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Development and performance analysis of switched reluctance motor for E-rickshaw

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Abstract

Objectives: The main purpose of this study is to investigate switched reluctance motor for E-rickshaw propulsion system. **Methods:** The paper gives details of Literature review of current system incorporated in electric three wheeled propulsion, selection process of SRM, the design procedure of 8/6, 48V, 0.5 kW, 2000 rpm Switched reluctance motor for E-Rickshaw. Design validation and performance estimation is done by virtue of finite element analysis (FEA) tool using Ansys Maxwell Software. **Findings:** In this present work we found that it is possible to deploy SRM instead of current existing brushless direct current motors (BLDC) and PMSM (Permanent magnet synchronous motors) which are used in power train of electric three wheelers. Incorporating SRM would boost to promote “MAKE IN INDIA” and thus the country would become independent in electric vehicle market, hardware of the proposed SRM is also developed and tested. **Novelty:** The work done with investigation of SRM for E-rickshaw has not been studied until now although it possesses various advantages over existing system like high reliability and wide torque-speed range which is the basic requirement of propulsion motor in electric vehicles. SRM also provides several benefits like simple construction, high speed, resilience and good fault tolerance capability as all phases function independently.

Keywords: ERickshaw; Brushless direct current motors; finite element analysis; Ansys Maxwell Software; Switched reluctance motor; Make in India

1 Introduction

Now a days there is a proliferation in the sector of electrification of vehicles especially 3-Wheelers as it is the most efficient mode of transport for “Last-Mile connectivity”. Selection of electric motor is a very important parameter in an E-Rickshaw. Key E-Rickshaw variants of various regional and international players like Bajaj, Mahindra, Kinetic Green, KAL etc. are using BLDC (Brushless direct current) and PMSM (Permanent magnets synchronous motors) motors ranging from 1kW to 5kW for its propulsion⁽¹⁾. These motors are having high efficiency, low torque ripple, less noise

and vibrations⁽²⁾. However, less availability and high cost of rare-earthed magnets used in them make them an unsuitable long term option for E-Rickshaws. Considering the long term productivity and mass manufacturing of E-Rickshaws it is necessary to find a low cost, highly reliable and high power density motor. Currently SRM is looking promising as an alternative to BLDC and PMSM as it offers various advantages like small size, low cost, low inertia rotor, high reliability, No rotor loss, robust, easy cooling, high pickup and high operating speed etc.⁽³⁾. SRM is also eco-friendly as it involves no use of rare-earthed magnets and it reduces the dependency on the nations producing them.⁽⁴⁾. After studying various kind of literature on E-Rickshaw, one major research gap was recognized. E-rickshaws employing switched reluctance motor are not seen in the market. It is perceived that E-Rickshaw application incorporating a SRM will be seen commonly in the near future. There is a dire need in the market to progress in electrification of three-wheeler segments. Thus, 500 Watt switched reluctance motor prototype analysis is carried out to propose an ever important alternative to the existing motors for E-Rickshaw application. This prototype is developed and studied by taking into account of a L5 category E-rickshaw.

The principle of operation of switched reluctance motor is to produce electromagnetic torque by varying magnetic reluctance. SRM is a doubly salient machine. It is also a single excited machine⁽⁵⁾. The switched reluctance motor works best when saliency ratio (L_d/L_q) is maximum. L_d = inductance in d-axis (here rotor is aligned with the poles) and L_q = inductance in q-axis (here rotor is aligned with the gaps). In SRM, the stator poles carry the winding wherein the rotor is constructed of steel stampings. Thus, there is no rotor loss due to absence of winding.⁽⁶⁾ It is an electronically switched motor i.e. it requires a SRD (switched reluctance drive) for its operation. When one of the stator poles (N_s) is excited, nearby rotor pole (N_r) tries to achieve the least reluctance position i.e. the output torque because of current flow in phase winding tends to shift the rotor in such a way so that it guides to curtailment in reluctance and eventually rise in inductance.⁽⁷⁾

Torque produced by machine when magnetic saturation neglected is given by:

$$T = \frac{i^2}{2} \frac{dL}{d\theta} \quad (1)$$

From above equation (1) it can be understood that torque is independent on polarity of stator current and can only be generated when inductance changes. Also, if N_s and N_r are aligned then starting torque could not be produced. Therefore, they have dissimilar number of stator, rotor poles. In SRM, the phase winding is connected in series with the switch. Thus after any occurrence of fault in converter circuit, the current rise can be restricted by an inductance of winding. Therefore, short time is required to operate protective relaying to detach the circuit. And in comparison with other motors, SRM has independent phases so, if a fault occurs to any of its phases, the motor and its drive are capable to carry on with the operation but with decreased power output.⁽⁸⁾ But still SRM has got some disadvantages like high torque ripple, high noise, vibrations and necessity of position sensor. Hence, it requires better, modern control strategy than AC and DC motor drives.⁽⁹⁾. Detailed analysis of SRM design procedure is carried out and research gap is addressed in this paper. This paper is arranged in following way: section II focuses on modeling of SRM, section III discusses the selection of switched reluctance motor, section IV deals with design approach of SRM for E-rickshaw, section V includes simulation results and section VI has concluding remarks.

2 Modeling of SRM

The equivalent circuit of single phase switched reluctance motor is shown in Figure 1

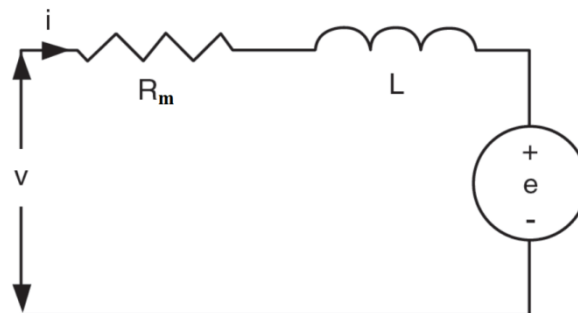


Fig 1. Single phase equivalent circuit of SR motor

A simple equivalent circuit for the SRM can be procured by ignoring the mutual inductance between the phases as follows. The voltage applied to a phase is equal to the sum of the resistive voltage drop and the rate of the flux linkages. The phase voltage

equation is given as:

$$V = R_m i + \frac{d\lambda(\theta, i)}{dt} \quad (2)$$

$$\begin{aligned} V &= R_{mi} + \frac{d(L(\theta, i)i)}{dt} = R_{mi} + L(\theta, i) \frac{di}{dt} + \frac{d\theta}{dt} \cdot \frac{dL(\theta, i)}{d\theta} \\ &= R_{mi} + L(\theta, i) \frac{di}{dt} + \frac{dL(\theta, i)}{d\theta} \omega_m i \end{aligned} \quad (3)$$

Where,

R_m = Resistance per phase

L = Inductance which is dependent on rotor position and phase current

λ = Flux linkage

$\lambda = L(\theta, i)i$

In above equation (3), the term on right side shows the induced emf & resistive, inductive voltage drop,

'e' is EMF induced,

$e = \frac{dL(\theta, i)}{d\theta} \omega_m i = K_b = \omega_m i$ where,

$K_b = \frac{dL(\theta, i)}{d\theta}$

Input power is as follows,

$$P_i = v_i = R_m i^2 + i^2 \frac{dL(\theta, i)}{dt} + L(\theta, i) i \frac{di}{dt} \quad (4)$$

Here, the last term is physically not interpretable; to draw a meaningful inference, it may be cast in terms of known variables as in the following:

$$\frac{d}{dt} \left(\frac{1}{2} L(\theta, i) i^2 \right) = L(\theta, i) i \frac{di}{dt} + \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt} \quad (5)$$

From equation 4 and 5 we obtain,

$$P_i = R_m i^2 + \frac{d}{dt} \left(\frac{1}{2} L(\theta, i) i^2 \right) + \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt}$$

Where, P_i is input instantaneous power

The power of air gap is,

$$P_a = \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt} = \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt} \frac{d\theta}{dt} = \frac{1}{2} i^2 \frac{dL(\theta, i)}{d\theta} \omega_m$$

The air gap power (P) is nothing but a product of torque (T) and rotor speed.

$$P_a = \omega_m * T_e$$

Therefore, the torque equation is expressed as,

$$T = \frac{i^2}{2} \frac{dL(\theta, i)}{d\theta}$$

This is the method to develop switched reluctance motor.

3 Selection of Switched Reluctance Motor

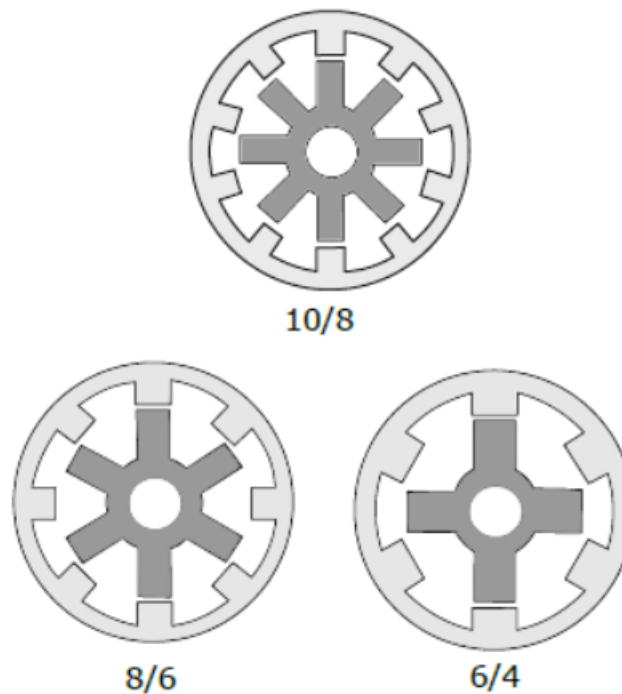


Fig 2. Common SRM topologies used

SRM in which (N_s) > (N_r) is often used. These three topologies (10/8, 8/6, 6/4) are widely used for different applications.⁽⁵⁾ In all topologies two opposite poles constitutes one phase. Eg. 10/8 topology has 5 phases whereas 8/6 SRM has 4 phases and so on. For electric vehicle application mainly 10/8 and 8/6 topology is used instead of 6/4.⁽¹⁰⁾

10/8 topology is costly as it requires more number of switches in its drive wherein 8/6 has a problem of high torque ripple. This problem may eventually be eliminated with proper tuning of motor. SRM topology is selected on the basis of application.⁽¹¹⁾

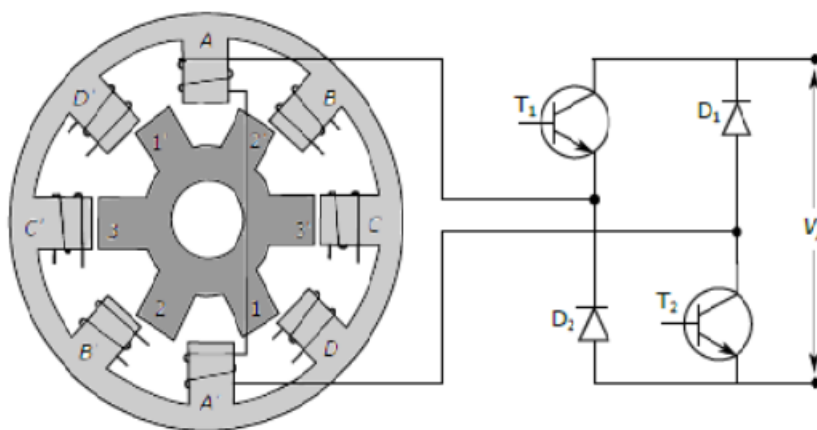


Fig 3. Conventional converter of SRD

Figure 3 shows the most popular switched reluctance drive which uses Conventional converter (also called classic or Asymmetric bridge converter). Other Power electronic converters (PEC) are n+1 PEC, C-dump PEC etc.⁽¹²⁾. SRM topology and drive system can not only be deployed in three wheeled vehicle but also two and four wheeler segment can use for its propulsion system.

3.1 Factors for selecting motor for E-rickshaw

1. Good power density
2. Fast torque response
3. Low weight
4. Reasonable cost
5. Fault tolerant

Currently, SRM is being used the electric and hybrid four wheelers but implementation of SRM in electric three vehicle segment has not been tested as around 90 % of E-rickshaws of various regional and international manufacturers are deploying BLDC and PMSM in their variants.⁽¹³⁾ The motor rating ranges from 1kW to 5kW for three wheeler traction.⁽¹⁴⁾

Hence, this research gap of incorporating SRM in E-rickshaw has been addressed in this article. For analysis purpose, a prototype of 500 W switched reluctance motor is selected and designing procedure, its simulation and hardware results is discussed in upcoming sections.

4 Design Approach of SRM for E-rickshaw

4.1 Initial parameters

1. Rated output power = 0.5 kW
2. Rated voltage = 48 V
3. Rated speed = 2000 rpm
4. Poles ratio = 8/6
5. Peak current = 17 A

4.2 Mathematical design procedure

After fixing the initial parameters the various motor variables which are an integral part in designing a motor can be found out as discussed below:

- First step is to find Torque required by the motor,

$$(T_{req.}) = \frac{P_{kW}}{2\pi(N \div 60)} = 2.38 \text{ N-m} \quad (6)$$

The machine will be designed for a standard Frame size = 63 mm given according to IEC recommendations.

- Outer diameter of stator can be given by,

$$D_0 = (\text{Frame size} - 3) * 2 = 120 \text{ mm}$$

- Number of stator poles (N_s) = 8
- Number of rotor poles (N_r) = 6

A standard configuration of SRM i.e. $N_s = 8$ and $N_r = 6$ is selected as they possesses to be the most efficient and economical configuration for electric vehicle application.

After examining the feasible triangle the angles of stator pole, rotor pole is predicted.

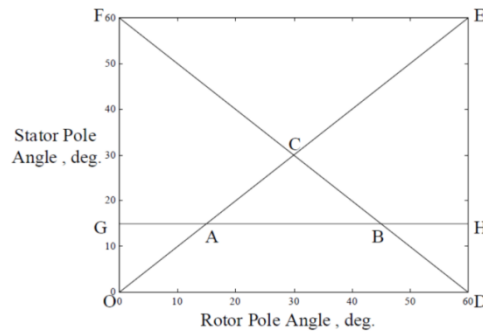


Fig 4. Feasible triangle for 8/6 SRM

The conditions which need to be followed while determining the stator and rotor pole angles are

- $\frac{2\pi}{N_r} - \beta_r > \beta_s$
- $\frac{2\pi}{6} > \beta_s + \beta_r$
- $\beta_s < \varepsilon$

If these conditions are not met, it may result in cogging of motor or low torque production.

Thus, considering the above mentioned limitations and avoiding the unwanted results the stator pole angle and rotor pole angle is predicted.

- Stator pole arc (β_s) = 22°
- Rotor pole arc (β_r) = 24°
- Stroke angle

$$(\varepsilon) = \frac{2\pi}{\frac{N_s}{2} * N_r} = 15^\circ \quad (8)$$

- Bore diameter is initially selected equal to Frame size i.e. $D = 63$ mm
- Stack length (L) is taken 100 mm
The stack length (L_d)/Rotor outer radius (D_{ro}) ratio is generally in between 0.4-3.0. ⁽¹⁵⁾
- Shaft diameter is calculated according to IEC (International Electro-technical Commission) (d_{sh}) = 11 mm
- Air gap (g) = 0.5 mm
Air gap between stator and rotor should be uniform and very small. ⁽¹⁶⁾
- Stator pole area (A_s) can be obtained as,

$$A_s = \frac{D}{2} L \beta_s = 1.2095 * 10^{-3} \text{ m}^2 \quad (9)$$

- Stator pole flux (ϕ) is specified as,

$$\Phi = B_s * A_s = 1.9956 * 10^{-3} \text{ mWb} \quad (10)$$

- The flux in the yoke (ϕ_y) is stated as,

$$\phi_y = \frac{\Phi}{2} = \frac{B_s * A_s}{2} = 9.978 * 10^{-4} \text{ mWb} \quad (11)$$

- Thus, yoke area (A_y) can be noted as,

$$A_y = A_s = 1.2095 * 10^{-3} \text{ m}^2 \quad (12)$$

- The back iron thickness is obtained as,

$$C = \frac{A_y}{L} = 12.095 \text{ mm} \quad (13)$$

- Height of stator pole (h_s) is estimated as,

$$h_s = \frac{D_o}{2} - C - \frac{D}{2} = 16.405 \text{ mm} \quad (14)$$

- Rotor pole area (A_r) is given by,

$$A_r = \left(\frac{D}{2} - g \right) L \beta_r = 1.2985 * 10^{-3} \text{ m}^2 \quad (15)$$

- Flux density of rotor pole (B_r) is given by,

$$B_r = \frac{B_s * A_s}{A_r} = 1.536 \text{ T} \quad (16)$$

- Rotor core area (A_{rc}) is given by,

$$A_{rc} = \frac{A_s}{1.6} = 7.559 * 10^{-4} \text{ m}^2 \quad (17)$$

- Rotor pole height (h_r) is obtained as,

$$h_r = \frac{D}{2} - g - \frac{dsh}{2} - \frac{A_{rc}}{L} = 18.19 \text{ mm} \quad (18)$$

- Air gap area can be estimated as,

$$A_g = \left(\frac{D}{2} - \frac{g}{2} \right) * \left(\frac{\beta_r + \beta_s}{2} \right) L \quad (19)$$
$$A_g = 1.254 * 10^{-3} \text{ m}^2$$

- Air gap flux density is stated by,

$$B_g = \frac{A_s * B_s}{A_g} = 1.5914 \text{ T} \quad (20)$$

- Magnetic field intensity of air gap is,

$$H_g = \frac{B_g}{4\pi * 10^{-7}} = 1266395 \frac{\text{AT}}{\text{m}} \quad (21)$$

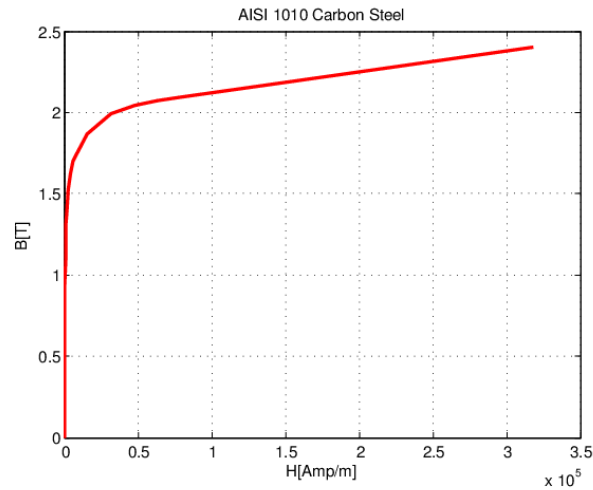


Fig 5. B-H curve of AISI Steel 1010

- $B_s = B_{max}$ is assumed initially and other parameters are calculated $B_s = 1.65 \text{ T}$
- Rotor pole flux density:

$$B_r = \frac{B_s * A_s}{A_r} = 1.536 \text{ T} \quad (22)$$

- Stator yoke flux density:

$$B_y = 0.5 * B_s = 0.825 \text{ T} \quad (23)$$

- Rotor core flux density:

$$B_{rc} = 0.8 * B_s = 1.32 \text{ T} \quad (24)$$

From the B values the corresponding H values are obtained with the help of B-H curve of the material⁽¹⁷⁾

- Copper loss (P_{Cu}) = Initial step in evaluating the copper loss requires estimation of resistance of each phase winding of SRM.

$$\therefore I_m = \left[2L + 4W_t + 2D \sin \left(\frac{\beta_s}{2} \right) * 10^{-3} \right]$$

$$R_s = \frac{0.0177 * I_m * T_{ph}}{ac} \text{ (ohm)}$$

- Cu loss at rated current –

$$(P_{Cu}) = I_p^2 * R_s \text{ (Watts)} = 120.7 \text{ Watts} \quad (25)$$

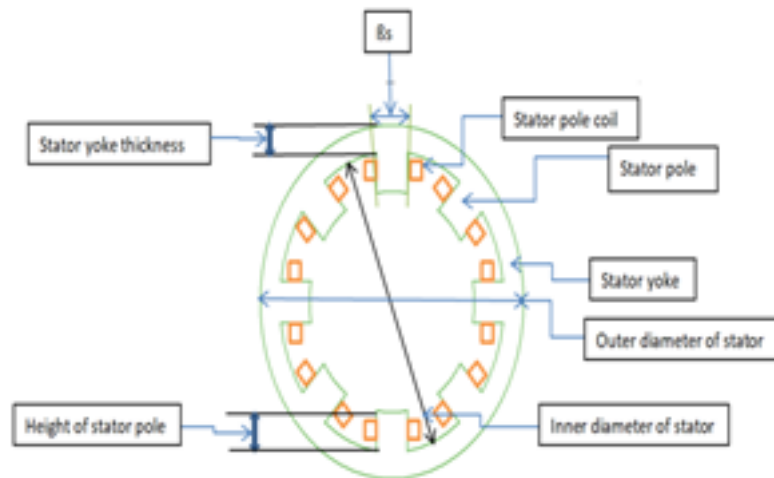


Fig 6. Stator dimensions

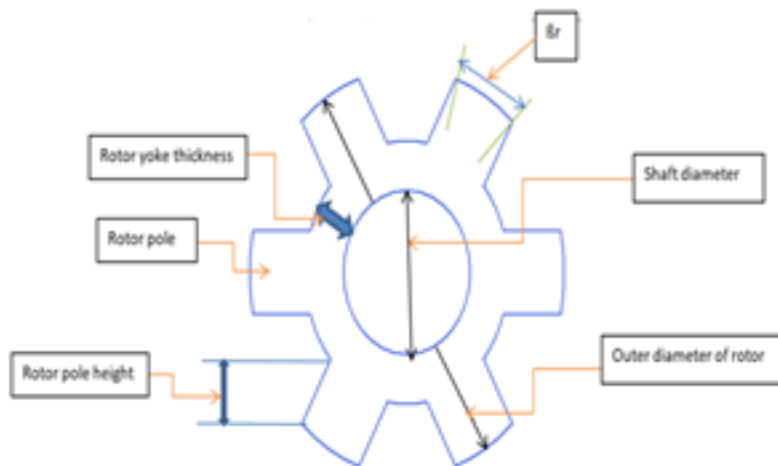


Fig 7. Rotor dimensions

Figures 6 and 7 shows the general construction and main dimensions of SRM.

Figure 6 shows the 8 pole stator schematic obtained from RMxpert tool of Ansys Maxwell software.

Figure 7 shows the 6 pole rotor schematic obtained from RMxpert tool.

Various important constructional parameters like stator yoke thickness, outer diameter of stator and rotor, position of shaft diameter etc. are visible.

5 Simulation results of SRM

The same prototype motor (500 W, 48V) is simulated with Ansys Maxwell RMxpert tool and results are discussed below.

5.1 Machine specification

The specification of selected machine is given in Table 1

Table 1. Motor main parameters

Parameter	Rating value	Unit
Rated Power	0.5	kW
Rated Voltage	48	V
Rated speed	2000	rpm
Shaft diameter	11	mm
Number of stator poles	8	-
Stacking factor of stator core	0.95	-
Stator pole angle	22	degree
Number of rotor poles	6	-
Rotor pole angle	24	degree
Air gap	0.5	mm
Stator outer diameter	120	mm
Stator inner diameter	75	mm
Length of stator core	100	mm
Rotor outer diameter	74	mm
Rotor inner diameter	30	mm
Operating temperature	75	⁰ C
Operation type	Motor	-
Mechanical load type	constant type	-
Type of material used	AISI Steel_1010	-

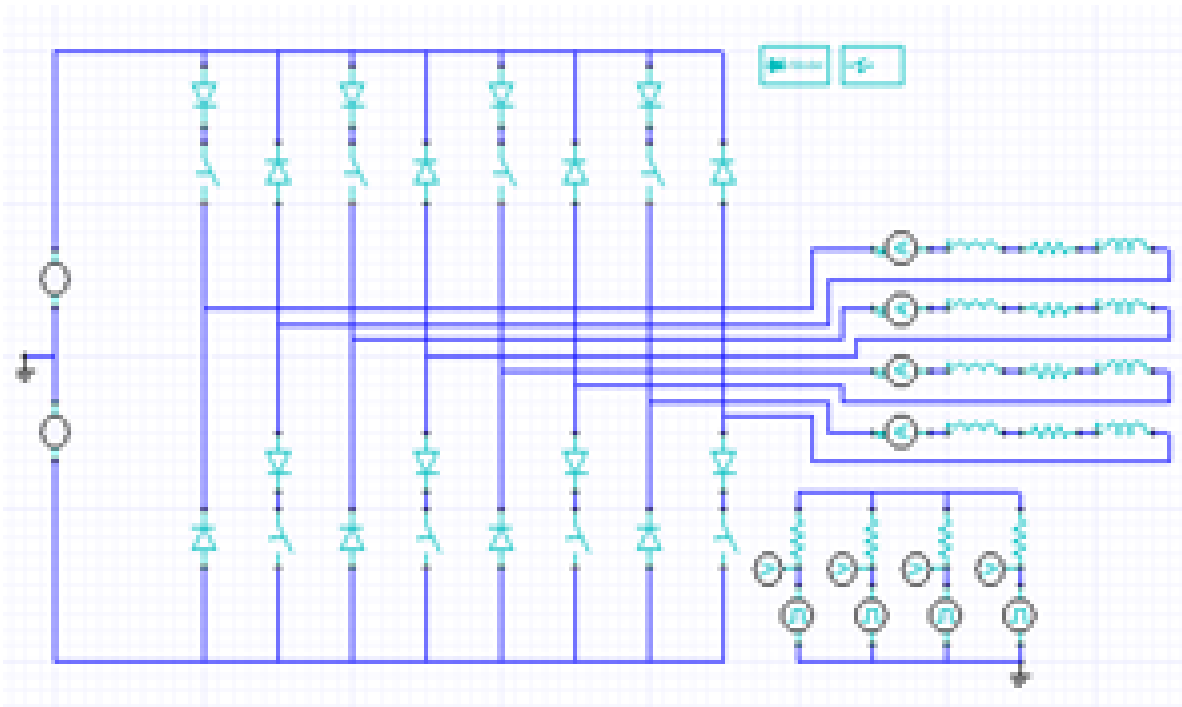


Fig 8. Drive circuit for SRM

Figure 8 shows the conventional drive circuit of SRM. It is obtained from the Ansys Maxwell software. The type of circuit used is Full voltage circuit with constant power load. Trigger pulse width is 120⁰, Diode Loss = 4.50569 Watt and transistor loss contribute to be 11.2459 Watt which is obtained from after analyzing the system.

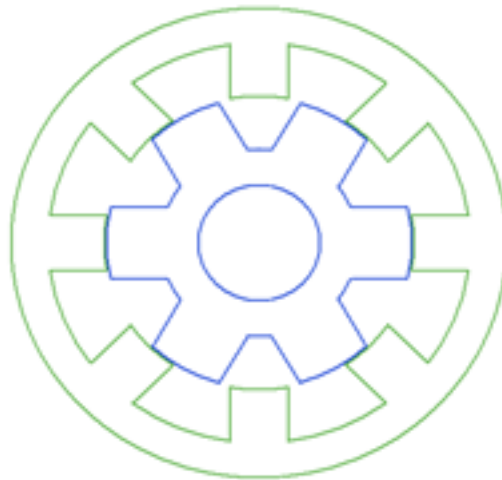


Fig 9. 8/6 SRM schematic

Figure 9 shows the schematic of 8/6 SRM obtained from Ansys maxwel RMxpert software where, $N_s = 8$ and $N_r = 6$. With the help of SRD the sequential switching and flow of current in the pairs of stator winding takes place and thus the rotor rotates continuously.

5.2 Performance analysis

Table 2. In depth examination of 6 possible stator and rotor pole combinations

Stator pole angle (degree)	Rotor pole angle (degree)	Efficiency (%)	Total loss (W)	Rated torque (Nm)	Speed (rpm)
17	19	73.047	184.306	2.45986	1939.09
18	20	73.3876	181.131	2.51789	1894.37
19	21	73.668	178.418	2.44567	1948.98
20	22	75.8625	158.77	2.42718	1963.24
21	23	75.5697	161.125	2.37198	2006.52
22	24	76.9734	149.022	2.3464	2027.36

Effect of different stator and pole angles: β_s and β_r should be properly selected in order to get desired output torque, efficiency and minimal losses. For proposed machine, it should be noted that $\beta_s = 22^\circ$ and $\beta_r = 24^\circ$, the important parameters like output torque, efficiency, losses and speed are obtained as per our requirement. (Table 2)

Table 3. Effect of stack length of various SRM parameters

Stack length	Efficiency (%)	Total loss (W)	Rated torque (Nm)	Speed (rpm)
70	75.1138	164.964	2.30844	2059.71
80	76.383	153.992	2.30431	2063.96
90	75.4647	162.357	2.46678	1933.14
100	76.9734	149.022	2.3464	2027.36
110	76.3049	154.97	2.4292	1961.78
120	75.6865	160.572	2.48616	1919.92

Effect of stack length on efficiency, torque, speed and losses. From the analysis an observation is made that for stack length 100 mm we get maximum efficiency, minimum losses and a very close value to the average torque. (Table 3)

Effect of stacking factor on SR motor parameters. Stacking factor should not exceed 1 so different stacking factor is taken and system is analysed. and thus, observed that stacking factor = 0.95 should be taken in order to get desired efficiency, less losses

and require output torque. (Table 4)

Table 4. Effect of stacking factor on SRM

Stacking factor	Efficiency (%)	Total loss (W)	Rated torque (Nm)	Speed (rpm)
0.95	76.9734	149.022	2.3464	2027.36
0.90	76.8587	149.853	2.3381	2032.73
0.85	76.7636	150.649	2.32836	2041.15
0.80	76.6518	151.617	2.31645	2051.94
0.75	76.5033	152.74	2.29573	2068.61
0.70	76.3789	153.468	2.26262	2094.35

Ansys Electronics desktop is used for finite element analysis and general data, No-load and full load operation data of 500 W SRM is obtained from the RMXprt module of the software. This designed sheet gives information of motor operation like No-load, Full load operation of motor, total consumption of material and copper consumption of winding can also be obtained.

SWITCHED RELUCTANCE MOTOR DESIGN	
File: 500.res	
GENERAL DATA	
Rated Output Power (kW):	0.5
Rated Voltage (V):	48
Given Rated Speed (rpm):	2000
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

Fig 10. General data

In general data, above specified parameters are to be keyed in by the designer while initializing the simulation.

NO-LOAD OPERATION DATA	
No-Load Speed (rpm):	6639.71
No-Load DC Current (A):	3.991
No-Load Input Power (W):	191.568
START OPERATION DATA	
Estimated Start Torque (N.m):	57.5894
Estimated Start DC Current (A):	250.682
Maximum Start Current (A):	200.564

Fig 11. No-load operation data

In Figure 11 No-load operation and start operation data is obtained.

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):	1.32945
Stator Core Steel Weight (kg):	3.5079
Rotor Core Steel Weight (kg):	1.7324
Total Net Weight (kg):	6.56975
Stator Core Steel Consumption (kg):	7.58034
Rotor Core Steel Consumption (kg):	3.24247

Fig 12. Material consumption

With the motor stator and rotor data, the material consumption is calculated and the results are as given in Figure 12 .

FULL-LOAD OPERATION DATA	
Input DC Current (A):	13.4785
Phase RMS Current (A):	11.2912
Phase Current Density (A/mm ²):	8.62575
Frictional and Windage Loss (W):	12.2816
Iron-Core Loss (W):	0.00083408
Winding Copper Loss (W):	120.776
Diode Loss (W):	4.50608
Transistor Loss (W):	11.2441
Total Loss (W):	148.808
Output Power (W):	498.158
Input Power (W):	646.966
Efficiency (%):	76.9991
Rated Speed (rpm):	2027.93
Rated Torque (N.m):	2.34577
Flux Linkage (Wb):	0.0690997
Stator-Pole Flux Density (Tesla):	0.876481
Stator-Yoke Flux Density (Tesla):	0.69671
Rotor-Pole Flux Density (Tesla):	0.815106
Rotor-Yoke Flux Density (Tesla):	0.261266
Coil Length per Turn (mm):	246.318
Winding Resistance in Phase (ohm):	0.236832
Winding Resistance at 20C (ohm):	0.194814
Winding Leakage Inductance (mH):	0.126624
Iron-Core-Loss Resistance (ohm):	6.06652e+006
Frequency of Phase Current (Hz):	202.793
Maximum Output Power (W):	1330.76

Fig 13. Full-load operation data

In Figure 13 various important parameters like output power, efficiency, rated torque etc. can be obtained.

5.3 Simulation results

Some important graphs from our proposed SRM motor (500W,48V) are obtained and discussed below.

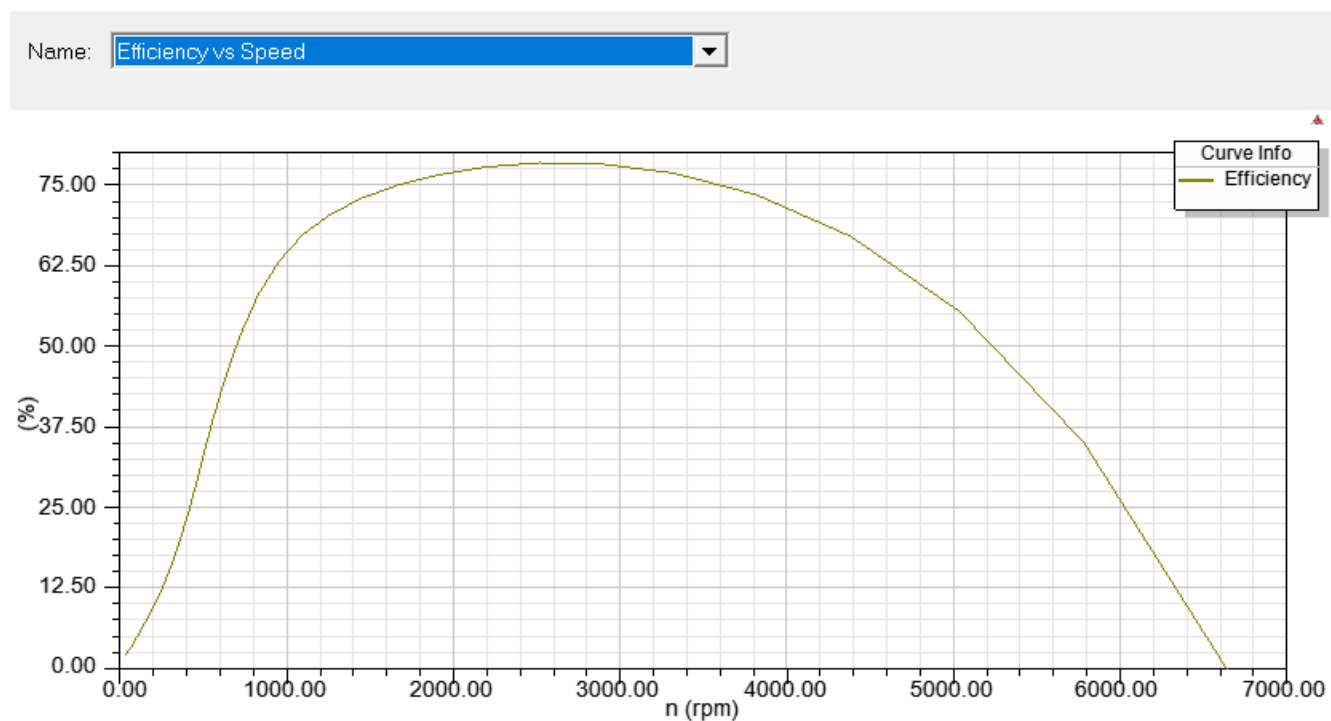


Fig 14. Efficiency vs Speed

Figure 14 shows efficiency at several speeds. At rated speed(2000rpm), obtained efficiency is 76.97%. Graph concludes that the efficiency decreases with increase in speed.

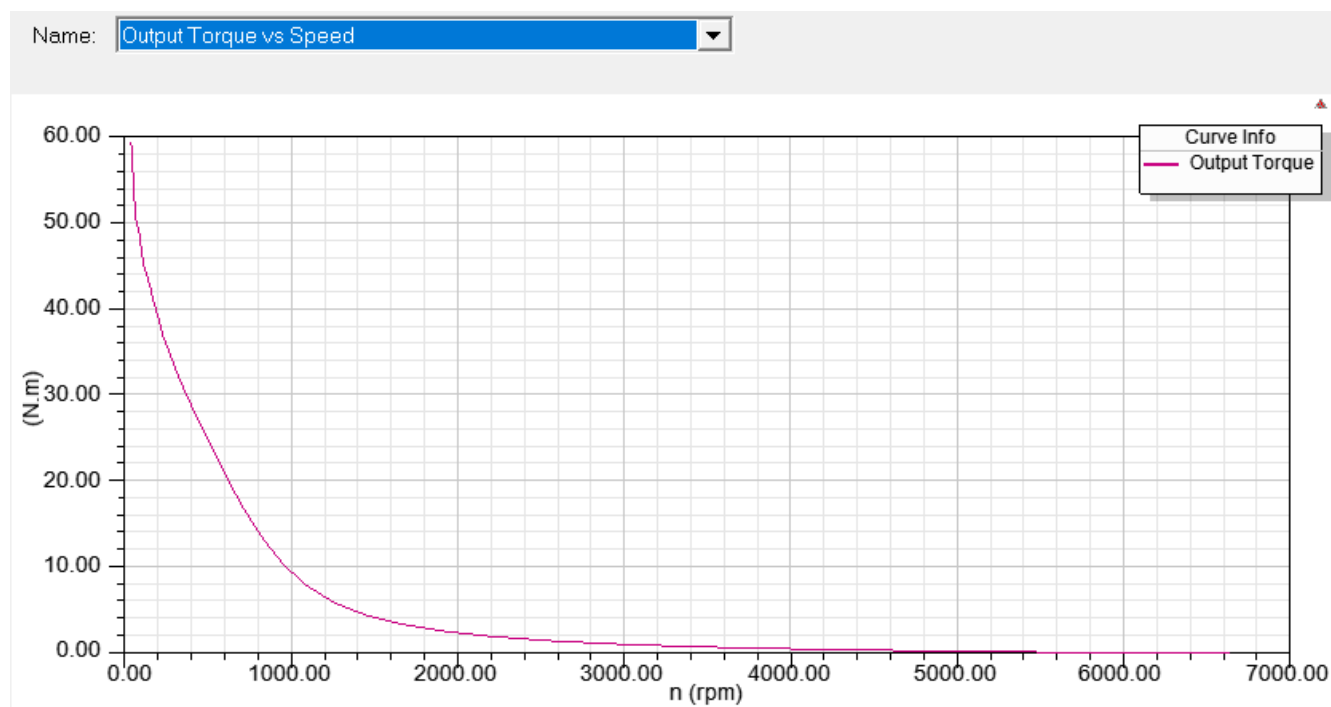


Fig 15. Output Torque vs Speed

Figure 15 gives information regarding Output torque v/s Speed. At rated speed i.e 2000 rpm the output torque is 2.35 Nm. It is observed that, as the speed increases the torque decreases.

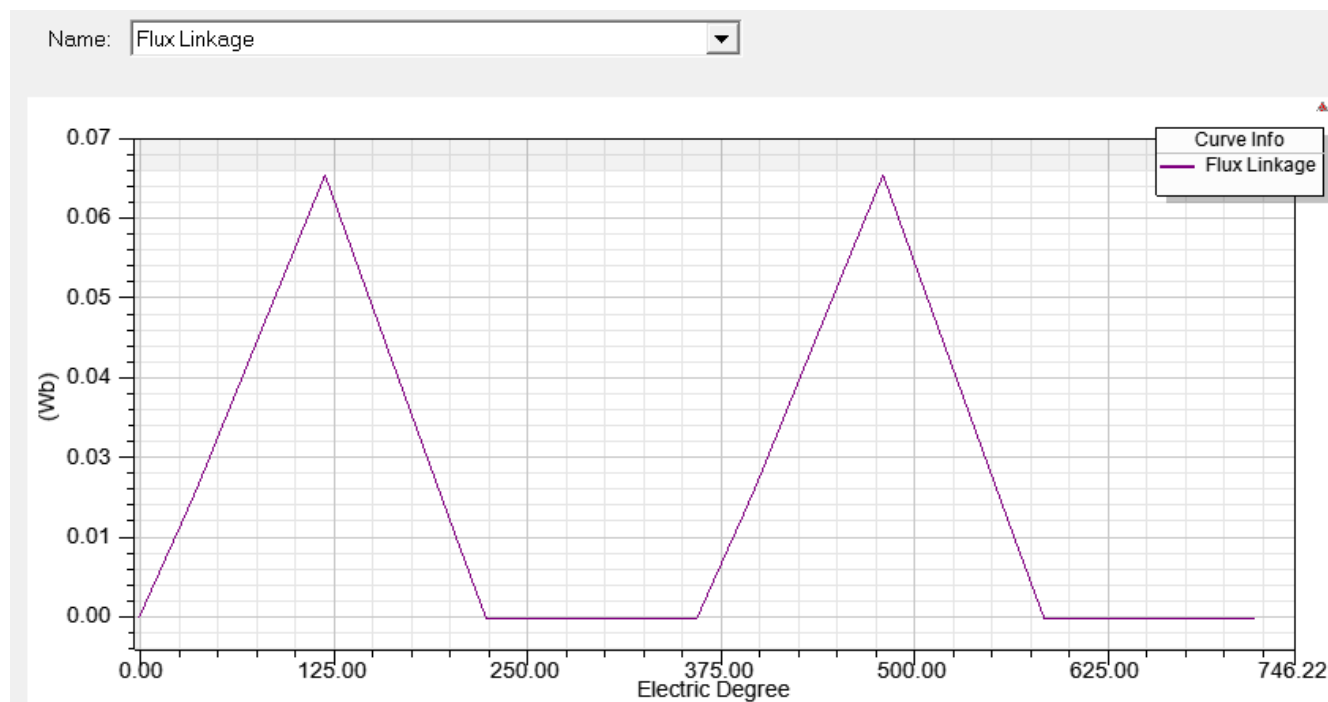


Fig 16. 5 Flux linkages at different electrical degree

Figure 16 shows the flux linkages at different electrical degree. It is observed that flux linkage curve changes after 120° . Flux linkage value obtained from the graph is 0.0691082 Weber (Wb).

5.4 Developed hardware model details



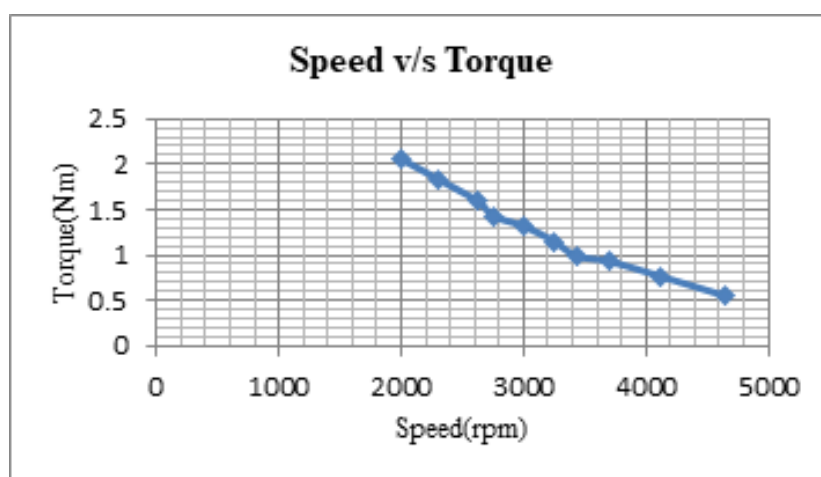
Fig 17. 6 Hardware of proposed switched reluctance motor

Figure 17 represents the hardware of SRM developed and it is tested with variation of load and observations are presented in Table 5.

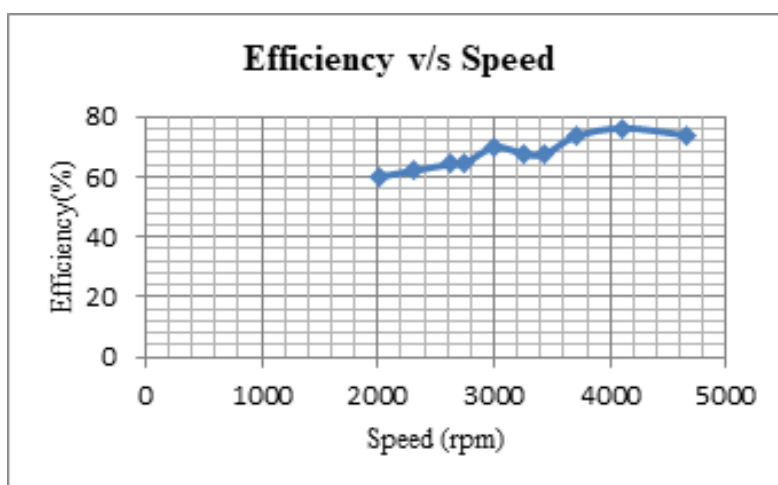
Hardware model is developed and its important parameters like torque, speed and efficiency are compared.

Table 5. Routine Test report

Voltage (VDC)	I/P current (A)	rpm	Torque (Nm)	I/P power (watts)	O/P power (watts)	Efficiency (%)
48	2.7	14700	No-load	130.4	No-load	No-load
48	7.5	4650	0.55	360	266	73.88
48	9	4110	0.77	432	329.12	76.18
47.3	10.3	3700	0.93	487.19	357.86	73.45
47.2	11.1	3430	0.99	523.92	353.15	67.41
47.0	12.2	3250	1.15	573.40	388.70	67.79
46.8	12.6	3000	1.32	589.68	411.84	69.84
46.6	13.6	2750	1.43	633.76	408.98	64.53
46.4	14.6	2630	1.59	677.44	434.90	64.19
46.3	15.3	2310	1.83	708.39	439.60	62.06
46.2	16.0	2010	2.05	739.20	443.46	60

**Fig 18.** Speed v/s Torque

From Figure 18, obtained output torque at rated speed 2000 rpm is 2.05 Nm.

**Fig 19.** Efficiency v/s Speed

From Figure 19, the obtained efficiency at rated speed 2000 rpm is 60%.

After examining all the parameters some important parameter which are obtained from simulation, mathematical calculation and actual results got from motor after performing tests is compared and concluded with Table 6.

Table 6. Comparison of parameters

Parameters	Simulated results	Calculated results	Actual Motor results
Rated torque (Nm)	2.3464	2.38	2.05
Efficiency (%)	76.9734	62.56	60
Speed (rpm)	2027.36	2000	2010

Simulated efficiency is 76.97% but it is likely to be 10 % less due to presence of gear box system. After performing routine test it is observed that the efficiency at rated speed 2000 rpm is around 60 % as there is a mechanical system present between motor and wheels.

6 Conclusion

In this study, switched reluctance motor for low powered electric three wheelers is presented and analyzed. Mathematical model has been developed and it is compared with the simulation results carried out from Ansys Maxwell software which is a FEA tool. With help of these results SRM hardware has been also developed and results are presented. The proposed system has advantages like small size, low cost, low inertia rotor, high reliability, No rotor loss, robust and most importantly no use of rare earthed magnets. As per the finite element analysis and design calculations, the proposed motor is 0.5 kW, 2000 rpm, 48 V, 8/6 pole construction which develops average torque up to 2.35 Nm and is able to operate at efficiency of 60-65%. Although SRM for E-Rickshaw possesses certain limitations like torque ripple and acoustic noise, they can be removed by proper tuning. In the coming future SRM incorporated E-Rickshaws would be seen commonly as it fits the bill in terms of efficient, reliable and ecofriendly execution of electric three wheeler segment. Implementation of switched reluctance motor would be a great alternative to current BLDC and PMSM motors for E-Rickshaw application. Also it would save millions in terms of CAD (Current account deficit). Switched reluctance motor could pave the way in intensifying the electrification in 3-Wheeler sector and achieving the targets under Go Electric campaign sooner than later. Use of such ecofriendly vehicles will eventually reap benefits for our diversity in future. Also, this designing approach made in this paper to determine the various important parameters of SRM prototype can further be helpful in designing the actual rating motor required for E-Rickshaw application.

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