved a balanced enhancement across all metrics. The resulting configuration yielded an efficiency of 77.37%, a rated torque of 2.75 N-m, and a torque ripple of 54.75%. This outcome highlights that the proposed approach can effectively reduce torque ripple while maintaining efficiency and rated torque, indicating its potential for improved SRM performance, especially in applications demanding smoother operation.

Summarizing the discussion, the appropriate selection of material for stator as well as rotor and rotor pole embrace plays a crucial role in reducing torque ripple and enhancing the performance of the SRM drive system for EVs. The efficiency and torque of the proposed simulated motor are superior to those of conventional SRMs available in the market. Torque ripple in the conventional SRM has been reduced by 24.52% with nearly the same efficiency and rated torque.

6. CONCLUSION

This paper presents ongoing research and development efforts to enhance the performance of SRMs for EV applications. The study highlights the significant potential of stator and rotor materials for reducing torque ripple in SRM. The testing of an 8/6 Pole, 48 V, 500 W, 2,000 rpm conventional SRM hardware is conducted to address the poor performance of SRM available in market. Also, simulation studies of the same SRM have been performed using ANSYS MAXWELL to separately assess the individual impact of increase in rotor embrace and different material of stator and rotor. SRM drive system performance can be improved through constructional changes and proper selection of stator and rotor materials. This work proposes a novel technique to reduce torque ripple of SRMs. The results of the study show that torque ripple is reduced by 24.52% without a reduction in the efficiency and rated torque of the motor 2D and 3D models of the SRM were developed using ANSYS Maxwell software. The performance of the simulated SRM model is better compared to the conventional SRM available in market. (e.g., rated torque=2.74 N-m, efficiency=77.37% at rated speed of 2,000 rpm, torque ripple=54.75%). Thereby, it can be concluded that the torque ripple of a conventional SRM can be reduced by increasing the rotor pole embrace and using proper selection of material i.e., steel 1008 for the stator and steel 1010 for rotor. A hardware model of the simulated SRM model will be prepared in the further stages of the research. The proposed system can be studied with different SRM controllers (e.g., ITC and ATC) and various materials using professional software, such as ANSYS Maxwell. Integrated ITC, ATC, and CCC (chopped current control) with the proposed design can lead to a more efficient, reliable, and smooth-operating SRM, particularly beneficial for EV applications.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Yogesh B. Mandake	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Deepak S. Bankar	✓	✓			✓	✓	✓		✓	✓	✓	✓	✓	✓
Amit L. Nehete	✓		✓	✓			✓	✓		✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author Mr. Yogesh B. Mandake on request.

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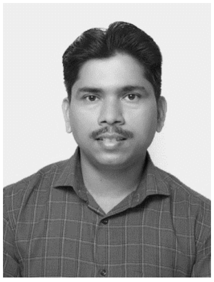
BIOGRAPHIES OF AUTHORS



Yogesh B. Mandake received master degree of M.Tech. in power systems in 2014 and presently pursuing Ph.D. in electrical engineering from Bharati Vidyapeeth (Deemed to be University), College of Engineering, Pune, India. He has teaching experience of 7 years and Industrial experience of 2.5 years in automobile industry. His research interest includes electrical power system, electric vehicles, and electrical machines. He can be contacted at email: yogesh.mandake@bvucoep.edu.in.

Dr. Deepak S. Bankar received B.E. degree in electrical engineering from Pune University, Pune, India, M.E. degree in electrical power systems from Government College of Engineering, Pune, India, and Ph.D. degree in electrical engineering from Bharati Vidyapeeth (Deemed to be) University (BVDUCoE), Pune, India. Having academic experience of over two decades, currently, he is a professor and head of the Department of Electrical and Computer Engineering at BVDUCoE Pune. He has guided more than 20 students for M.Tech. and 03 research candidates have completed Ph.D. His research areas are renewable energy systems, and power quality. He has authored more than 42 research publications and 22 books. He can be contacted at email: dsbankar@bvucoep.edu.in.

Amit L. Nehete received the B.E. degree in electrical engineering from North Maharashtra University, Jalgaon, India, M.Tech. degree in electrical power systems from Bharti Vidyapeeth (Deemed to be University), College of Engineering, Pune, India, and pursuing Ph.D. degree in engineering from Bharti Vidyapeeth (Deemed to be University), Pune, India. With the academic experience of over 13 years, presently, he is working at the Department of the Electrical and Electronics Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, India an assistant professor. He is a research student member of IEEE and the life member of Indian Society for Technical Education (ISTE). He has authored several research publications and textbooks in his areas of interest: power system protection, electric vehicles, and energy audit. He can be contacted at email: amit.nehete@mitwpu.edu.in.