International Journal of Ambient Energy

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/taen20

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To cite this article: Mahesh A. Patel , Kamran Asad , Zeel Patel , Mohit Tiwari , Purv Prajapati , Hitesh Panchal , M. Suresh , Ralli Sangno & Mohammd Israr (2021): Design and optimisation of slotted stator tooth switched reluctance motor for torque enhancement for electric vehicle applications, International Journal of Ambient Energy, DOI: 10.1080/01430750.2021.1873857

To link to this article: https://doi.org/10.1080/01430750.2021.1873857

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INTERNATIONAL JOURNAL OF AMBIENT ENERGY
https://doi.org/10.1080/01430750.2021.1873857

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Design and optimisation of slotted stator tooth switched reluctance motor for torque enhancement for electric vehicle applications

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ABSTRACT

The switch reluctance motor (SRM) drive receives growing attention from different researchers and from the vehicle industry. The SRMs are widely used in the electric vehicle applications due to its tailor-made characteristics. This paper introduces a novel topology of the slotted stator tooth switched reluctance motor (SST-SRM). In the proposed topology, the stator of the conventional SRM is modified with slotted stator tooth, aiming for better performance of the machine. The stator tooth is slotted with different depths from the inner periphery and the parameters of the SRM are optimised for acquiring the maximum torque output. Finite element analysis (FEA) has been carried out for the modified topology. The parameters are calculated analytically and results are compared with FEA results.

ARTICLE HISTORY
Received 23 October 2020
Accepted 5 January 2021

KEYWORDS
Electric vehicles (EV); finite element analysis (FEA); finite element tool (FET); performance analysis; slotted stator tooth (SST); switched reluctance motor (SRM)

1. Introduction

The current scenario of the automobile industries is growing and improving with a rapid rate worldwide. Motors are the major part of many of the heavy machines in industries and automobiles to counter many of the operations for the accomplishment of task. Nowadays, profound motors are being used in electric vehicles for the energy conversion in achieving the successful transmission and rotation of wheels. A wide range of choices are available, among the various advanced electrical machines, for acquiring better performances and facilities with good reliability. Among all the latest advanced electrical machines, the switched reluctance motor, shown in Figure 1, provides unique features, which differentiate itself from other advanced electrical machines i.e. simple and rugged construction, higher reliability, high torque, precise speed control and low cost (Siadatan, Fatahi, and Sedaghat 2018). Switched reluctance motor is having higher speed than the stepper motor, lacking the use of expensive permanent magnets. It contains desirable qualities of an AC induction motor, a DC motor and a brushless motor. The SRM is also an economical alternative to other synchronous and induction machines for higher torque and higher speed applications (Li et al. 2019). For the past few decades, air pollution is a major concern for the environment. Most of the air pollution is due to the consumption of fuels in automobiles. For the reduction in air pollution level in terms of environment, electric vehicles are credible (Suresh et al. 2020; Karthik et al. 2020; Subasri et al. 2020; Sheela et al. 2020).

Most of the electric vehicles are manufactured with the switched reluctance motor (SRM). SRMs are used in electric vehicles due to their tailor-made characteristics (Aiso, Takahashi, and Akatsu 2019). The conventional SRMs show all these characteristics, but have some drawbacks too, i.e. such as torque ripples, noise and magnetic saturation (Qianfan, Shumei, and Xinjia 2007). All these things are responsible for their unsatisfactory efficiency in the operations. For enhancing their efficiencies, several types of topologies are invented by the researchers with unique and distinctive features despite having a few disadvantages. In, an alternative method of increasing torque profile has been proposed in which successful optimised design has been carried out and discussed the reason which sets barrier in its popularity. Double rotor topology is a unique topology suggested in Qianfan, Shumei, and Xinjia (2007) for improvement in efficiency. The novel dual-mode SRM (Miller 1989) has the characteristics of both a synchronous machine and a conventional SRM. Another effective way to uplift the torque by increasing the number of rotor poles is presented in Sun et al. (2019), which, in turn, results in a bulkier design and higher cost of machine. In Li, Ravi, and Aliprantis (2016) the rotor poles of SRM have been modified in order to reduce magnetic saturation and increased torque.

In this paper, the stator poles of the conventional SRM are modified and a novel topology is proposed in order to increase its torque profile and reduction in the mass of the material. The proposed topology consists of a slotted stator tooth at a certain depth by removing some portion of the core material. The winding of the proposed SRM motor is similar to the conventional model. This will serve the purpose, i.e. for providing a new path to the magnetic flux lines flowing across the core, for reducing core material and make it cost effective and for reducing the

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weight of the motor. After optimising the new topology, the flux linkage and torque have been calculated and analysed using the finite element method (FEM). The comparison is made between the conventional model and proposed model to justify the characteristics of the proposed model are superior (Yang 2015; Kiyota et al. 2019; Desai et al. 2010; Zhu et al. 2017).

In this paper, a basic structure of the conventional and proposed SST-SRM is introduced in section 2 and the finite element analysis (Patel and Vora, 2020) has been carried out with different slot widths of stator tooth and results are compared in section 3 and torque profiles obtained through FEA are compared. The conclusion is presented in section 4.

2. Construction of switch reluctance motor

2.1. Working of switch reluctance motor

Due to its rotor structure, as shown in Figure 1, the SRM structure is very basic. The stator consists of copper windings and its arrangement does not have a permanent magnet. Windings are supplied on the stator poles supplied by electronic power switches, in which the opposite poles provide the same series of windings. The research SRM consists of 8 stator and 6 rotor poles (8/6 configuration). For the stator and rotor cores, the steel material is used. The stator and rotor architectures are highly non-linear and discreet in their process of torque output.

The SRM operates on the rotor movement theory to a location where winding inductance is maximised. The rotor movement is regulated by the current commutation sequence through stator windings, where the current is pulsed one step at a time through stator windings. This is achieved by a general control and converter drive mechanism. SRM control depends on parameters, including turn-on/turn-off angle, rotor position and current reference (Suresh et al. 2020). The switched reluctance motor has salient poles on both the rotor and the stator and works like a variable-reluctance stepper motor except that the phase current is switched on and off, while the rotor is in precise positions, which can vary with speed and torque.

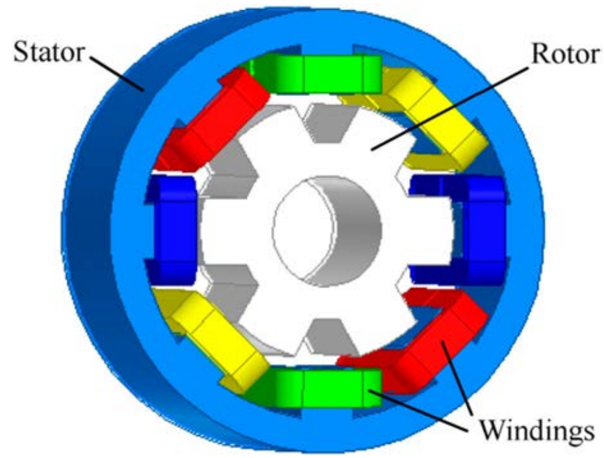

Figure 1. Construction of the conventional switch reluctance motor.

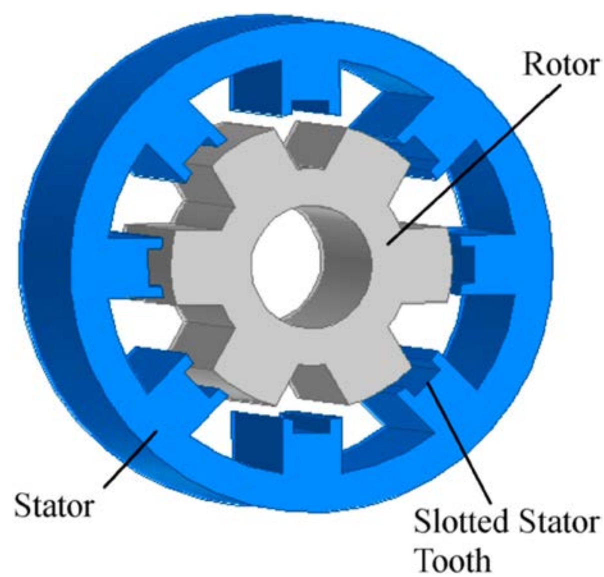

Figure 2. Cross-section of the proposed model of SST-SRM.

2.2. Construction of the proposed slotted stator tooth switch reluctance motor (SST-SRM)

The cross-section of stator and rotor core of the proposed SST-SRM is shown in Figure 2. The slotted stator tooth is utilised for the proposed model to minimise the utilisation of core material and hence the cost. The creation of core involves the suitable parameters of a stator core, such as its diameter, slotted stator teeth, type of poles, number of poles and stack length of the core. The iron material is used for the stator having a good permeability to help the flux to flow through it. Table 1 shows design parameters used for the finite element analysis. The torque of the SRM highly depends on the outer surface orientation of stator and rotor poles which defines the magnetic path for flux. For the design procedure for creating the 16/6 stator to rotor poles by splitting up the stator pole, a piece of core material is taken out such that the symmetricity of the newly formed two poles should remain the same, as shown in Figure 3. A slot is created on every stator pole having a certain depth and width. The width of the slot created remains the same in all the models that were used for analysis. The depth of the slot has varied in order to verify the torque at various depths for the slotted stator teeth design. The suitable depth of the slot formed can be calculated by performing multiple analyses on the SRM in the incremental order at which torque attains the highest value.

Table 1. Design parameters of the switch reluctance motor.

Particular	Values
Inner diameter of stator	75 mm
Outer diameter of stator	120 mm
Outer diameter of rotor	70 mm
Inner diameter of rotor	30 mm
Stack length	65 mm
Number of stator poles	8
Number of rotor poles	6
Stator yoke Thickness	9 mm
Pole arc to pole pitch ratio	0.5
Coil one-side end extended length	1 mm
Region length	200 mm
Info core	1
Air-gap length	0.5 mm
Winding type	Concentrated

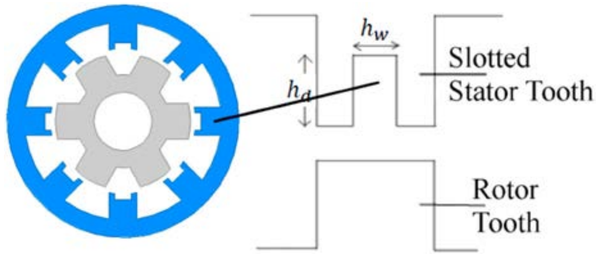

Figure 3. Slot characteristics.

Table 2. Design parameter of slots.

Design model	Slot width (mm)	Slot depth (mm)
1	9	2.35
2	9	2.85
3	9	3.35
4	9	4.35
5	9	5.35

The rotor design is similar to the rotor of the conventional SRM. For the rotor core design, the constraints are the same as the stator core.

Table 2 shows the variation of depth and width of the stator slot that is being taken out. When the slot depth changes the various output, parameters changes for flux distribution and torque. The best value of slot parameters can be obtained after the iterative finite element analysis. The torque of the SRM is calculated, as given in Li et al. (2019).

$$T = \frac{1}{2}.i^2.\frac{dL}{d\theta}\text{Nm} \tag{1}$$

which shows that the torque is proportional to the rate of change of inductance with the position and the square of current.

3. Result and analysis

The design procedure is applied to the 8/6 conventional SRM model and the proposed 16/6 SST-SRM. The transient analysis has been implemented using the finite element tool, ANSYS Maxwell v16.0 software. After the completion of analysis for both the designs, a set of outputs of vectors plots and graphs of various characteristics have been obtained. Also, the flux linkage plots and torque plots of conventional and proposed SST-SRM are compared and validated.

3.1. Conventional SRM

Figure 4 shows the magnetic field density vector plot where the path of magnetic flux is clearly indicated in the operation of the machine. The stator and rotor poles are shown with fully aligned condition and unaligned condition in Figure 4. This plot shows the variation in the magnetic flux densities as it can be observed the highest value of flux density at the corner of the stator and rotor tooth.

The flux linkage at every time step is recorded in order to get the plot graph with respect to time, as shown in Figure 5. At every step angle, the rotor rotates with 15 degree. The flux linkage with the rotor core is shown for all the 4 pairs of coils. The flux linkage obtained follows sinusoidal waveform after a certain period of

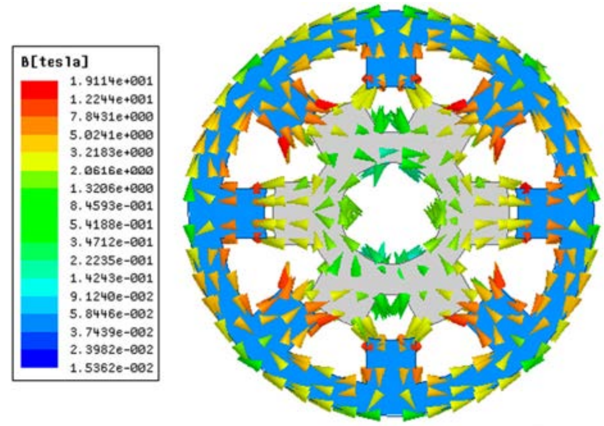

Figure 4. Magnetic field vector plot of the conventional SRM.

time as the reluctance between stator and rotor poles changes sinusoidally.

The torque obtained through FE analysis is shown in Figure 6. The maximum value of the torque measured is 6.5 N-m at a time of 8 ms. The calculated value of the torque, from Equation (1), is around 7.61 N-m. From the calculation, it is observed that there is a variation of 14.5% between the calculated torque and FEA analysis.

3.2. Proposed SST-SRM

In the proposed SST-SRM, the only changes are made with the number of stator poles with the slotted teeth. The finite element analysis of the slotted stator tooth (SST-SRM) has been carried out and stator poles with the 16/6 model of SRM show a variation in the output values with respect to the torque, current and flux linkage for the same set of parameters as in the conventional SRM. Figure 7 shows the vector plot of the magnetic flux density of the proposed SST-SRM. The behaviour of the magnetic field lines undergoes a drastic change under the agreement of its working principle. The magnetic field lines are becoming more concentrated over the narrow width of poles, which uplift its saturation value range. The FE analysis shows the superiority and improvement in results of the proposed SST-SRM model as compared to the conventional one.

Figure 8 shows the flux density plots under fully aligned and unaligned condition of rotor and stator poles. Figure 8(a) shows the vector plot under aligned condition. Figure 8(b) shows magnetic field plot under aligned condition. Figure 8(c,d) shows the vector plot under unaligned condition, and magnetic field plot under aligned condition.

Similarly, the flux linkage plot and torque plot of the proposed SST-SRM are shown in Figures 9 and 10, respectively. From the graph, it is observed that the maximum value of torque occurs at a depth of 3.35 mm in the stator tooth and the average torque at 2.35 mm. From this, the improvement in torque measurement is around 36.4% which can be taken as the evidence for proving the superiority of the proposed SST-SRM model over the conventional model of SRM.

For the different values of depth, the torque values are also different, as presented in the table. Table 3 shows the value

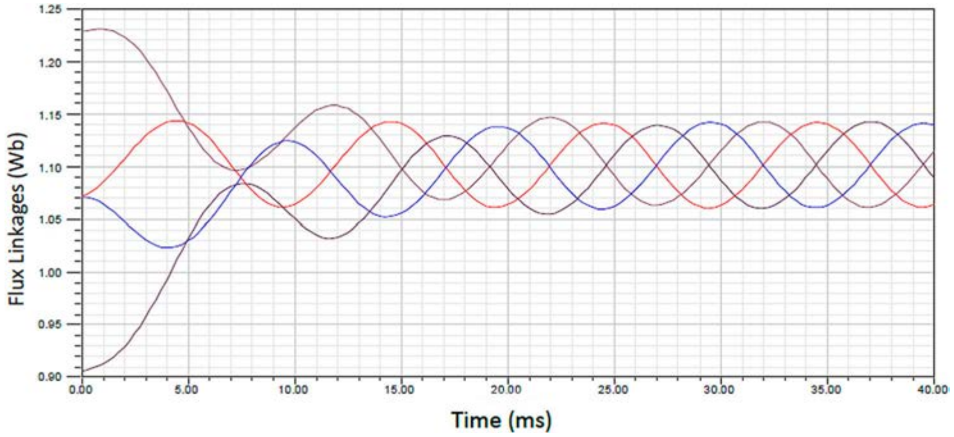

Figure 5. Flux linkages plot of the conventional SRM.

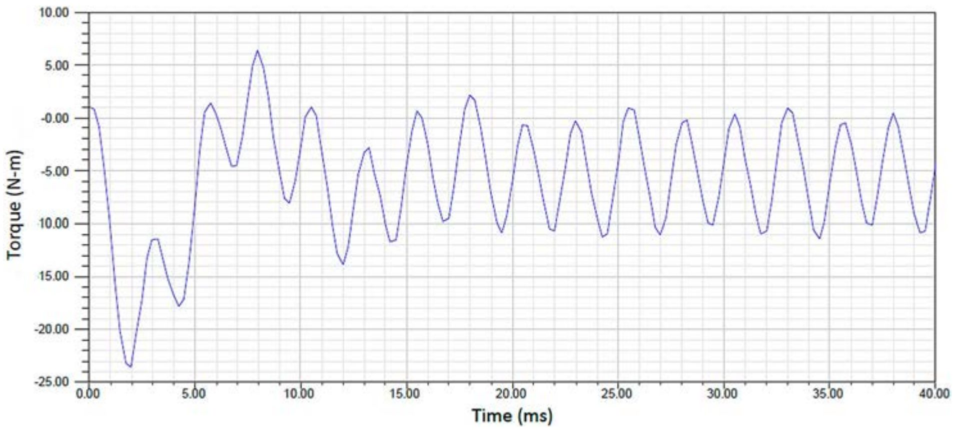

Figure 6. Torque of the conventional SRM.

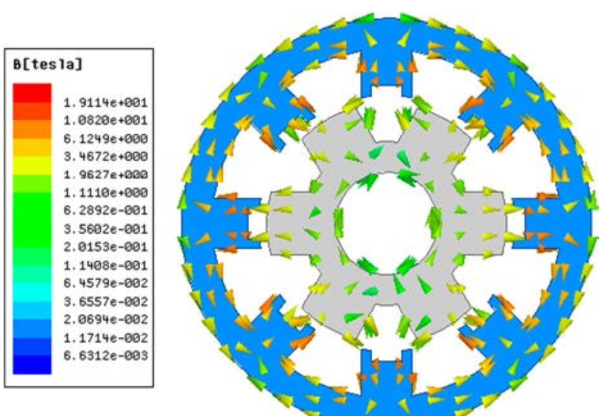

Figure 7. Magnetic field vector plot of the proposed model of SST-SRM.

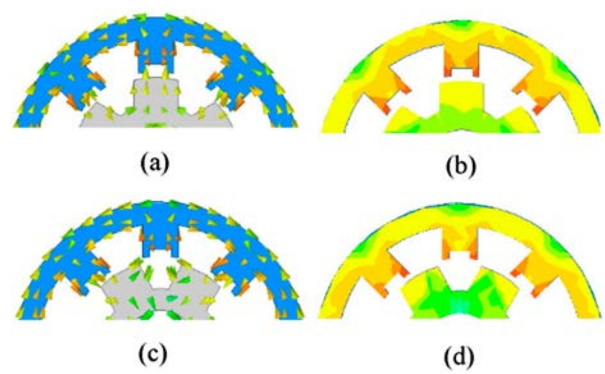

Figure 8. Orientation of magnetic field lines (a) vector plot under aligned condition, (b) magnetic field plot under aligned condition, (c) vector plot under unaligned condition, and (d) magnetic field plot under aligned condition.

Table 3. Values of torques at different depths.

Depth	Maximum torque (Nm)	Average torque (Nm)
0 (Conventional)	6.5	2.5413
2.35	8.8125	5.3004
2.85	8.3694	5.0394
3.35	8.8678	5.0056
4.35	7.7009	4.6196
5.35	8.3702	5.0145

of maximum and average torques obtained through the FE analysis.

The torque characteristics of the proposed SST-SRM are shown in Figure 11. Despite the improvement in torque, there is also a reduction in mass, volume and weight of the material, which certainly lead to reduction in cost. Table 4 shows the comparison between the conventional and proposed (3.35 mm depth) models for the material having the same mass density

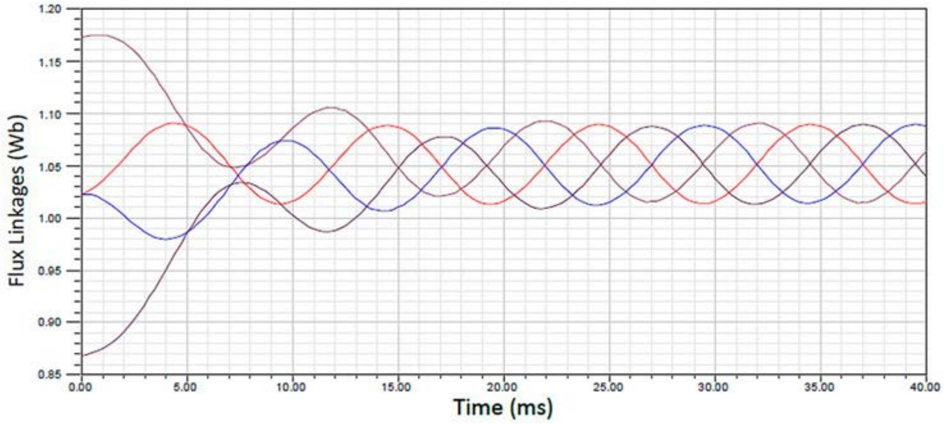

Figure 9. Flux linkages of the proposed model of SST-SRM.

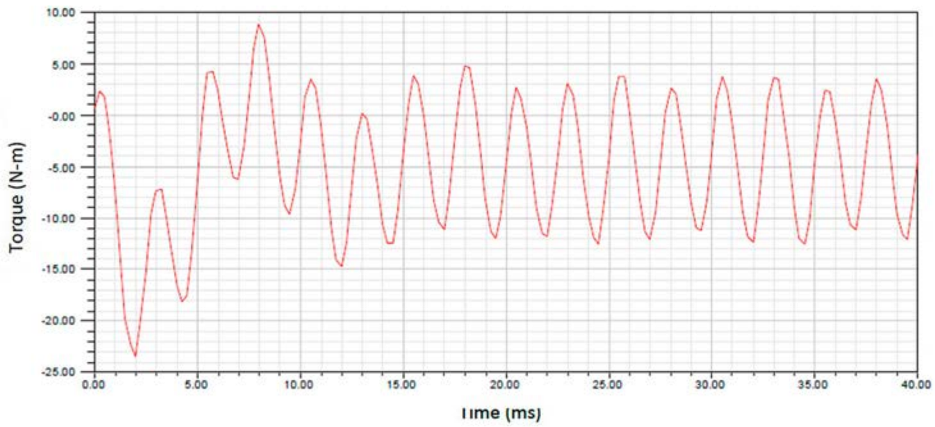

Figure 10. Torque of the proposed model of SST-SRM.

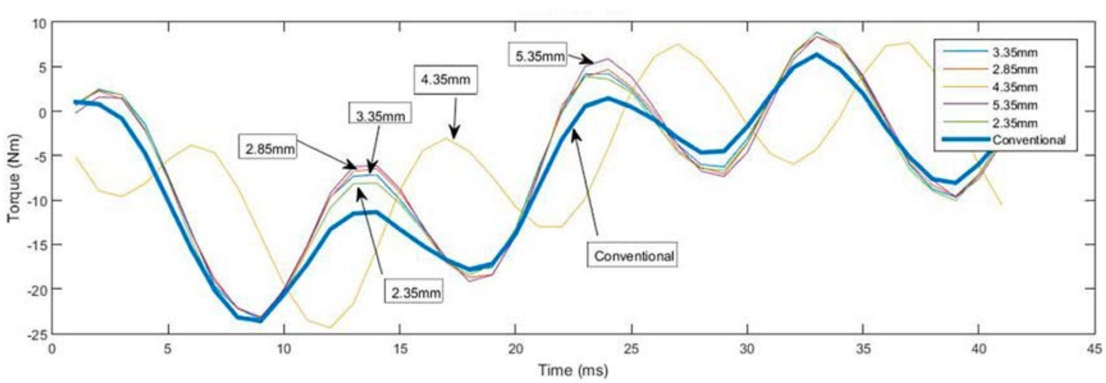

Figure 11. Torque characteristics of the proposed model of SRM.

Table 4. Mass comparison of the conventional SRM and proposed SST-SRM.

Design topology	Volume (mm^3)	Mass (kg)
Conventional SRM	307,185.02	2.417
Proposed SST-SRM	292,730.29	2.303

of Iron (7.870 gm/cm^3). From Table 4, the reduction in mass of the SST-SRM is around 0.114 kg which is almost 4.7% of the total mass of the conventional SRM.

4. Conclusion

This paper presents a new proposed design of SST-SRM and the analysis has been carried out for the application of electric vehicle using the finite element analysis tool. An approach for the optimisation of the design has been carried out in order to get the enhancement in torque values. The new proposed design consists of the slotted stator tooth of stator poles to a certain depth to perform design optimisation. The new slotted stator tooth stator pole (16/6) design shows the wide range of variation in torque magnitude for around 36.4% improvement in peak torque while comparing with the conventional SRM. Also, the saving of stator core material has been observed of around 4.7% which eventually makes it cost effective and light weighted for the same rated output. Overall, the proposed model of SRM shows strong vibrancy and improvement in the output parameters for its application in electric vehicle.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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