Selection, Design and optimization of Switched Reluctance Motor Drive System for E-Rikshaw Application

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Abstract

The human awareness for energetic and environmental problems encourages the electrification of vehicles. The government of India is promoting the usage of electric vehicles through the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme. Research work supports to replace conventional IC Engine vehicles by electric vehicle. Currently different types of electric vehicles are there in the market like full electric vehicle, hybrid electric vehicle, plug-in hybrid electric vehicle, etc. The most popular public transportation system in India is the E- rikshaw which is mainly owned by the lower middle-class people. Electric Vehicles are driven by electric motors. Electric Vehicles are facing the problems related to performance of the motor and its controller. The motor currently used in e-rickshaw is not compatible for production of sufficient torque to cope up with load requirements and draws significantly high current which causes failure of the controller. Currently most of the e-rikshaws use BLDC (Brush less DC) motors imported from China. BLDC motors are having requirement of rare-earth magnet. The Switched Reluctance Motor (SRM) has very limited use in Electric Vehicles, although it meets many of the requirements needed for the application of electric vehicles and benefits from magnet-less construction. This paper mainly presents the selection of motor size and design of SRM for e-rikshaw application with compact motor size. Design of SRM and drive system for e-rikshaw application is carried out using ANSYS Maxwell software.

Keywords: Electric vehicle, Switched Reluctance Motor drive system, E-Rikshaw, ANSYS Maxwell software

I. INTRODUCTION

A vehicle propelled by an electric motor, rather than a petrol or diesel engine is called as electric vehicle. The electric motor is powered by rechargeable batteries that can be charged using household mains electricity through an electric vehicle charging point at home or at a more powerful electric vehicle charging station. Battery electric vehicle uses electricity stored in a battery pack to drive the electric vehicle. The Government of India is promoting the usage of electric vehicles through the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme. Electric vehicles mainly classified as follow: [11]

i) HEV (Hybrid Electric Vehicle): In this electric vehicle, Internal Combustion Engine (ICE) and electric motor are combined within drive train. Electric motor helps Internal Combustion Engine for the purpose of fuel economy or electric drive. Vehicle is either propelled by Internal Combustion Engine or electric drive system.

ii) PHEV (Plug-in Hybrid Electric Vehicle): Plug-in Hybrid Electric Vehicle are having battery of larger size than that of Hybrid Electric Vehicle and it allows recharging of battery through charging stations or home-outlets. Internal Combustion Engine can be used to produce the electricity for electric drive directly or to recharge the battery. When battery is charged fully, it can be operated in fully electric mode.

iii) FEV (Full Electric Vehicle):Full Electric Vehicle runs by electric drive system. Batteries are of larger size and can be recharged at home-outlets or at charging station. Full Electric Vehicle act as zero-emission vehicle.

II.SELECTION OF SWITCHED RELUCTANCE MOTOR

Now a day's electric vehicles are using various types of motors. Following table gives comparison of major motors used for Electric Vehicle (EV) application, where 5 represent the lowest weigh, highest efficiency and lowest cost respectively:[15]

Table I. Comparison of motors used for e-vehicles

Index	DC motor drive	Induction Motor drive	PM BLDC motor drive	SRM drive
Weight	2	4	4.5	5
Efficiency	2	4	5	4.5
Cost	5	4	3	4
Total	9	12	12.5	13.5

Table I indicates that Switched Reluctance Motor (SRM) drives are best choice for electric vehicles, if we consider three factors i.e. weight, efficiency and cost. Advantages of SRM drives are as follow:

- Lowest material cost.[1]
- Simple construction [2]
- Lower production cost. [2]
- Higher robustness. [2]
- Lower maintenance requirement. [2]
- Large starting torque. [3,4]
- Wide speed range. [3,4]
- High reliability. [3,4]
- Less weight.[16]
- Improves temperature profile of the motor.[16]

Thus SRM is capable of replacing BLDC motor for EV application. Literature review proved that SRM is fulfilling most of the motor characteristics needed for electric vehicle application and also having benefits of magnet less construction, but still it is having very limited use for electric vehicle purpose. More research on SRM drive system will develop good option for existing drive system used in electric vehicles.

III. ELECTRIC RIKSHAW:

Electric rikshaw is most popular public transportation system in India and mainly owned by the lower middle-class people. Figure1shows construction and major components of e-rikshaw.

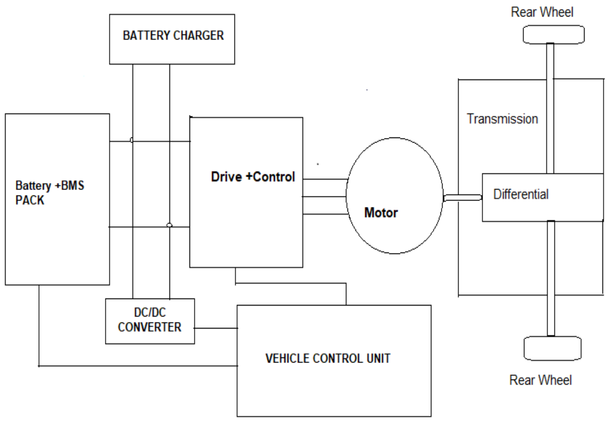

Fig. 1. Construction and major parts of e-rikshaw

One of the major problems faced by the e-rickshaw is weak performance of the motor & controller. Motors currently used in e-rickshaws are not compatible to produce the sufficient torque to cope up with load requirements and draws significantly high current and causes failure of the controller. Most of the e-rikshaws are fitted with BLDC (Brush less DC) motors which are imported from China and these motors are having requirement of rare-earth magnet. There is need of good alternative motor with better performance and magnet-less construction.

IV. SRM DRIVE FOR E-RIKSHAW

Switched Reluctance Motor (SRM) drive for e-rikshaw has more potential to become more popular because of following advantages:

1) Benefits to the consumers:
- More consumers will be attracted to buy e-rikshaws which will start mass production by manufactures.
- Mass production by manufacturers will help to provide e-rikshaws with reasonable price in market.
- Consumers will get satisfied by good performance of e-rikshaws.
- Reduced import of rare-earth magnet from China.

2) Benefits to manufacturers:
- Mass production of E-vehicles is possible because of increased demand by consumers which will provide better cost options for existing e-rikshaws.
- Possible to reduce cost of e-rikshaws.
- Availability of alternative to existing drive system with enhanced performance.
- Reduction in cost of magnets and reduced dependency on China for availability of magnets.
- Reduced dependency on china made motors.

3)Benefits to government/society:
- Positive response to governments FAME scheme.
- Clean environment.
- Better health of peoples.
- Reduced import of rare-earth magnet from China.
- Positive response for Make in India scheme.

V. SIZE SELECTION OF SRM FOR E-RIKSHAW

Size of motor is selected for E-rikshaw with following specification :[6,9,10,11,12]

Table II. Specifications of e-rikshaw

PARAMETERS	SYMBOL	VALUES
Mass of Vehicle (Kg) (Kerb weight)	M_v	270 Kg
Mass of Passenger	M_p	250 Kg
Frontal Area	A_{front}	2.223 m^2
Coefficient of Rolling Resistance	C_{rr}	0.01
Drag Coefficient	C_{drag}	0.034
Top Seed	$V_{vehicle}$	25Km/Hr
Radius of Wheel (m)	R_w	0.1524
Density of Air	D_{air}	1.2 Kg/m^3
Radius of wheel	R_w	0.2365 m
Rational Inertia Compensation Factor	R_i	1.02

Other assumptions:

Acceleration Due to Gravity(g)=9.81m/s^2
V_{wind}=Wind velocity component=2m/s
r_i=Rotational inertia compensation factor = 1.02
a=Acceleration/Deceleration Rate=0.9
g=Acceleration due to Gravity=9.81m/s^2

<u>1.Rolling Resistance Force (F_{RR})</u>

$$F_{RR} = (M_V + M_P) \times g \times cos\emptyset \ \times C_{rr}$$
$$= 51.012\ N \quad (Considering\ \emptyset = 0)$$

<u>2.Aerodynamic Drag Force(F_{AD})</u>

$$F_{AD} = 1/2 \times D_{air} \times C_{drag} \times \ A_{front} \times (V_{vehicle} \pm V_{wind})$$
$$= 0.406\ N$$

<u>3.Inertia Force (F_I)</u>

$$F_I = (M_V \times R_i + M_P) \times a$$
$$= 475.86\ N$$

<u>4.Force due to grading</u>

$$F_g = (M_V + M_P) \times g \times sin\emptyset$$

Let us consider the e-rikshaw runs on flat road.

$Hence, \emptyset = 0$

$$F_g = 0\ N$$

5.<u>Tractive Power</u>

$$P_{total} = \int_0^T (F_{RR} + F_{AD} + F_I) V_{vehicle} dt$$
$$= \ 3.64\ kW$$

<u>6.Transmission Power:</u>

$$M_{power} = \ P_{total} / \ \eta$$
$$= 4.282\ kW$$

Thus, from above calculations, we can select 4.5 kW rated motor for e-rikshaw of given specification.

7.Tractive torque:

$$T_{total} = \int_0^T (F_{RR} + F_{AD} + F_I)\, Rw\, dt$$
$$= 79.89\ N - m.$$

Thus, as per theoretical calculations, 4.5 kW Switched Reluctance Motor proposed for selected e-rikshaw application.

VI. SOFTWARES USED FOR MOTOR DESIGN

Currently various software's are used for analysis of drive system used in electric vehicle. Few of them are listed below:

- Infolytica Magnet software.[5]
- ANSYS software (RMXprt).[6]
- MATLAB (Simulink) software [3,7]
- 2D FEM software Ansoft Maxwell.[8]

VII. CONVERTERS FOR SRM DRIVE

Conventional Switched Reluctance Motor (SRM) drive consist of the Switched Reluctance Motor (SRM), power inverter, control circuitry and sensors (voltage, current and position sensors) etc.[13]There are various types of converters used for Switched Reluctance Motor i.e. Asymmetric, Miller, C-dump, R-dump, Bifilar, Buck-Boost, Resonant, etc. The standard type of converter used for modeling of SRM is the Asymmetric bridge type converter.[14]

VIII. CONTROLLER OF SRM DRIVE

There are various types of controllers which are used for speed control of SRM. Main types of controller include PI (Proportional Integral) controller, Hysteresis type, Pulse Width Modulation (PWM), Self- Tuning Adaptive Control, Fuzzy-PI Control, ANFIS (Adaptive Neuro-Fuzzy Inference System) Control.[14]

IX. ANALYSIS OF SRM USING ANSYS MAXWELL SOFTWARE.

Switched Reluctance Motor of following specification is designed and analyzed using ANSYS Maxwell RMXprt tool.
Specifications:
8/6 pole, 48V, 550W, 3500 rpm Switched Reluctance Motor

SRM drive circuit:

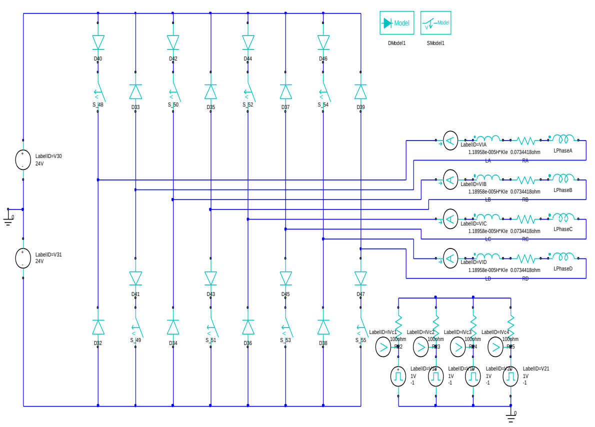

Fig. 2.SRM drive circuit

Fig. 2. shows the SRM drive circuit used for simulation of 8/6 pole 48V,550W,3500 rpm motor using ANSYS Maxwell RMXprt tool. Standard type of converter used for modeling SRM is asymmetric bridge converter.

Machine design :

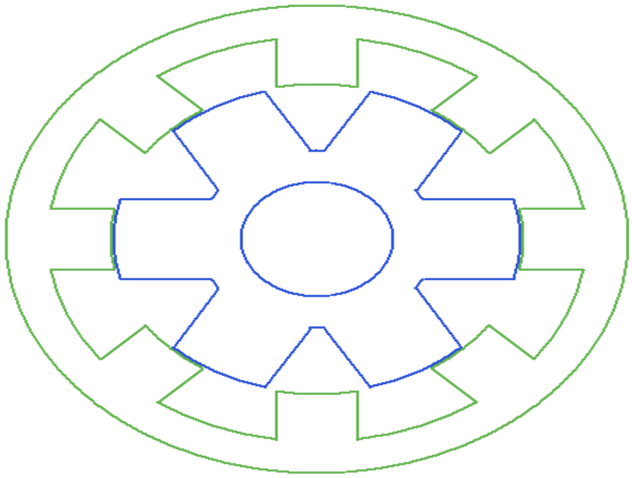

Fig. 3. Machine design of 8/6 SRM

Fig. 3 shows the geometry of machine design using RMXprt tool of ANSYS Maxwell software for 48V,550W,3500 rpm motor. Number of stator poles are 8 and number of rotor poles are 6.

Input Data

Input data for RMXprt design of 48V, 550W, 3500 rpm motor is given below:
Rated Output Power (kW):0.55
Rated Voltage (V): 48
Given Rated Speed (rpm): 3500
Frictional Loss (W): 8
Windage Loss (W): 4
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): 0.5
Total Diode Voltage Drop (V): 0.5
Operating Temperature (C): 75

Motor performance

Simulation results are discussed below:

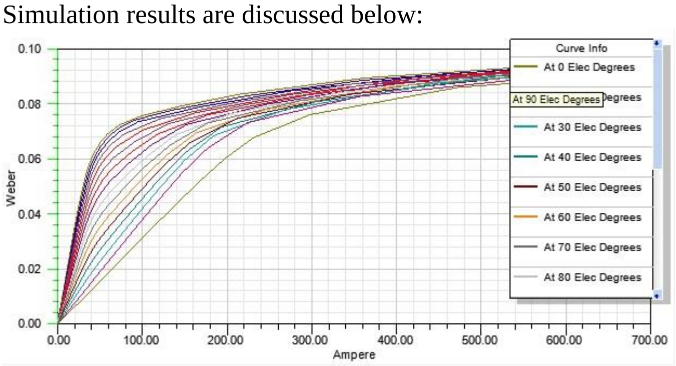

Fig. 4. Flux linkage vs Current at different positions

Fig. 4. shows the Flux linkage vs Current at various positions for 48V,550W,3500 rpm motor as per result analysis using RMXprt tool .

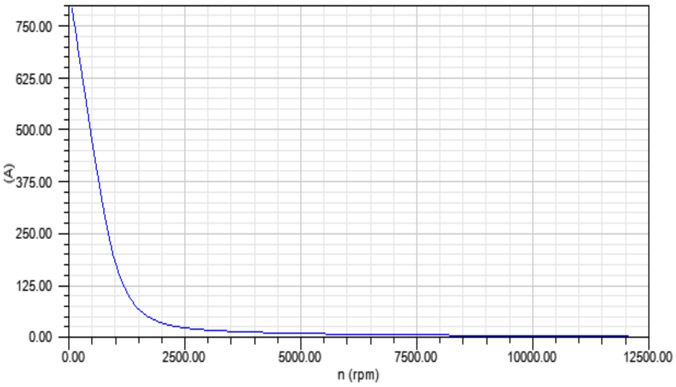

Fig.5. Input DC current vs Speed characteristic

Fig.5. shows the Input DC current vs Speed characteristic for 48V,550W,3500 rpm motor as per result analysis using RMXprt tool.

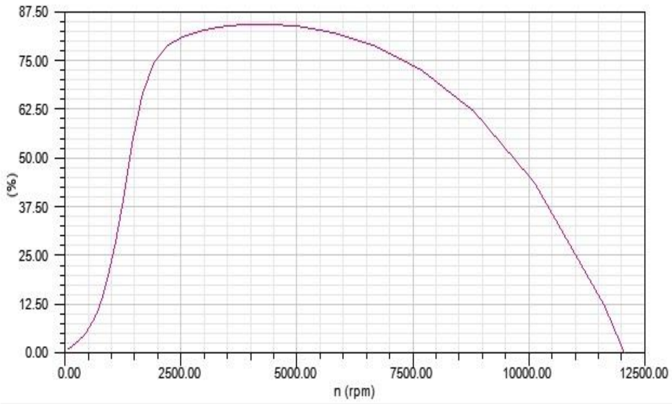

Fig. 6. Efficiency vs Speed characteristic

Fig.6.shows the Efficiency vs Speed characteristic for 48V,550W,3500 rpm motor as per result analysis using RMXprt tool. At rated speed of 3500 rpm ,efficiency is 84.22%.

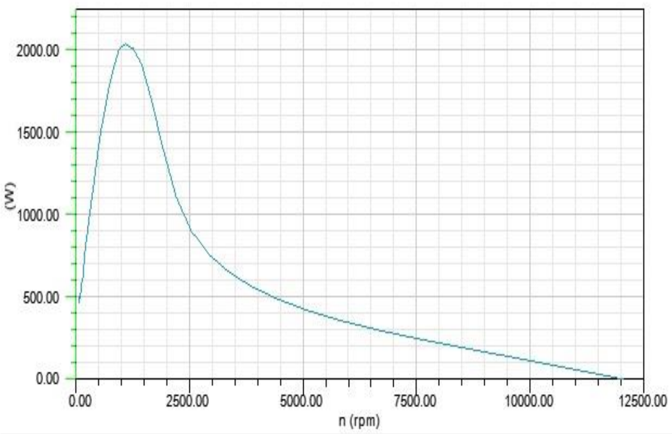

Fig. 7. Output power vs Speed

Fig. 7 shows the Output power vs Speed characteristic for 48V,550W,3500 rpm motor as per result analysis using RMXprt tool.

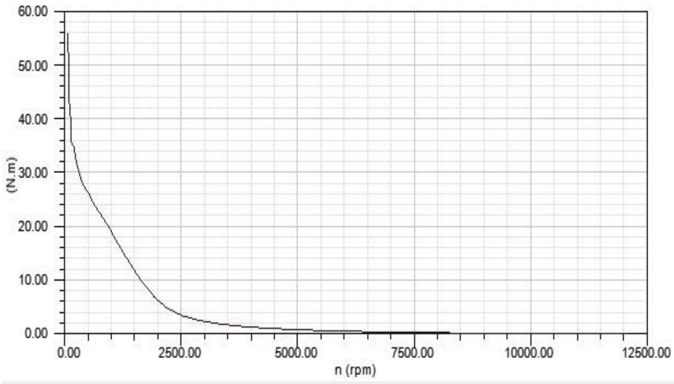

Fig. 8. Output torque vs Speed characteristic

Fig. 8 shows the Output torque vs Speed characteristic for 48V,550W,3500 rpm motor as per result analysis using RMXprt tool. Required torque of 1.3N-m is obtained at 3000 rpm speed.

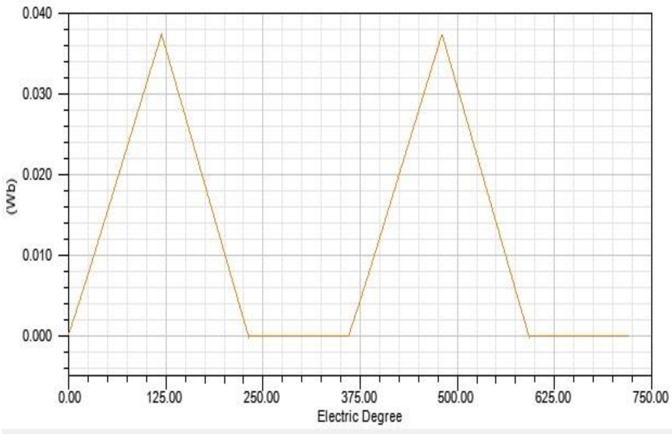

Fig. 9. Flux Linkage characteristic

Fig.9.shows the flux linkage characteristic for 48V,550W,3500 rpm motor as per result analysis using RMXprt tool. Flux linkage is zero at unaligned position of rotor and stator poles.

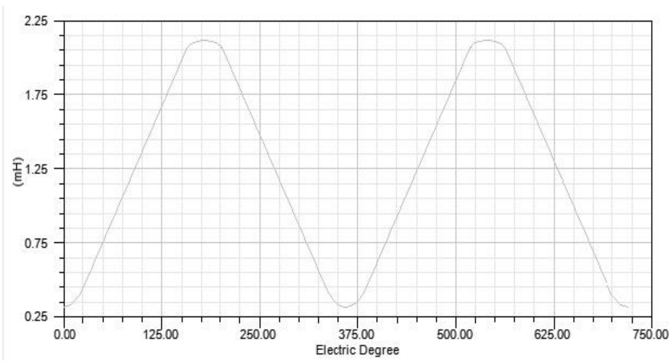

Fig.10. Air Gap Inductance characteristic

Fig. 10 shows the air gap inductance characteristic for 48V,550W,3500 rpm motor as per result analysis using RMXprt tool.

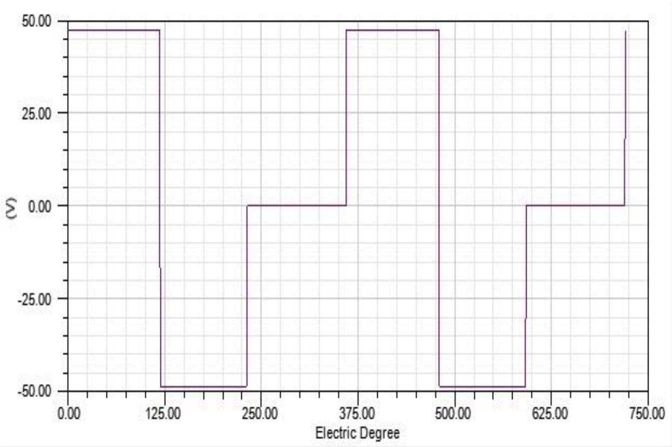

Fig. 11. Phase Voltage

Fig.11 shows the phase voltage characteristic for 48V,550W,3500 rpm motor as per result analysis using RMXprt tool.

Material consumption :

Material consumption data for 48V, 550W, 3500 rpm motor (as per result analysis using RMXprt tool) is as below:

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): 1.04415
Stator Core Steel Weight (kg): 2.29736
Rotor Core Steel Weight (kg): 1.27536
Total Net Weight (kg): 4.61687
Stator Core Steel Consumption (kg): 4.92722
Rotor Core Steel Consumption (kg): 2.10761

Full load operation data:

Full load operation data for 48V, 550W, 3500 rpm motor (as per result analysis using RMXprt tool) is as below:

Input DC Current (A): 13.5569
Phase RMS Current (A): 14.9976
Phase Current Density (A/mm^2):7.2048
Frictional and Windage Loss (W):15.0141
Iron-Core Loss (W): 0.00252911
Winding Copper Loss (W):66.0761
Diode Loss (W): 7.38337
Transistor Loss (W): 14.1608
Total Loss (W): 102.637
Output Power (W): 548.095
Input Power (W): 650.731
Efficiency (%): 84.2274
Rated Speed (rpm): 3985.24
Rated Torque (N.m): 1.31333
Flux Linkage (Wb): 0.037328
Stator-Pole Flux Density (Tesla): 1.03286
Stator-Yoke Flux Density (Tesla): 0.839585
Rotor-Pole Flux Density (Tesla): 0.789059
Rotor-Yoke Flux Density (Tesla): 0.314844
Coil Length per Turn (mm): 176.126
Winding Resistance in Phase (ohm):0.0734418
Winding Resistance at 20C (ohm): 0.0604118
Winding Leakage Inductance (mH):0.03707
Iron-Core-Loss Resistance (ohm): 2.17664e+06
Frequency of Phase Current (Hz): 398.524
Maximum Output Power (W): 2033.4

Maxwell 2D design

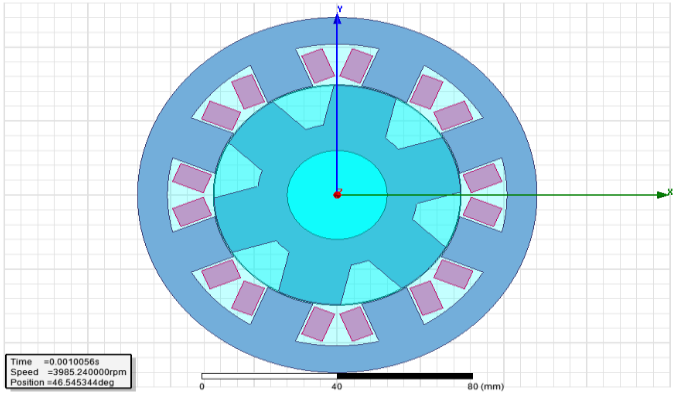

Fig. 12. Maxwell 2D design for 8/6 SRM

Fig. l2 shows the full maxwell 2D design of 48V, 550W, 3500 rpm SRM obtained by ANSY Maxwell software.

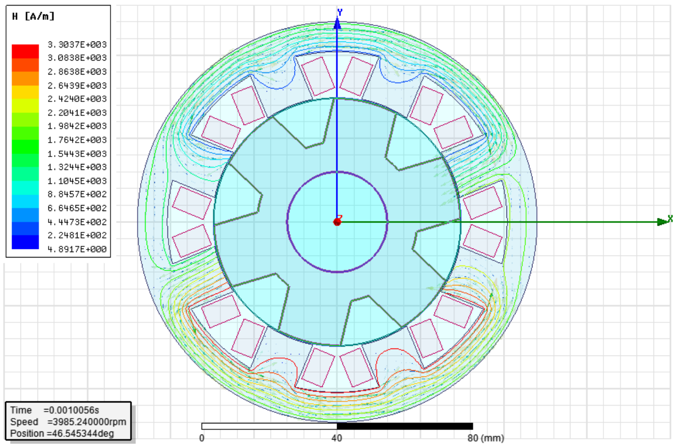

Fig. 13. Variation of magnetic field strength

Fig. 13 shows the variation of magnetic flux strength for 48V,550W,3500 rpm SRM obtained by simulation usingANSY Maxwell software. Colour code shows variation of magnetic filed strength at different part of motor.

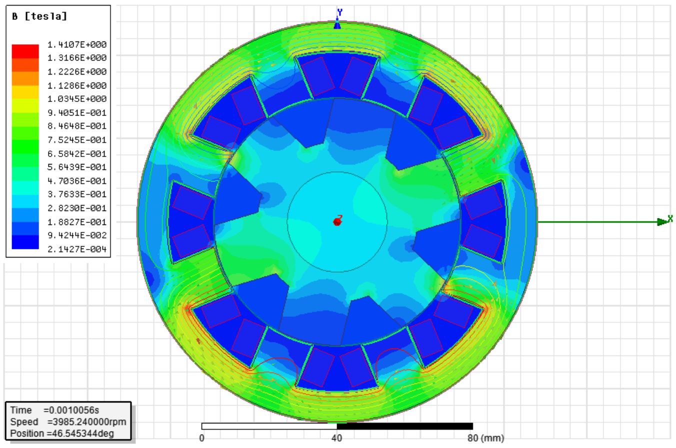

Fig.14. Variation of magnetic flux density

Fig. 14 shows the variation of magnetic flux density for 48V,550W,3500 rpm SRM obtained by simulation using ANSY Maxwell software. Variation of magnetic field strength is shown by different colours..

Maxwell 3D design

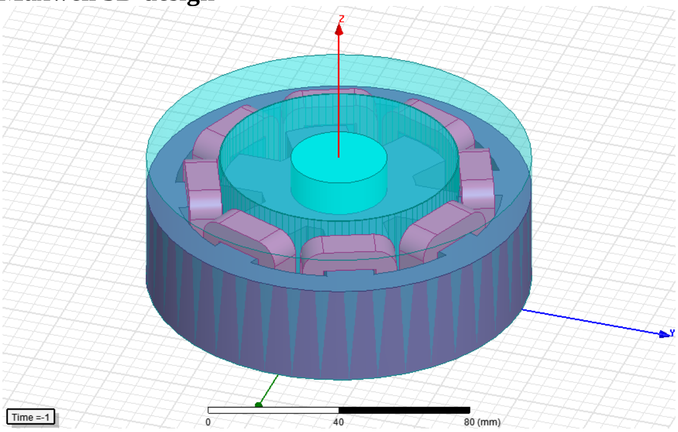

Fig. 15. Maxwell 3D design for 8/6 SRM

Fig.15 shows the full maxwell 3D design of 48V, 550W, 3500 rpm SRM obtained by ANSY Maxwell software.

Thus 48V,8/6 pole,550 Watt SRM design completed with RMXprt tool and also 2D as well as 3D simulation completed. Geometry shows that SRM construction is simple as compared to BLDC motor. SRM design results shows 84.22% efficiency,1.31 N-m rated torque and less material consumption because of magnet-less construction. More trials with different dimensions can provide optimized design with increased efficiency and better torque.

X. Design optimization:

There are various factors need to be consider for design optimization and performance enhancement of Switched Reluctance Motor for EV application. Effect of stack length, stacking factor and type of steel material discussed below:

10.1 Effect of stack length:

Stack length (mm)	% Efficiency	Total loss (W)	Rated torque (Nm)	Speed (RPM)
50	84.24	102.854	1.03	5084.56
55	84.32	101.708	1.12	4677.48
60	84.28	102.166	1.22	4305.19
65	84.22	103.264	1.31	3991.64
70	83.75	106.373	1.32	3952.95
75	83.34	109.673	1.34	3917.88
80	82.94	112.998	1.35	3884.24
85	82.52	116.451	1.36	3851.00
90	82.11	119.744	1.37	3824.15
95	81.68	123.13	1.38	3798.4
100	81.27	126.518	1.389	3773.32

From analysis it is observed that with increase in stack length, efficiency and speed goes on decreasing and rated torque goes on increasing. Stack length of 65 mm selected for detailed analysis work.

10.2 Effect of stacking factor: Stack length=65 mm

Stacking factor	% Efficiency	Total loss (W)	Rated torque (Nm)	Speed (RPM)
0.70	83.41	108.202	1.25	4145.94
0.75	83.63	106.831	1.2756	4085.28
0.80	83.79	405.842	1.29	4043.06
0.85	83.92	104.843	1.30	4019.71
0.90	84.03	103.998	1.305	4004
0.95	84.22	103.264	1.31	3991.64

From simulation and analysis it is observed that as stacking factor increases efficiency and rated torque increases and speed decreases. Stacking factor 0.95 selected for detailed analysis work.

10.3 Effect of material: (Stacking factor=0.95 and stack length=65 mm)

Steel type material	% Efficiency	Total loss (W)	Rated torque (Nm)	Speed (RPM)
Steel_1010	84.22	103.264	1.31	3991.64
Steel_1010_2DSF0.950	83.428	108.036	1.25	4152.3
Steel_1010_3DSF0.950	83.55	107.255	1.27	4099.95
Steel_1008	85.2348	94.5156	1.27	4097.11

Above table represents effect of different types of steel material (used for stator and rotor) on machine performance. Steel_1010 material selected for detailed analysis work.

XI. Conclusion

Switched Reluctance Motor is better option for electric rikshaw application. Paper included discussion for selection of Switched Reluctance Motor based drive system with its advantages for e-rikshaw application. Paper also present mathematical calculations regarding selection of Size of the motor for e-rikshaw application.

The proposed Switched Reluctance Motor is having simple construction, reduced use of rare-earth magnet, easy maintenance and better performance. Motor performance is analyzed by using RMxprt tool and results are discussed. As per the finite element analysis and RMXprt design, rating of the prototype SRM is 48V, 550Watt, 8/6 pole,3500 rpm, rated torque 1.31 N-m and efficiency is 84.22%. Design of SRM and its optimization along with Maxwell 2D & 3D analysis results discussed in the paper.

Motor efficiency can be increased by further analysis. The prototype motor is to be fabricated and tested for the e-rikshaw application.

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