Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 13 Issue 5, May 2024

Optimized Design of 5 KW Switched Reluctance Motor

Aashish Kawale, Eshan Dhar, Akash Gaddamwar, Dinesh Kamble

Gyrodrive Machineries Pvt. Ltd. Pune
Department of Mechanical Engineering Vishwakarma Institute of Information Technology, Pune

Abstract:
This paper delves into the optimized design of a 5 kW Switched Reluctance Motor (SRM) using outcomes from many research papers, while keeping our primary focus on achieving higher torque output while maintaining a compact package size. The study involves a comparative analysis between analytical and simulation results. Additionally, the focus is primarily on minimizing torque ripple and ensuring continuous torque for improved starting procedures, thereby reducing noise and vibrations. Through comprehensive characterization, the optimized SRM design is expected to enhance its applicability in the rapidly expanding Electric Vehicle (EV) sector.

Keywords:
Switched Reluctance Motor; compact package size; torque ripple; Electronic Vehicle.

INTRODUCTION:

In e-rickshaws, the primary type of motor used is often the brushless DC (BLDC) motor or permanent magnet synchronous motor (PMSM). These motors are chosen for their efficiency, reliability, and suitability for electric vehicle applications. BLDC motors are commonly used in e-rickshaws due to their high efficiency and low maintenance requirements. These motors offer excellent torque characteristics and can provide the necessary power for propelling the vehicle while carrying passengers and cargo. BLDC motors are also known for their smooth operation and quiet performance, which enhances the overall driving experience for passengers. PMSM motors are another popular choice for e-rickshaws. Likewise, to BLDC motors, PMSM motors offer high efficiency and torque density, making them well-suited for electric vehicle applications. They also provide precise control over speed and torque, which is essential for optimizing the performance and energy efficiency of e-rickshaws.

However, Switched Reluctance Motors (SRMs) are gaining attention in various industries, including electric vehicles, due to their unique characteristics and potential advantages over traditional motor types like BLDC or PMSM. While BLDC and PMSM motors have been commonly used in e-rickshaws for their efficiency and performance, SRMs offer several benefits that make them suitable candidates for replacement in certain applications. SRMs inherently support regenerative braking [1], can operate efficiently over a wide range of speeds without the need for complex control algorithms or sensors [2] are inherently robust and can operate reliably in harsh environments [3], including high temperatures and dusty conditions, high torque density, simple construction compared to BLDC or PMSM motors.

Switched Reluctance Motors (SRMs) are a type of electric motor that operates, based on the principle of reluctance torque. Unlike conventional motors that use electromagnetic attraction between the rotor and stator, SRMs utilize the principle of magnetic reluctance to generate torque [4], [5], [6]. More about the concept, control and applications of SRMs is mentioned here [7].

SRMs consist of a rotor with salient poles and a stator with windings. The rotor and stator poles are typically not aligned, creating a variable air gap between them. When the stator windings are energized with current, they create a magnetic field based on Maxwell’s right hand thumb rule. The rotor tends to align itself with the stator poles due to the magnetic reluctance, causing torque to be developed. The orientation of the magnetic flux within the motor depends on how the poles of the rotor and stator are aligned. The torque produced is a result of the tendency of the rotor to align itself with the stator poles to facilitate magnetic flux paths.

SRMs offer environmental benefits, such as reduced energy consumption and lower carbon emissions, due to their high efficiency and energy-saving capabilities. They contribute to sustainability efforts and may qualify for incentives or certifications related to energy efficiency. SRMs are capable of operating at higher temperatures compared to some other motor types, such as permanent magnet motors, without experiencing demagnetization or performance degradation. This feature makes them suitable for applications in high-temperature environments.

Design Procedure:

Performance analysis of the SRM requires the dimensions for stator and rotor laminations, winding details, pole numbers, and pole arcs. An approximate sizing of the SRM is obtainable using a power output equation familiar to machine designers. The resulting machine dimensions form the starting point in design evaluation, and final design is achieved through an iterative process of steady-state performance calculations.[8]

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ISSN: 2278-0181
Vol. 13 Issue 5, May 2024

$$P_d = k_d.k_e.k_1.k_2.B.A_s.D^2.L.N_r \quad (1)$$

Where,

P_d = Power Developed

k_e = Efficiency of motor

k_d = Duty cycle

$$k_d = \frac{\theta_i \, .qP_r}{360} \quad (2)$$

Where,

P_r = number of rotor poles

q = number of stator phases

$$q = \frac{P_s}{2} \quad (3)$$

P_s = number of stator poles

θ_i = current conduction angle

$$k_1 = \frac{\pi^2}{360} \quad (4)$$

$$k_2 = 1 - \frac{1}{\sigma_s \sigma_u} \quad (5)$$

$$0.65 < k_2 < 0.75$$

Where,

σ_s = Ratio between aligned and unaligned inductance at saturation

σ_u = Ratio between aligned unsaturated inductance and unaligned inductance

$$\sigma_s = \frac{L_a^s}{L_a^u} \quad (6)$$

$$\sigma_u = \frac{L_a^u}{L_u} \quad (7)$$

L_a^u = aligned inductance but\ unsaturated

L_a^s = aligned inductance but saturated

B = stator pole flux density at aligned pole position

A_s = Specific electric loading

$$A_s = \frac{2T_{ph}im}{\pi D} \quad (8)$$

Where,

T_{ph} = number of turns per phase

m = number of phases conducting

i = peak phase current

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D = bore diameter

N_r = rotor speed (rpm)

L = axial length of stator

L= k.D [8] (9)

Where,

L = Length

D = Diameter

k = Constant

0.25 < k < 0.70

As for the Torque calculation, we can use equation, [8]

$$T = k_d k_e k_3 k_2.(B.A_s)D^2 L \quad (10)$$

Where,

$$k_3 = \frac{\pi}{4} \quad (11)$$

Stack length and Bore diameter:
Larger bore diameters (stator Internal diameter) allow for larger rotor volumes, which can potentially increase torque output and power density. However, larger bore diameters may also lead to increased losses due to higher reluctance and eddy current effects.
Stack length refers to the axial length of the stator and rotor laminations. Longer stack lengths generally result in higher torque output and better efficiency. However, longer stacks may also lead to increased losses and higher material costs. Stack length should be optimized based on the specific torque-speed requirements of your application. Shorter stack lengths are preferable for high-speed applications, while longer stack lengths are suitable for high-torque applications.

$$25000 < A_s < 90000$$

Stator and rotor pole width:
Selecting the stator pole width and rotor pole width in a SRM is crucial for optimizing its performance, efficiency, and torque characteristics. Torque produced in a motor is highly influenced by pole widths. The width of stator and rotor poles directly influences the amount of magnetic flux that can link the stator and rotor windings. By carefully choosing pole widths, it's possible to reduce torque ripple, resulting in smoother motor operation and improved performance in applications requiring precise speed or position control. Also pole widths affect the magnetic flux density distribution within the motor, which directly impacts core losses (hysteresis and eddy current losses) [9]. While selecting widths, you must also consider the manufacturability of the dimensions selected.

$$\omega_{sp} = D \sin\left(\frac{\beta_s}{2}\right) \quad (12)$$

Where,

ω_{sp} = stator pole width in terms of stator pole arc

β_s = stator pole arc (rad)

$$\omega_{rp} = k.\omega_{sp} \quad (13)$$

Where,

ω_{rp} = Rotor pole width in terms of stator pole arc

$$0.5 \le k \le 2$$

Stator and rotor back iron thickness:
The stator back iron thickness, b_{sy}, is determined on the basis of maximum flux density in it and by the additional factor of vibration minimization to reduce acoustic noise. The flux density in the stator back iron is approximately half that of the stator poles. If ω_{sp} is the pole width given in terms of pole arc as follows:[8]

$$\omega_{sp} > b_{sy} \geq 0.5\omega_{sp} \quad (14)$$

The rotor back iron thickness, b_{ry} , is based on structural integrity and operating flux density. It need not be as much as the stator back iron thickness and neither has to be equal to the minimum value equal to half the stator pole width. It is desirable to have shorter rotor poles to generate minimum vibration in the rotor.

$$0.5\omega_{sp} < b_{ry} < 0.75\omega_{sp} \quad (15)$$

Stator Outer Diameter:
For selecting OD of stator lamination,

$$D_0 = D + 2b_{sy} + 2h_s \quad (16)$$

Where,

D_0 = stator outer diameter (m)

h_s = height of stator pole (m)

D = bore diameter (m)

Selection of topologies:
The motor is assembled in a laminated form to increase power density and reduce torque ripple [10]. Mostly, used topologies for 3-phase SRMs are 6/4, 12/8, 18/12 and for 4-phase SRMs are 8/6, 12/8, (first unit representing number of stator poles and second unit representing number of rotor poles). From the different topologies available 12/8 with 3-phase produces low torque ripple compared to its lower number topologies [11]. Also, to get the higher torque it is seen that an increase in number of poles results in increase torque [12], the noise and vibrations produced by 12/8 topology is lower [13]. The topologies with higher number of poles will produce lower torque ripple however, the controlling part and assembling becomes complex by each of higher topologies.

Table 1: Machine Specification

Parameters	Values
Rated output power	5000 W
Rated voltage	60 V
Rated speed	2000 rpm
Maximum Current supply	150 A

International Journal of Engineering Research & Technology (IJERT)
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Table 2: Motor Specification

Parameters	Values
Stator OD	150 mm
Stator ID	95 mm
Stack length	150 mm
Air gap	0.2 mm
Number of Stator pole	12
Number of Rotor pole	8
Stator back iron	10 mm
Rotor back iron	23 mm
Turns per phase	12
Number of strands	12

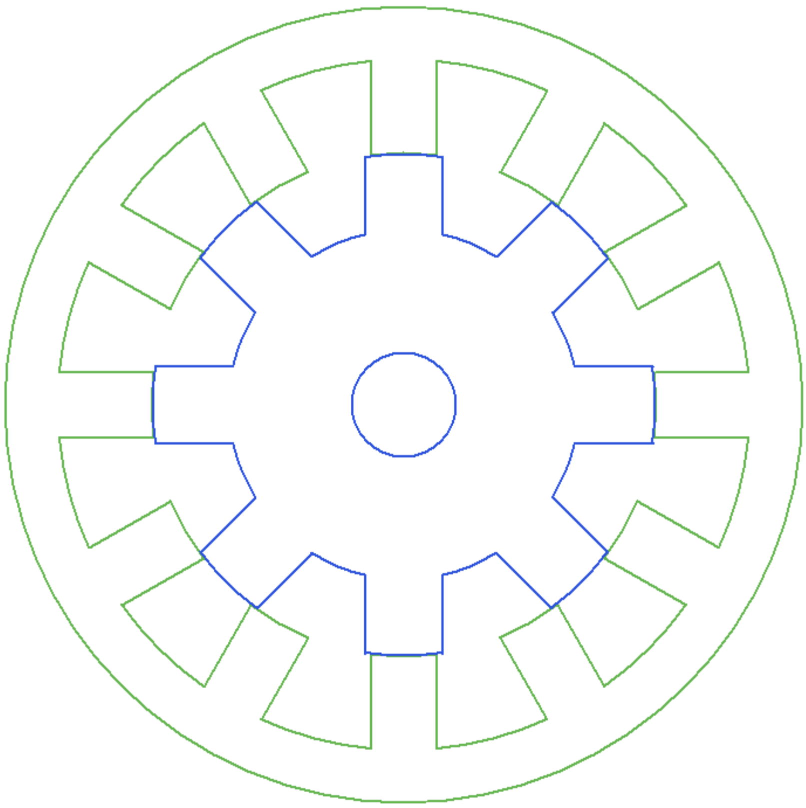

Fig. 1: Stator and Rotor initial position configuration

As it is shown in Fig. 1, we can see how the stator and rotor of a motor with configuration 12/8 looks. We can also understand by fig.1 that at the starting time it is ideal position. Also, rotor pole width is greater than that of stator pole width to facilitate lower torque ripple.

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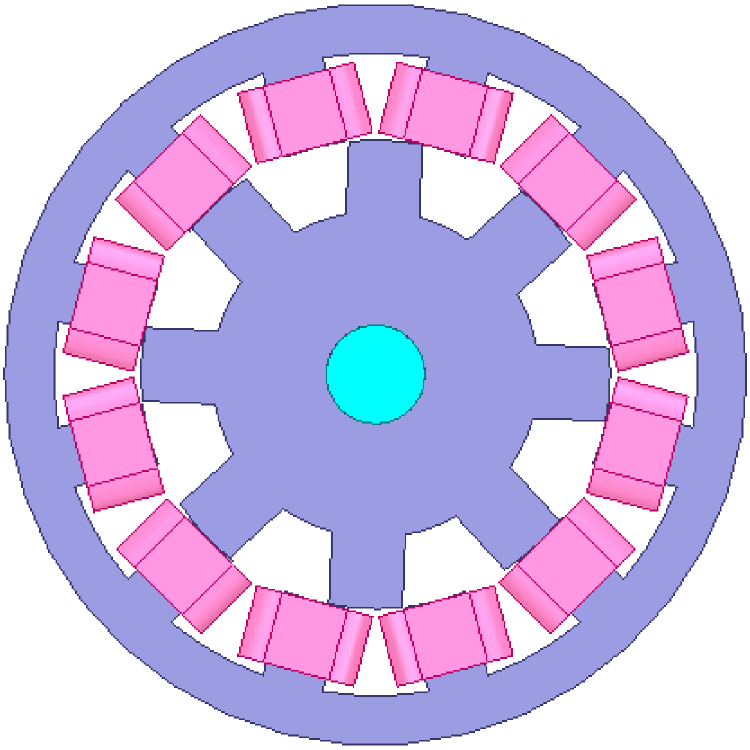

Fig. 2: Motor after Windings are placed

Generally, the copper fill factor for SRMs should be around 40% to 60%. In the selected motor design, as from fig. 2, the copper fill factor is 51.6 %. The copper fill factor should also be considered based on the final cost factor of the motor.

RESULTS OBTAINED:

Table 3: Analytical output by using Eqn. (1), (6), (7), (10)

Max. Output Power	5860 W
Max. Output Torque	44
Max. Air gap Inductance	3.380 mH
Power @ 2000 rpm	5710 W
Torque @ 2000 rpm	27.3 Nm
Efficiency @ 2000 rpm	94 %

Table 4: FEA software output as shown in fig.6, fig.7, fig.8

Max. Output Power	5560 W
Max. Output Torque	41.08 Nm
Max. Air gap Inductance	3.484 mH
Power @ 2000 rpm	5120 W
Torque @ 2000 rpm	24.65 Nm
Efficiency @ 2000 rpm	91 %

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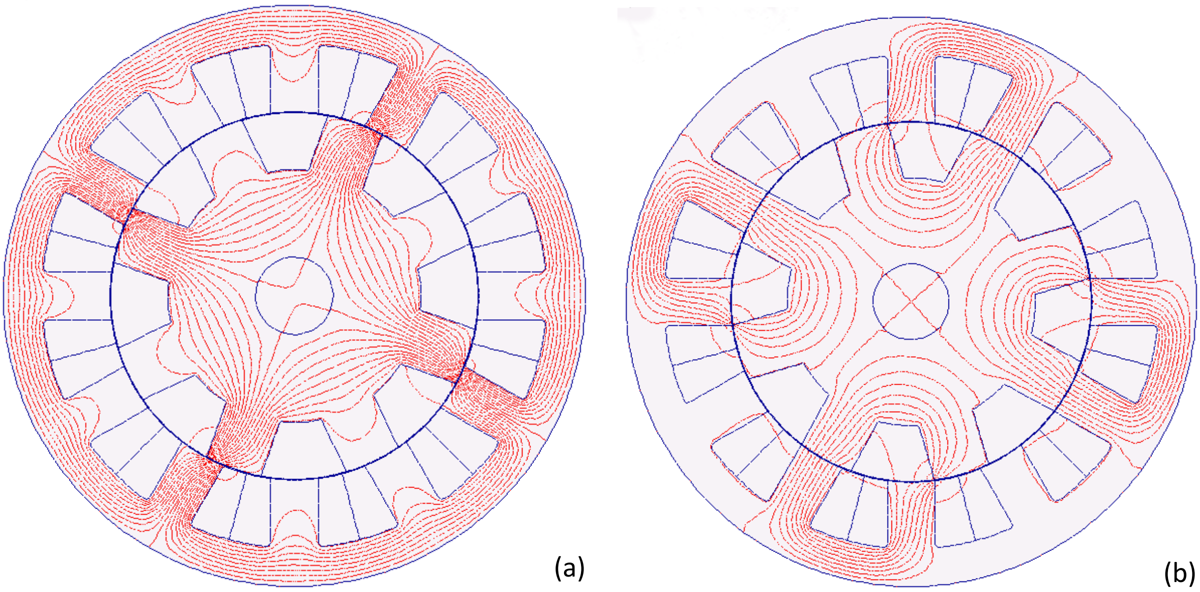

Fig. 3 (a) Unaligned rotor at 22deg. and (b) aligned rotor at 29deg. Shows, Eddy Current paths followed

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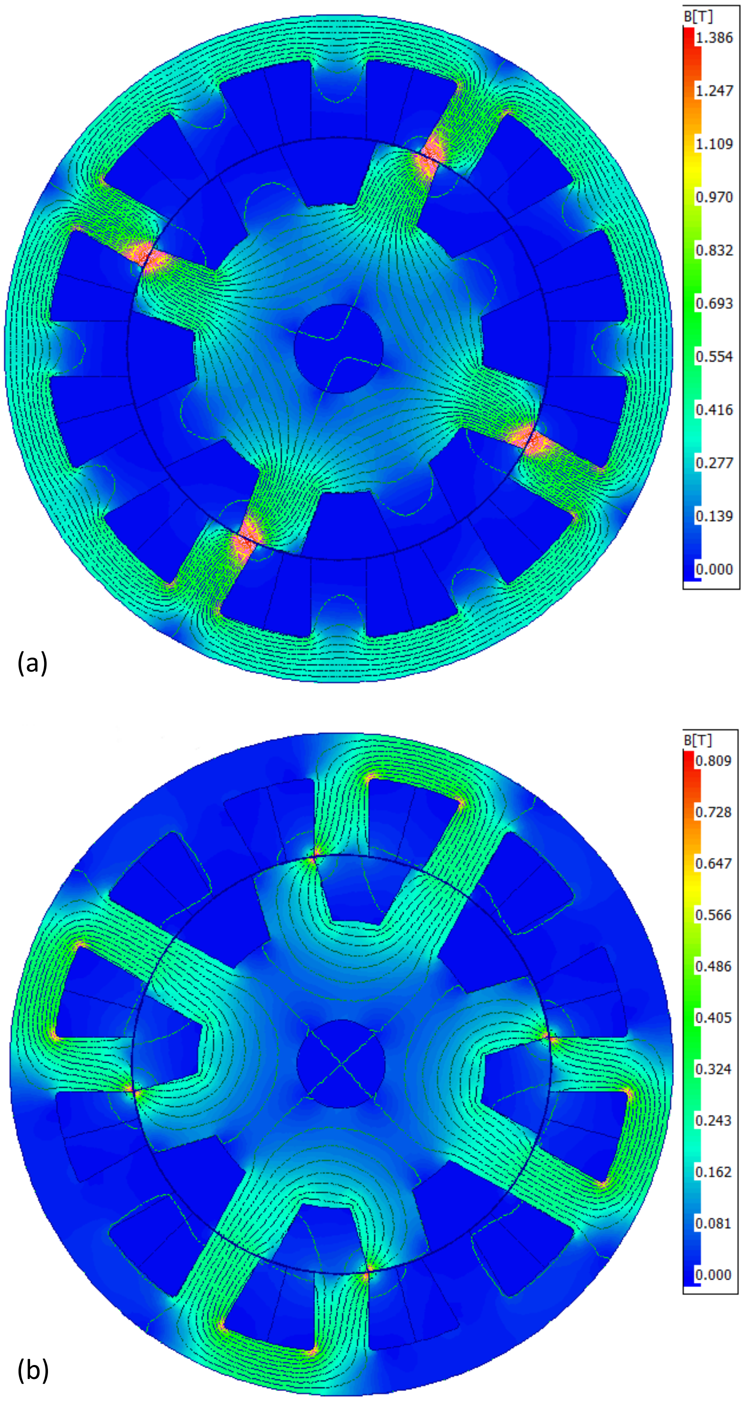

Fig. 4 (a) Unaligned rotor at 22deg. and (b) aligned rotor at 29deg. Shows, Flux Density paths followed

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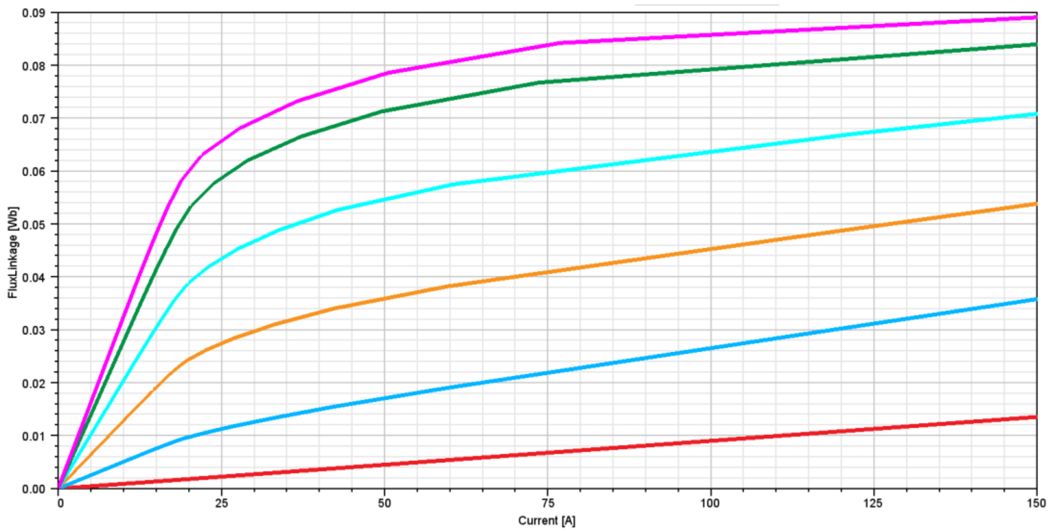

Fig. 5 By using FEA software, Flux Linkages (Wb) vs current (A) at different electrical degrees (0-180)

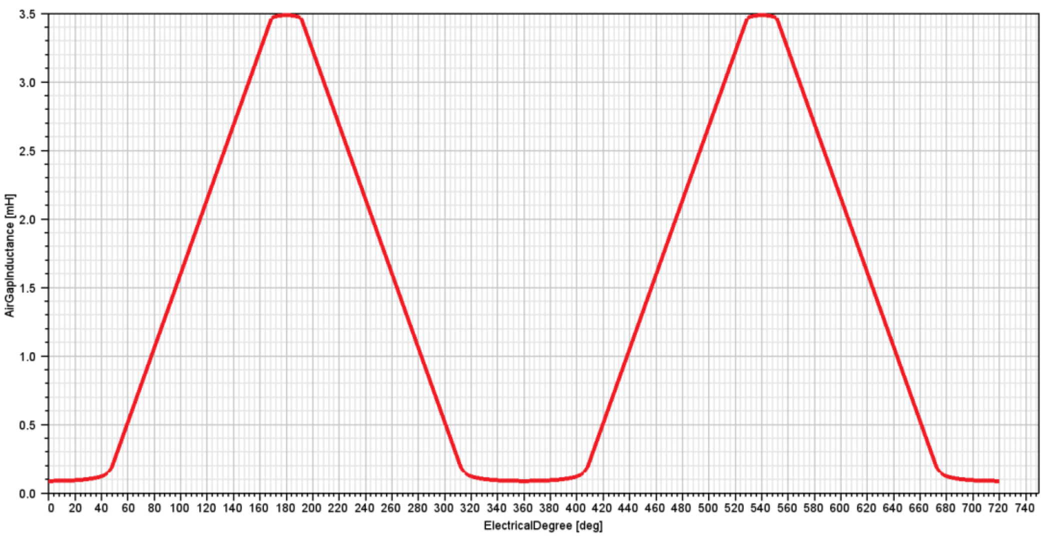

Fig.6 By using FEA software, Inductance vs Electrical degree of rotor

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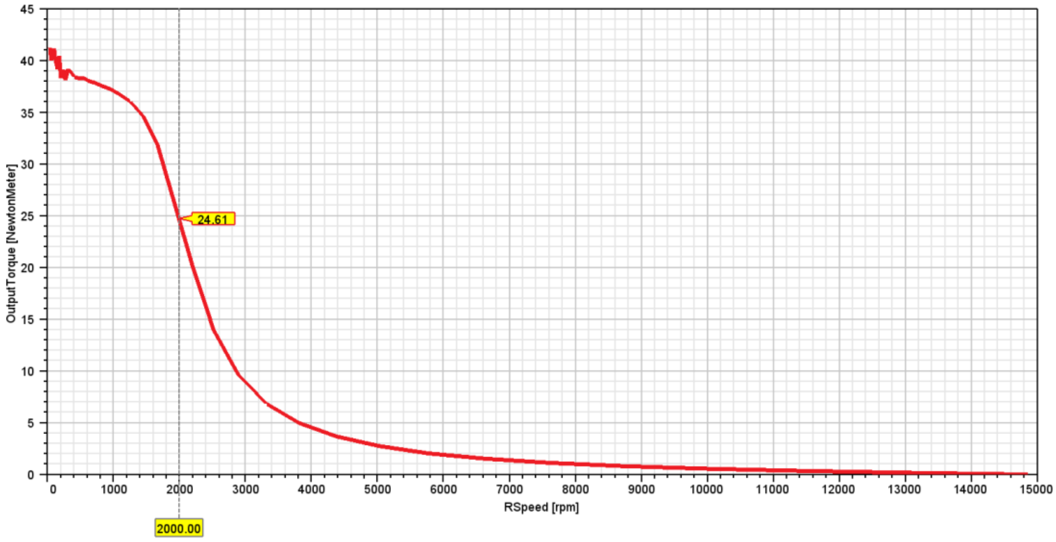

Fig. 7 By using FEA software, Output torque (Nm) vs speed (rpm)

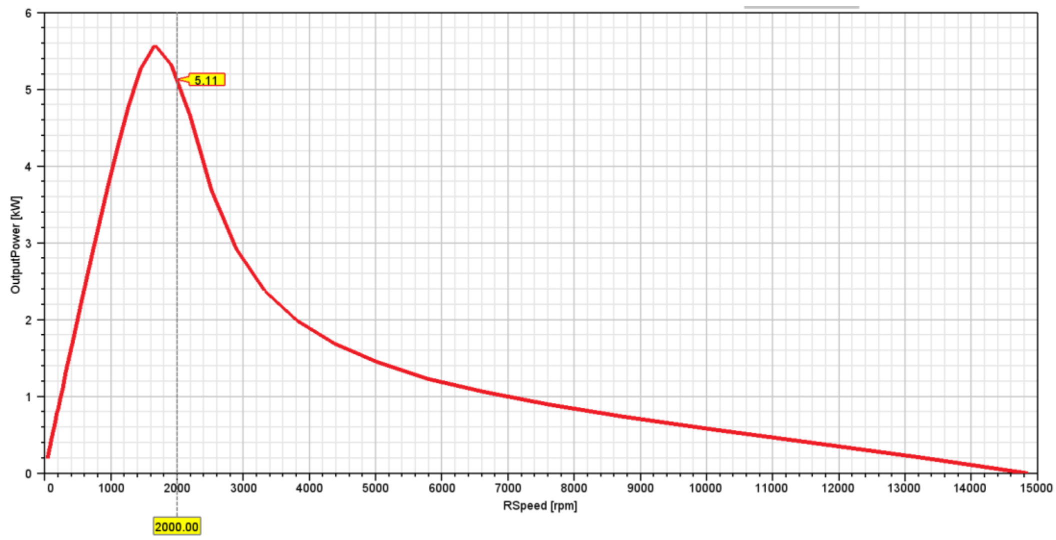

Fig. 8 By using FEA software, Output power (kW) vs speed (rpm)

As delineated in Table 3 and 4, the numerical data therein aligns with the results obtained through Finite Element Analysis (FEA) software, as depicted in Figures 5, 6, 7, and 8. The analytical results presented in the tables showcase some correspondence with the outcomes derived from the FEA software simulations, reinforcing the reliability and consistency of the analytical approach. This convergence between analytical and FEA software results not only enhances the credibility of the findings but also underscores the robustness of the employed methodologies. The figures visually represent the congruence between the two sets of results, providing a comprehensive and complementary understanding of the study's outcomes. This alignment serves as a validation of the analytical methods employed and reinforces confidence in the accuracy and applicability of the obtained results.

CONCLUSION:

This research endeavor has addressed a critical need within the realm of electric vehicle propulsion by focusing on the optimized design of a 5 kW Switched Reluctance Motor (SRM). Our primary objective was to enhance both torque performance and compactness, thereby making the SRM more viable for integration into today's rapidly expanding Electronic Vehicle (EV) sector. Through a combination of analytical modeling and simulation techniques, we have meticulously analyzed various design parameters and their impact on motor performance. By leveraging this comprehensive approach, we have achieved notable advancements in reducing torque ripple and ensuring a smoother starting procedure, ultimately enhancing the overall operational efficiency of the SRM. The comparative analysis between analytical and simulation results has provided valuable insights into the accuracy and reliability of our modeling approaches. This rigorous validation process not only bolsters the credibility of our findings but also underscores the robustness of the proposed design methodology.

ACKNOWLEDGEMENT:

I express my gratitude for the support and contribution from Gyrodrive Machineries Pvt. Ltd. Pune, as well as the assistance of ChatGPT, an AI language model developed by OpenAI, for its valuable input during the writing of this paper. ChatGPT provided beneficial suggestions and aided in rephrasing, thereby improving the clarity and coherence of our work.

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