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Design and Simulation of Switched Reluctance Motor for E-Rickshaw using ANSYS Software

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ABSTRACT: An increase in environmental pollution has led to the growing trend of the public transportation system in India. E-rickshaw one of many has been the one that is normally utilized and owned by lower and middle-class people. Currently, approximately 90% of two and three-wheeler electric vehicles are using BLDC (Brush-less DC) motors. These motors are mostly manufactured in China. We are trying to take further a designed SRM and comparing their simulation results and theoretical calculations for an E-rickshaw which can be used further to promote make in India and decreasing the dependency on China simultaneously. Electric cars use a wide range of Three-phase Induction Motors, Permanent Magnet (PM) motors, Switched Reluctance motors (SRM), Brushless DC motors, etc. Most of the motors are having the requirement of rare-earth magnets and hence having more cost. China is the major exporter of Rare Earth Magnets, so reducing the usage of magnets directly reduces our dependency. This idea suggests using Switched Reluctance Motor (SRM) as a drive for e-Rickshaw application which meets up the demands of E-Rickshaw and simulation will be done to show the results.

KEYWORDS: Switched Reluctance Motor(SRM), FAME, Foreign Exchange Reserves, Ansys Software.

I. INTRODUCTION

In recent times the SRM has been into limelight due to its advantages over other motors currently used in electric vehicles especially three wheelers. There are currently 1.5 million E-Rickshaws running on the Indian roads. And this number is only predicted to increase year by year. A predicted estimate of the growth of E-Rickshaws is approximately 10% for the next fiscal year.

Torque is developed by the tendency of its moveable part to move to position where the inductance of the excited winding is maximized in a reluctance motor.^[3] To investigate performance of SRM, including the design of the control circuit, its parameters should be known. Few of the important parameters which are to be known are flux linkage, inductance and static torque.^[5]

This paper includes theoretical design equations to assume the performance and to guide the design of SRM. This paper focuses on design and simulation of Switched Reluctance Motor to obtain high motor efficiency by using analytical design equation and simulating it on Ansys software. This paper will help out in practical designing of the SRM and further can be used for research and maximizing its efficiency and make any changes to make the motor practically available in the market.^[6]

II. OBJECTIVE OF PROJECT

The main goals of this project of designing of SRM is to reduce fossil fuel use, reduce dependency for magnets on China, save manual labor so as to make save humankind. Now a new study shows that by reducing air pollution, a growing fleet of EVs in the nation could also save thousands of lives. Though the process will take some time but the change will be seen.

Diesel and gas trucks make up only a small portion of the vehicles on Indian roads and highways, they emit massive amount of pollutants and cause air pollution to great extent. In the most impact communities, the

pollution caused by these trucks may cause severe respiratory and heart problems.

When we look over other problems, one of the major problem which we face right now is the availability of magnets. Since the increase in usage of electric vehicles is increasing, the demand of magnets is also increasing. One of the key exporters of magnets at present is China. When we think about the problems the major problem which arises is the political connections of India with China. Post Covid the relations between the two countries might be in tension and if China suddenly stops the export of magnets to India there might be a condition of huge losses in automobile industries which are currently in developing e-vehicles for Indian roads. One objective can be set as to reduce dependency on China for the magnets used.

Now, when we look at the economic point of view, when we manufacture a SRM we save approximately Rs.3000 over motors being manufactured right now. At current scenario if we have to calculate the total money that could have been saved by switching over to SRM then $1.5 \text{ million} \times 3000 = \text{Rs.}450 \text{ million}$ would be saved in the Foreign exchange reserves. The amount shown is a rough estimate of the total savings. In coming years when the manufacturing will grow specially for SRM India can save a lot of money on magnets.

III. PROBLEM STATEMENT

Literature review has concluded that no single motor is suitable for all the electric vehicle applications. Switched Reluctance Motor is currently having a very small proportion in Electric Vehicles (currently only in 4 wheelers) although it is having an upper hand in almost all characteristics required for electric vehicle applications and having benefit of no usage of magnets in its construction. Research work is planned to design and manufacture, efficient and economical drive system using a Switched Reluctance Motor for higher efficiency and great characteristic for the motor enhancing the performance Electric Vehicle.

IV. RESEARCH METHODOLOGY

Research methodology for proposed research work is **experimental type of quantitative research** which includes:

1. Literature review and scenario of the present situation which includes the study of different research paper along with the situation of e-rickshaw in today's market and the various steps taken by the government to ensure the proper development in the field of e-vehicle with the best used motor and battery.
2. Mathematical design calculations of proposed design along with formula. The design says the design procedure of Switched Reluctance Motor which includes the machine specification, frame size selection, pole selection, stator and rotor pole angle selection, preliminary design process, winding design, and calculation of average torque. Also, we have analyzed the SRM by calculating the various losses in the SRM motor which includes Copper loss and Iron loss. All the values we have calculated for 48 V, 550 W and 2000 rpm SRM motor.

Machine Specification: The design specification of SRM required the power output P in KW, speed N in rpm, allowable peak phase current I in Amps, and available supply voltage V_{ac} in Volts for the system.

Frame Size Selection: The frame size of the motor is automatically determined by the outer diameter of the stator.

Practically, the outer diameter of the stator is fixed as follows:

$$D_o = (\text{Frame Size} - 3) \times 2$$

Where the frame size is given according to the IEC recommendations. The 3mm subtraction is used in industry to account for the foot of the machine, which is used for mounting.

Pole Selection: This project primarily focuses on the popular combination of 8 stator and 6 rotor poles, also commonly known as the 8/6 machine. This machine has the advantage of lesser torque ripple than the other common combination of 6 stator and 4 rotor poles (6/4 machine) while having the disadvantage of using more switches in the converter, two extra terminals and higher core losses because of higher switching losses.

Stator and Rotor Pole Angle Selection: The stator and rotor pole angle selection are the crucial part of the design process. The standard design normally has the stator pole arc angle (β_s) smaller than the rotor pole angle (β_r).

- 1] The stator pole arc angle is less than the rotor pole arc angle, i.e., $\beta_s < \beta_r$.
- 2] The effective torque zone is lesser than the stator pole angle β_s but greater than the stroke angle ϵ . The stroke angle is defined as:

$$\frac{2\pi}{\frac{N_s}{2} N_r}$$

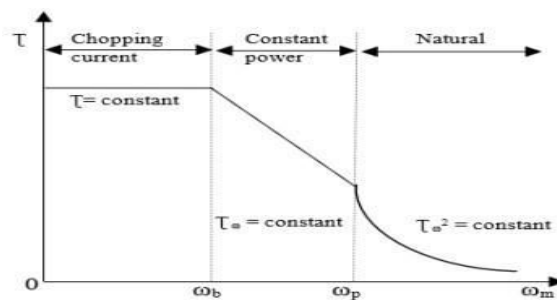
In an 8/6 machine the stroke angle is $= 0.2618$ rads $= 15$ degree. If $\beta_s < \epsilon$, then there may be some positions in the machine from where the machine may not start.

- 1] The angle between the corners of adjacent rotor poles must be greater than the stator pole arc or there will be an overlap between the stator and rotor poles in the unaligned position.

Calculation of Average Torque: The average torque of the required SRM is calculated by the formula:

$$T_{av} = (WN_s N_r) / 4 * \pi$$

Where W is the total work done, which is calculated by the subtraction of unaligned work from the aligned work.



(Fig. 1 – Torque Speed Characteristic)

Copper Losses: The first step in calculating the copper losses involves the calculation of the resistance of each phase winding of the SRM. The mean length of a winding turn is given as,

$$l_m = (2L + 4Wt + 2D \sin(\frac{\beta_s}{2})) * 10^{-3} \text{ m}$$

$$\text{The resistance of a single phase is calculated as } R_s = \frac{0.0177 * l_m T_{ph}}{a} \Omega$$

The copper losses at rated current are given by $P_{cu} = i_p^2 R_s W$

Iron Losses: The iron losses are classified as Eddy- Current Losses and Hysteresis Losses.

3. Design of proposed system using software tools i.e., ANSYS Maxwell. After the whole calculation part, we have designed the detailed structure of Switched Reluctance Motor using ANSYS Maxwell Software and analyze it thoroughly.

V. DESIGN SPECIFICATION

The specification of selected machine is- Operation type: Switched Reluctance Motor

Type of Load: Constant Power (EV requires constant power) Rated Output Power: 550W

Rated Voltage: 48V

Given Rated Speed: 2000rpm Type of Circuit: Full- Voltage

Operating Temperature: 75 degree C

Number of Stator Poles: 8

Number of Rotor Poles: 6

Stator pole embrace: 0.44

Rotor pole embrace: 0.5

Stack length L: 80

Bore diameter D: 63

Type of Steel: steel_1010 (because it has high tensile strength and yield strength as compared to steel_1008)

The torque to be developed by the motor as,



$$T_{req} = P_{kw} * 745.6 / 2 \pi * (N/60)$$

$$T_{req} = 2.38 \text{ N-m}$$

where, P_{kw} is the power output in watts, N is the speed in RPM.

By neglecting leakage and stacking factor the stator pole area is given by,

$$A_s = D/2 * (L_s \beta_s)$$

$$A_s = 8.80 * 10^{-4} \text{ m}^2$$

where, D is the frame size, L is the stack length, β_s is the stator pole angle, the flux in the stator pole is given as follows,

$$\Phi_s = B_s * A_s$$

$$\Phi_s = 1.45 * 10^{-3} \text{ wb}$$

Where as, B_s is the stator flux density, the flux in the yoke is given as follows,

$$\Phi_y = \Phi_s / 2$$

$$\Phi_y = 7.25 * 10^{-4} \text{ wb}$$

The area of the stator is equal to the area of the rotor. So, the area of the yoke is given by,

$$A_s = A_y$$

Back iron thickness will get calculated by following equation,

$$C = A_y / L$$

$$C = 0.011 \text{ m}$$

The stator pole height is given by,:

$$h_s = D_o/2 - C - D/2$$

$$h_s = 17.5 \text{ m}$$

Where as, D_o is the outer diameter of the stator, C is the back iron thickness, D is frame size

The rotor pole area is given by,

$$A_r = (D/2 - g) * L_r \beta_r$$

$$A_r = 1.25 * 10^{-3} \text{ m}^2$$

Where as, g is the air gap, β_r is the rotor pole angle

The rotor pole flux density is given by,

$$B_r = B_s A_s / A_r$$

$$B_r = 1.15 \text{ wb/m}^2$$

The rotor pole height is given by,

$$h_r = D/2 - g - D_{sh}/2 - A_r / L$$

$$h_r = 15.13 \text{ m}$$

The area of the rotor core is given by,

$$A_{rc} = L(D/2 - g - h_r - D_{sh}/2)$$

$$A_{rc} = 5.5 * 10^{-4} \text{ m}^2$$

The average area of A_g is given by,

$$A_g = A_s + A_r / 2$$

$$A_g = 1.08 * 10^{-3}$$

The flux density in air gap is given by,

$$B_g = A_s B_s / A_g$$

$$B_g = 1.34 \text{ wb/m}^2$$

Pole Embrace	Efficiency%	Total Loss (W)	Rated Torque (N.m.)	Speed (RPM)
0.30	68.30	231	2.52	1892
0.35	69.63	217	2.58	1839
0.40	73	181	2.45	1938
0.45	71.49	199	2.48	1919
0.50	71.21	201	2.30	2064

(Table 1)

According to the mathematical observations as the pole embrace increases the speed also increases so we have selected the highest pole embrace. Pole Embrace: 0.50



Stack Length	Efficiency %	Total Loss (W)	Rated Torque (N.m)	Speed (RPM)
80	72.53	188	2.38	1994
100	71.60	197	2.40	1980
111	71.13	202	2.40	1922

(Table 2)

We observe that as the stacking factor increases the efficiency and rated torque increases and total loss decreases but the starting torque decreases so we have selected stacking factor 0.95 which is more convenient one. Slot insulation thickness (mm): 0.3 Number of Turns per Pole: 20 Wire Diameter (mm): 1.628 (Round type, 14 Gauge)

Stacking Factor	Efficiency %	Total Loss (W)	Rated Torque (N.m)	Speed (RPM)
0.90	72.40	189	2.36	2006
0.95	72.53	188	2.38	1994
0.99	72.60	187	2.39	1988

(Table 3)

VI. OPTIMIZED DESIGN AND ANALYSIS

SWITCHED RELUCTANCE MOTOR DESIGN

GENERAL DATA

Rated Output Power (kW): 0.5
 Rated Voltage (V): 48
 Given Rated Speed (rpm): 2000
 Frictional Loss (W): 4
 Windage Loss (W): 8
 Type of Load: Constant Power
 Type of Circuit: Full-Voltage
 Lead Angle of Trigger in Elec. Degrees: 0
 Trigger Pulse Width in Elec. Degrees: 120
 Total Transistor Voltage Drop (V): 2
 Total Diode Voltage Drop (V): 2
 Operating Temperature (C): 75

STATOR CORE DATA

Number of Stator Poles: 8
 Outer Diameter of Stator (mm): 120
 Inner Diameter of Stator (mm): 75
 Yoke Thickness (mm): 9
 Pole Embrace: 0.44
 Length of Stator Core (mm): 80
 Stacking Factor of Stator Core: 0.95
 Type of Steel: steel_1010

STATOR COIL DATA

Slot Insulation Thickness (mm): 0.3



End Length Adjustment (mm): 0
 Number of Parallel Branches: 1
 Number of Turns per Pole: 28
 Number of Wires per Conductor: 1
 Wire Diameter (mm): 1.45
 Wire Wrap Thickness (mm): 0.08
 Slot Fill Factor (%): 47.132

ROTOR CORE DATA

Number of Rotor Poles: 6
 Length of Air Gap (mm): 0.5
 Inner Diameter of Rotor (mm): 30
 Yoke Thickness (mm): 9
 Pole Embrace: 0.5
 Length of Rotor Core (mm): 80
 Stacking Factor of Rotor Core: 0.95
 Type of Steel: steel_1010
 Magnetic Shaft: Yes

MATERIAL CONSUMPTION

Stator Copper Density (kg/m^3): 8900
 Stator Core Steel Density (kg/m^3): 7872
 Rotor Core Steel Density (kg/m^3): 7872
 Stator Copper Weight (kg): 1.36391
 Stator Core Steel Weight (kg): 2.71387
 Rotor Core Steel Weight (kg): 1.56968
 Total Net Weight (kg): 5.64745
 Stator Core Steel Consumption (kg): 6.06427
 Rotor Core Steel Consumption (kg): 2.59398

FULL-LOAD OPERATION DATA

Input DC Current (A): 14.311
 Phase RMS Current (A): 13.0313
 Phase Current Density (A/mm^2): 7.89155
 Frictional and Windage Loss (W): 11.9251
 Iron-Core Loss (W): 0.00112715
 Winding Copper Loss (W): 103.55
 Diode Loss (W): 22.2697
 Transistor Loss (W): 50.9183
 Total Loss (W): 188.664
 Output Power (W): 498.266
 Input Power (W): 686.93
 Efficiency (%): 72.5352
 Rated Speed (rpm): 1994.64
 Rated Torque (N.m): 2.38544
 Flux Linkage (Wb): 0.0700343
 Stator-Pole Flux Density (Tesla): 1.27614
 Stator-Yoke Flux Density (Tesla): 0.914191
 Rotor-Pole Flux Density (Tesla): 0.859175
 Rotor-Yoke Flux Density (Tesla): 0.342822
 Coil Length per Turn (mm): 207.153
 Winding Resistance in Phase (ohm): 0.152445
 Winding Resistance at 20C (ohm): 0.125398
 Winding Leakage Inductance (mH): 0.0799486
 Iron-Core-Loss Resistance (ohm): 4.55665e+06

Frequency of Phase Current (Hz): 199.464
Maximum Output Power (W): 1331.47

NO-LOAD OPERATION DATA

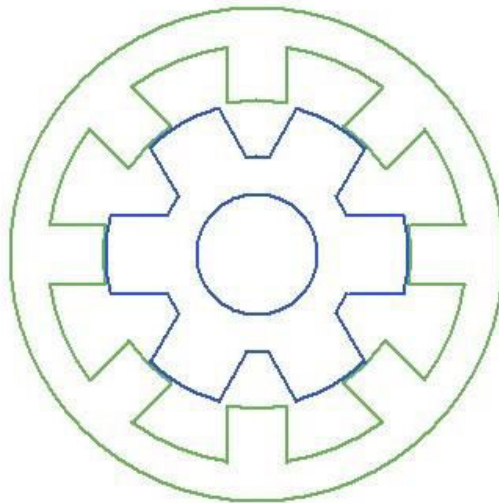
No-Load Speed (rpm): 5639.67
No-Load DC Current (A): 4.89198
No-Load Input Power (W): 234.815

START OPERATION DATA

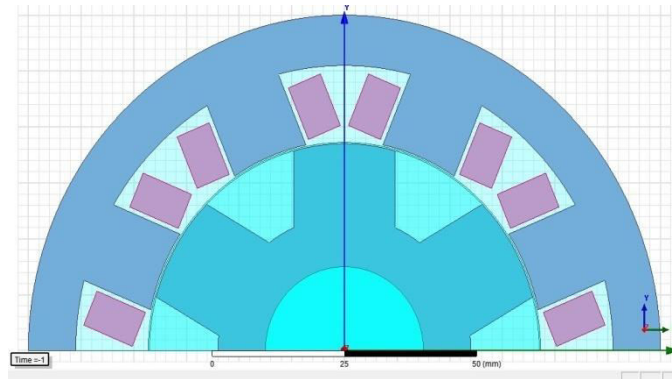
Estimated Start Torque (N.m): 47.0549
Estimated Start DC Current (A): 376.942
Maximum Start Current (A): 301.748

TRANSIENT FEA INPUT DATA

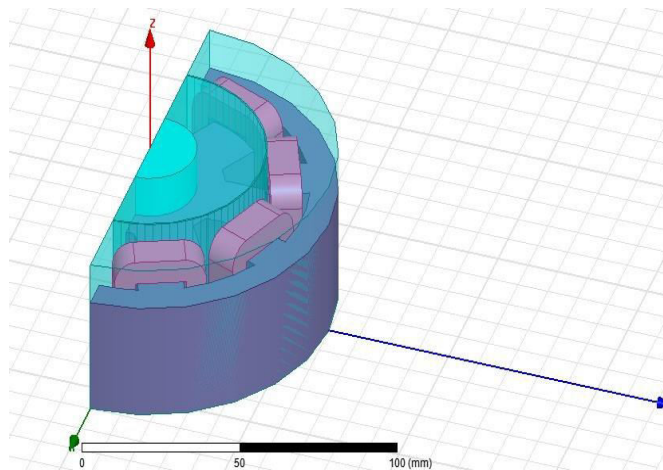
For Armature Winding:
Number of Turns: 56
Parallel Branches: 1
Terminal Resistance (ohm): 0.152445
End Leakage Inductance (H): 2.06894e-05
2D Equivalent Value:
Equivalent Model Depth (mm): 80
Equivalent Stator Stacking Factor: 0.95
Equivalent Rotor Stacking Factor: 0.9



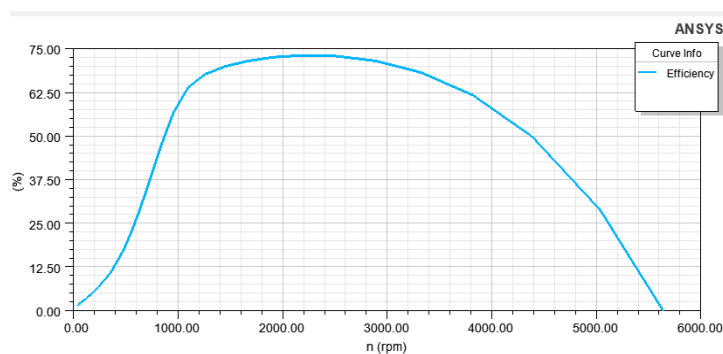
(Fig. 2 – Stator and Rotor)



(Fig. 2 – Maxwell 2DDesign)

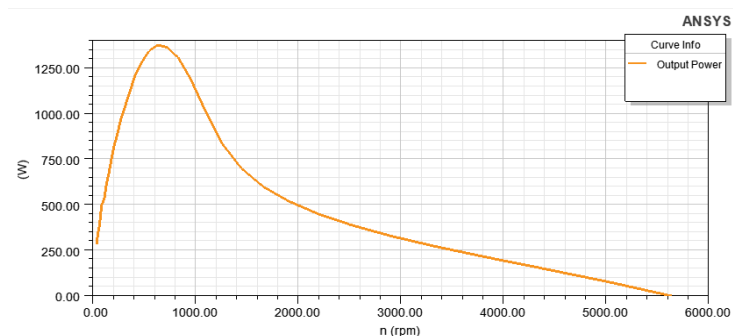


(Fig. 3- Maxwell 3DDesign)



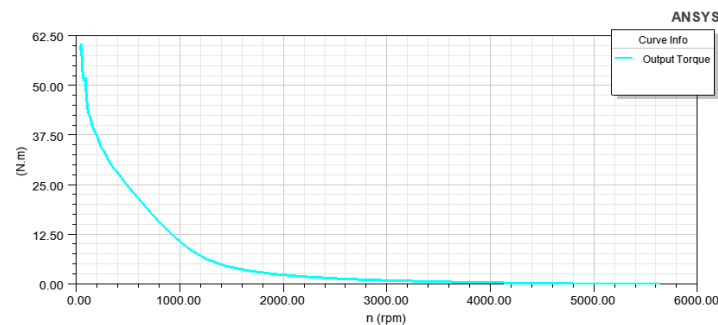
(Fig. 5- Efficiency vs Speed)

The above graph represents that the efficiency increases and then decreases and the efficiency is maximum at the proposed rated speed, i.e., 2200 rpm.



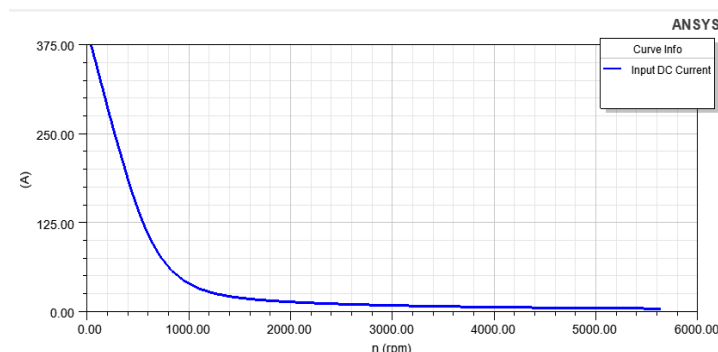
(Fig. 6 – Power Output vs Speed)

From this graph we observe that for the given rating of motor, the motor gives the highest output power at nearly 600 rpm.



(Fig. 7 – Output Torque vs speed)

From the above graph it is clear that the flux linkage must be high for the good performance of the motor.



(Fig. 8 – Input Current vs speed)

VII. CONCLUSION

For choosing SRM motor upon other motors for electric vehicles various characteristics are taken into count. The motor characteristics such as power density, efficiency, pros and cons are compared with their applicability in electric vehicles. In SRM motor, stator has coil and rotor is made of iron. There are no conductors on rotor which means there are no I^2R losses in rotor, which ultimately improves its efficiency as there are only stator losses and no rotor losses. As losses occur only in stator, the pressure on cooling mechanism reduces and it does not have permanent magnets on rotor hence its weight and size are decreased. In case of other motors, a cooling device is required which affects cost and size of the overall system.

Based on practical and theoretical study, it has been shown that SRM can achieve highest torque to power



performance, low vibration and low acoustic noise compared to other motors currently available. After the complete analysis of all motors, it can be concluded that SRM motor is a better option with respect to other motors in the application of electric vehicles especially E-Rickshaw.

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