Analysis of Single Phase Induction and Switched Reluctance Motor for Domestic Appliances

Asok Kumar A., Bindu G.R.

Abstract— With the new developments in power electronics, the application of Switched Reluctance Motor (SRM) are now widely researched. However, the applications of this versatile machine in home appliances has not been investigated much. This paper examines the possibility of utilizing Switched Reluctance Motor in such applications. The paper mainly focuses on the efficiency of the SRM and compares it with Single Phase Induction Motor (SPIM) which is presently in use in many low-power home appliances. Analytical and Finite Element Methods (FEM) are employed which is further validated through experiment. It is clear from the results that, SRM gives better performance is energy efficient and cost effective as compared to the commonly used SPIM and hence is a better alternative for domestic applications.

Index Terms— Switched Reluctance motor, Finite Element Method, Home appliance drives, Inverters, Converters.

1 Introduction

Efficiency improvement of the home appliances results in large overall savings of energy, which is extremely important in the present scenario of global climate change. Presently, Single Phase Induction Motors (SPIM) are commonly used for such applications. These machines consume more power, by way of their low efficiencies. The SRM has higher efficiency and less losses compared to SPIM [1] in the low and medium power range. However, it cannot run directly from a dc bus or an ac line and requires a power controller that is designed for the specific application. Efficiency improvement in the SRM drives depends on the converter in addition to the motor. Attaining maximum efficiency in single pulse controlled SRM drive is explored in [2]. Performance and functional improvements on the other hand depending on the control method and its implementation with converter are explained in [3]. The design optimization is very important in the effective utilization of any electrical machines, in particular the SRM drives. A technique to optimize the performance of SRM drives is presented in [4]. The work in [5] presented the development of SRM drive with ”Power Factor Corrected (PFC)” front-end, which has efficiently reduced the Electro Magnetic Interference (EMI) problems found in typical SRM drives and improved the performance of the motor. However, the major disadvantage of the SRM is the non-uniform torque characteristics. The work reported in [6] presented a dynamic two phase excitation method. There are several researchers working in the area of improvement of single- phase induction motor also. A new scheme for speed control of capacitor-run single phase induction motor with improved energy saving scheme is introduced in [7]. The design and fabrication of single phase capacitor run induction motor in an optimized manner using Perturb and Observe method to enhance the efficiency of existing design is discussed in [8]. Many domestic applications that use SPIM seldom employ any power converters for the speed control. Addition of a power controller increases the cost of such equipment. However, a power converter will add functional improvements along with scope for increased energy efficiency. In the case of using an SPIM with a power converter for speed control, the overall drive system is comparable to an SRM drive. Hence a efficiency analysis to find out which among these two is the most efficient drive, becomes important from the long term energy savings point of view.

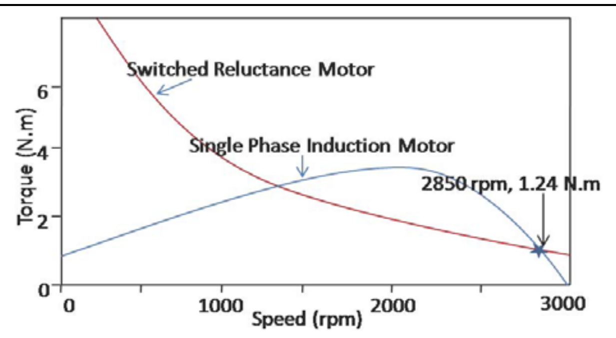

Fig. 1. Operating point.

Finite Element Method (FEM) is used for analysis of different electrical machines, so that the nonlinearity and saturation of flux are also considered in the design. It will give an accurate account of the time harmonics, actual geometry and the material properties [9]. The intention of this paper is to present an energy efficient low and high speed drive system suitable for domestic applications. The design and specifications of these two motors are based on the operating point of 2850 rpm speed and 1.24 N-m torque as shown in the Fig. 1. The performance analyses are done with FEM software. The simulation comparison shows that the switched reluctance motor will give higher efficiency, high starting torque and that can

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TABLE 1
SPECIFICATIONS OF SPIM

Parameters	Values
Rated Output Power (kW)	0.37
Rated Voltage (V)	240
Number of Poles	2
Frequency (Hz)	50
Rated Speed (rpm)	2850

operate in low and high speed ranges. The experimental results of the switched reluctance motor agree with the simulation results. The remainder of this paper is organized in six sections.

Section 2 contains a description of design considerations. In section 3, the losses and design of SRM are briefly discussed. Analysis of the performance characteristics of SPIM and SRM along with the 2D FEM analysis are discussed in section 4. Section 5 presents the discussion of results in these two types of motors using Maxwell software and Section 6 deals with the experimental validation on SRM. Finally, Section 7 presents the conclusions.

2 SINGLE PHASE INDUCTION MOTOR

Single Phase Induction motors are used in many applications including the domestic sector. In domestic sector, other type of motors like universal motors and brushless motors are also used in different home appliances. The efficiency of a single phase induction motor in normal working conditions varies from 10% to 70% depending on the rating, for the range of output power from 70 W to 750 W with power factor varying from 0.55 to 0.65. The machine is simple in construction, rugged and economical. The design simplicity is also worth mentioning. The output equation of the motor depending on the physical dimensions is [10],

$$Q = \frac{P}{\eta \cos \phi} \tag{1}$$

Therefore,

$$D^2 L = \frac{P}{\eta \cos \phi C_0 n_s} \tag{2}$$

where, Q is the output power, C_0 - is the output coefficient, D is the stator bore diameter, L is the length of core and ns is the synchronous speed.

The core length is generally made equal to the pole pitch but the exact dimensions are governed by manufacturing conditions and the diameter is selected with reference of frame size available in the market. Once the power, speed, power factor and efficiency of the machine are specified, in order to find D^2L the output coefficient must be evaluated. The output coefficient depends on the specific electric loading. The usual values of specific electric loading are 5000 to 15000 A/m and flux density in the air gap are 0.35 to 0.55 Wb/m². The selected values of outer diameter, depth of stator slot, depth of stator core are verified with the flux per pole and the flux density in the stator core. If flux density in the stator core is within the limits the selected dimensions are correct.

The number of stator slots and the slots per pole are selected, the total number of stator series turns in main winding can be determined. The rotor bar is selected based on the number of rotor slots. Running performances are calculated by the equivalent circuit that can be developed by double revolving field theory. The equivalent circuit of SPIM based on double revolving field theory for any slip s is shown in Fig. 2. For any slip s, forward torque, backward torque and gross motor torque are calculated. The net motor torque is the difference of gross motor torque and iron, friction and windage losses. Therefore, Net output of the motor = (net motor torque) * (1-s) watt.

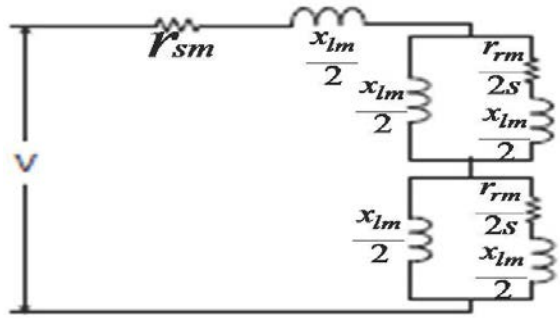
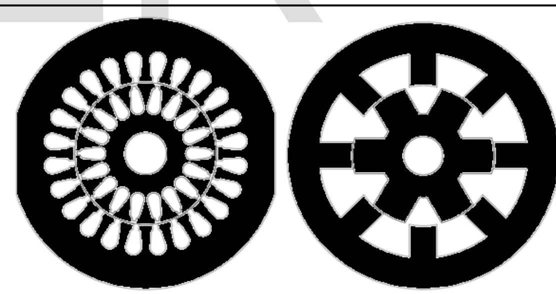


Fig. 2. Equivalent circuit of single phase indiction motor.



(a) SPIM (b) SRM

Fig. 3. Cross sectional view

Based on the above design procedure, a single phase induction motor with a rating of 370 W power output is designed. Figure 3(a) shows the cross sectional view of the designed single phase induction motor. The design and performance calculations are done with the theoretical approach. The specifications used for the design of SPIM are shown in Table 1. The designed values for SPIM are as in Table 2. These were further used for investigation.

3 SWITCHED RELUCTANCE MOTOR

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The SRM has wound field coils of a dc motor for its stator winding and has no coils or magnets on its rotor and the stator and rotor have salient poles. The switched reluctance motor has some advantages such as simple construction, robustness and low cost and possible operation at high temperatures. The torque production in switched reluctance motor comes from the tendency of rotor poles to align with the excited stator poles. The operation principle is based on the difference in magnetic reluctance for magnetic field lines between aligned and unaligned rotor position when a stator coil is excited. The rotor experiences a force which will pull the rotor to the aligned position. The torque ripple is an inherent drawback of switched reluctance motor. Fig. 4 shows the elementary equivalent circuit for the SRM.

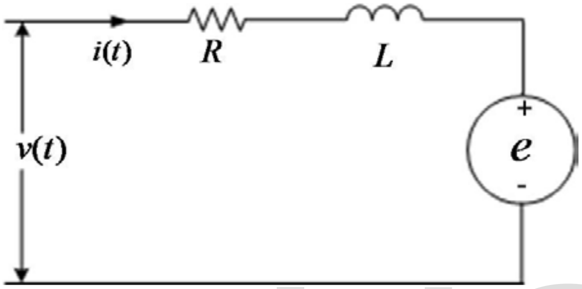

Fig. 4. Equivalent circuit of switched reluctance motor.

This can be derived neglecting the mutual inductance between phase as follows. The applied voltage to a phase is

TABLE 2
DESIGNED VALUES OF SPIM FOR USE IN SIMULATION STUDIES

Parameters	Values
Type of Load	Constant Power
Physical dimensions of Designed motor	
Iron Core Length (mm)	45
Number of Stator Slot	24
Outer Diameter of Stator (mm)	105
Outer Width of Stator (mm)	100
Inner Diameter of Stator (mm)	55.25
Main-Phase Wire Diameter (mm)	0.724
Aux.-Phase Wire Diameter (mm)	0.683
Number of Rotor Slots	18
Air Gap (mm)	0.25
Inner Diameter of Rotor (mm)	16

equal to the sum of the resistive voltage drop and the rate of the flux linkages and is given as,

$$V = Ri + \frac{d\lambda(\theta, i)}{dt} \tag{3}$$

$$e = \frac{dL(\theta, i)}{d\theta}\omega_m i = K_b \omega_m i \tag{4}$$

where, θ is the rotor position in rad, ω_m is the rotor speed in rad/sec and K_b may be constructed as an emf constant similar to that of the dc series excited machine.

3.1 Total losses of SRM

Driver circuit loss: Power losses in IGBT and diode are conduction losses, switching losses and blocking losses [12]. Therefore, Total losses in the SRM = Driver circuit loss + Core loss + Copper loss and,

Efficiency of SRM, $(\eta) = \frac{Output}{Output + Losses}$ (5)

The thermal capability of the motor is an important characteristic. It will be determined by the losses in the machine, the available surface area for cooling, and additional cooling arrangements provided by a fan.

3.2 Design of Switched Reluctance Motor

Torque of the machine,

$$T_m = \frac{P}{2\Pi\left(\frac{N}{60}\right)} \tag{6}$$

$$\text{Step angle} = \left(\frac{1}{N_r} - \frac{1}{N_s}\right) \times 360 \tag{7}$$

The speed of the motor depends on the frequency at which each phase is switched on and off.

Therefore the speed of the motor is,

$$N_s = \frac{f \times \text{step angle} \times \text{number of stator phases}}{360} \times 60 \text{ rpm}$$

Thus for the 8/6 motor, the step angle is 150, and it can be run at 3000 rpm, and each phase should be switched on and off at a frequency of 300 Hz. The frame size selection is based on the IEC, ISO and NEMA. The stator and rotor pole angle selection, inductance profile variation are described in [8]. The material selection for the stator and rotor are based on the BH characteristics of the material (Fig. 7).

$$A_s = \frac{D}{2} \times L\beta_s \tag{8}$$

Equation (8) gives the area of the stator pole. The area of the yoke also can be taken as area of the stator pole. The area of air gap is found out by the mean area of the rotor core and area of the stator core. The mean length of the circular yoke of the SRM can be found out from equation (9).

$$l_y = \left(\frac{D_0}{2} - \frac{C}{2}\right) \tag{9}$$

From the BH characteristics of the material, the field inten-

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TABLE 3
Specifications of SRM

Parameters	Values
Rated Output Power (kW)	0.37
Rated Voltage (V)	240
Number of Poles	8/6
Rated Speed (rpm)	2850

sities in the stator pole, stator yoke, rotor pole and rotor core are obtained. The equivalent magnetic circuit of the SRM can be drawn. Fig. 5 shows the simplified magnetic circuit of the SRM.

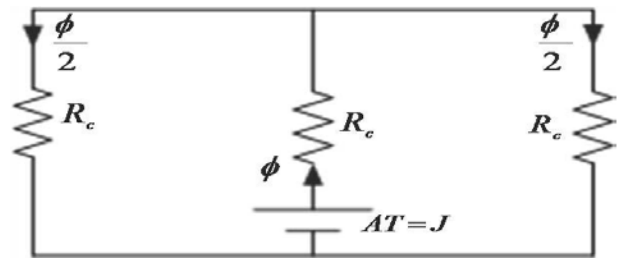

Fig. 5. Simplified magnetic circuit of SRM

TABLE 4
DESIGNED VALUES OF SRM FOR USE IN SIMULATION STUDIES

Parameters	Values
Type of Load	Constant Power
Physical dimensions of Designed motor	
Number of Stator Poles 8	8
Outer Diameter of Stator (mm)	105
Inner Diameter of Stator (mm)	55
Yoke Thickness (mm)	12.5
Length of Core (mm)	45
Number of Turns per Pole	200
Wire Diameter (mm)	0.683
Number of Rotor Poles	6
Air Gap (mm)	0.25
Inner Diameter of Rotor (mm)	15

The total ampere turns (AT) required for the operation of machine at full load can be calculated using (10)

That is, $J = T_{ph} i$ (10)

Turns per phase is, $T_{ph} = \frac{J}{i_p}$ (11)

The rated current is, $i_p = \frac{J}{T_{ph}}$ (12)

Considering equation (12) and the flux, aligned inductance is calculated. The stator pole pitch is determined and the minimum area of the conductor should be find out. The specifications used for designing the SRM are shown in Table 3. The designed values of SRM for further use in simulation studies are as in Table 4.

4 2-D FEM Characteristics of SPIM and SRM

The finite-element method is an efficient tool when dealing with complicated geometries such as in electrical machines. Analysis of radial-flux electrical machines necessitates a 2-D finite model only. In 2-D Finite Element formulation, as the first step; domain is divided into triangular finite elements. After discretization, node or mesh is formed and a corresponding function is defined as the Finite Element Method.

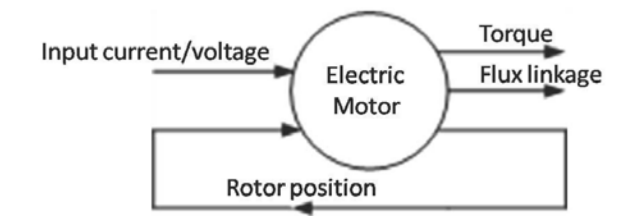

Fig. 6. Block diagram representation of FEM analysis

After taking the magnetic vector potential at any time and any location as the primary variable, approximation is done with the combination of solutions on the nodes of elements. The problem is completed only after considering the boundary conditions. Finite Element formula for the nth element can be found out by considering magnetic vector potential and weighting function for the boundary condition [13]. This paper discusses the possibility of using a machine like switched reluctance motor (SRM) with high efficiency in domestic applications and the performance analysis is done with the Ansoft Maxwell 2-D Design software using numerical solution of the equations describing the SPIM and SRM.

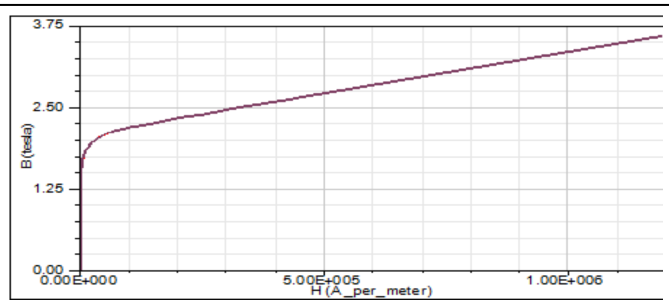

Fig. 7. B-H Characteristics of core material

Fig. 8 represent the cross sectional 3D view of SPIM. The current flow in the windings, induced voltages torque can be evaluated form the simulation. Fig. 9 shows and the currents in main winding and auxiliary winding. Fig. 10 shows the torque developed in the machine with a constant power output. The average torque developed is found to be 1.24 N-m. Fig. 11 shows the plot of SPIM efficiency vs Speed at rated

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condition. It shows that the rated speed, the efficiency is 72.22%. In Fig. 12 shows that when v/f control is applied and the motor is run at low speed (1710 rpm), the efficiency (52.58 %) is drastically reduced. Though the output power and other performance parameters of the designed SPIM satisfies the required specification, it may be noted that the efficiency at rated speed

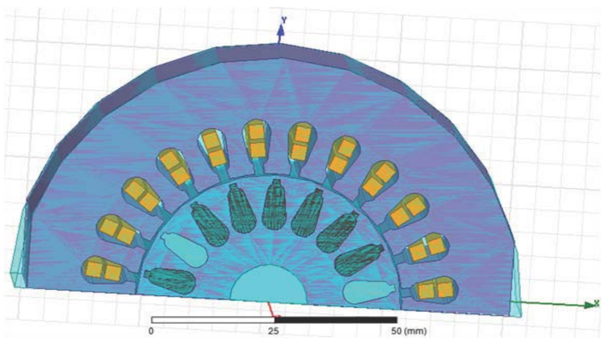

Fig. 8. Cross sectional 3D view of SPIM

of 2850 rpm is marginally higher as in the analytical method (Table 5). Fig. 13 represent the cross sectional 3D view of SRM. The performance characteristics obtained for the designed SRM are provided in Fig. 14-17. The performance characteristics of SRM clearly show the superiority of this machine over the existing SPIM, since SRM gives a higher efficiency for the same output power. Average torque developed in this machine with constant output power is 1.24 N-m as shown in the Fig.15. Fig. 16 shows the plot of SRM efficiency vs Speed at rated condition. It shows that the rated speed, the efficiency is 90.11 %. Fig. 17 shows that when the motor is run at low speed (1710 rpm), the efficiency (84.44 %) is reduced, but still is higher that the corresponding case of SPIM.

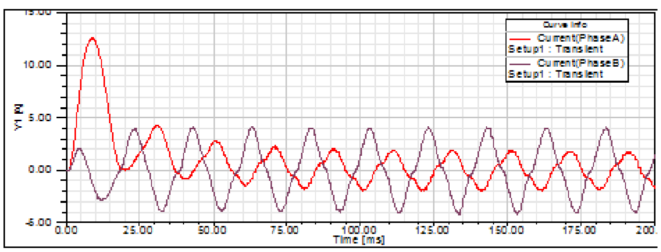

Fig. 9. Phase Current 2-phases of SPIM

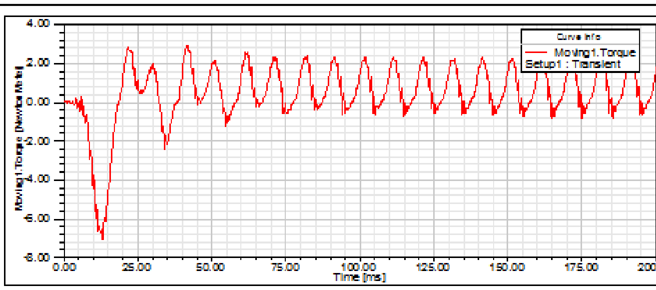

Fig. 10. Torque developed of SPIM

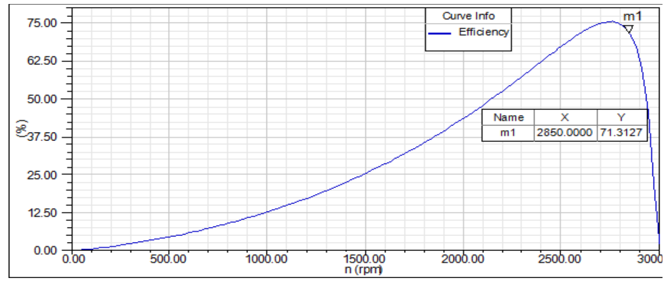

Fig. 11. Efficiency Vs Speed of SPIM at rated condition

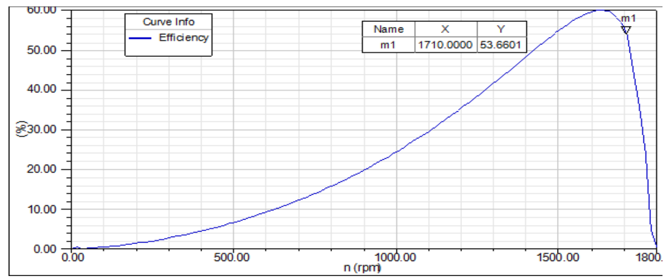

Fig. 12. Efficiency Vs Speed of SPIM at low condition

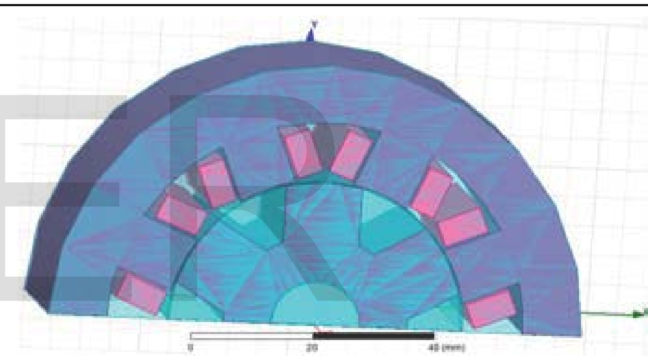

Fig. 13. Cross sectional 3D view of SRM

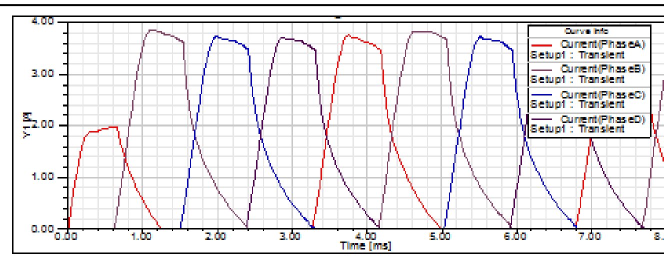

Fig. 14. Winding Current 4-phases of SRM

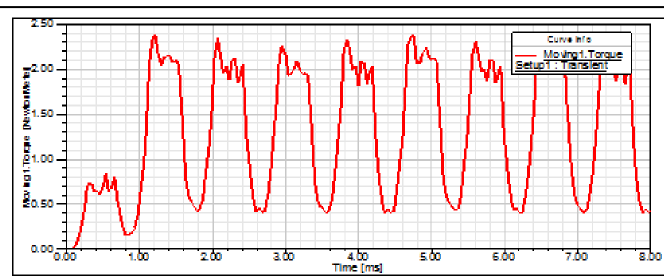

Fig. 15. Torque developed of SRM

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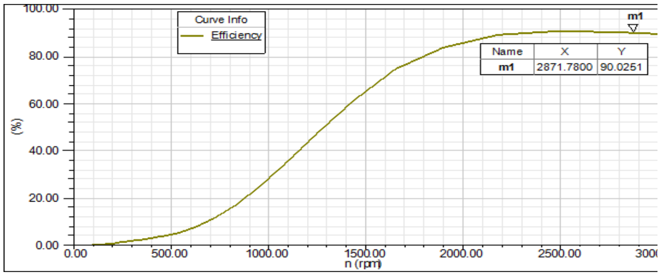

Fig. 16. Efficiency Vs Speed of SRM at rated condition

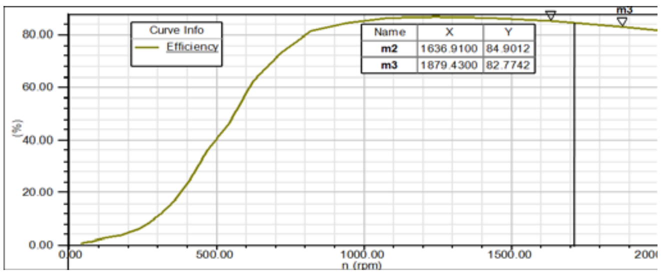

Fig. 17. Efficiency Vs Speed of SRM at low speed

5 Discussion of Results

TABLE 5
2D FEM Comparison of Performance of SPIM and SRM

Parameters	SPIM		SRM	
	Analytical	FEM	Analytical	FEM
Total Weight		6.12		3.48
Rated Speed 2850 rpm				
Total loss (W)	145.42	142.408	42.46	340.59
Output Power (W)	370	370.37	370	369.98
Input Power (W)	515.42	512.73	413.12	410.57
Efficiency (%)	71.78	72.23	89.562	90.11
Rated Torque (N-	1.24	1.241	1.24	1.239
Stator rated current	2.14	2.139	1.25	1.24
Rated Speed 1710 rpm				
Total loss (W)	68	64.69	14	13.17
Output Power (W)	1672	71.75	72	71.51
Input Power (W)	138.94	136.44	86	84.67
Efficiency (%)	51.82	52.59	83.72	84.45
Rated Torque (N-	0.42	0.401	0.42	0.40
Stator rated current	210	2.09	0.46	0.45

Based on the 2D FEM analysis, the performance of SPIM and SRM to be used in domestic applications is compared with the analytical method. This is detailed in Table 5. It is clear that, for the same output power of 370 W, SRM has a very high efficiency of 90.11% compared to a low efficiency of 72.22% of SPIM in the 2D FEM analysis. Also SRM analysis establish that the machine runs in low speed, the efficiency and torque produced is higher in compare with SPIM. Moreover, the net weight of the SRM machine is much lower than SPIM, with practically negligible difference in the torque produced.

6 Experimental Validation

Since the simulation studies and the analytical method shows an obvious superiority of SRM over SPIM in terms of efficiency and net weight. The experimental study is conducted on the Switched Reluctance Motor for establishing the superiority of performance. The schematic for the experimental setup is as in Fig. 18. A diode bridge rectifier is used to convert ac in to dc and an IGBT based converter is used to convert a uncontrolled dc to controlled pulsed wave form. The

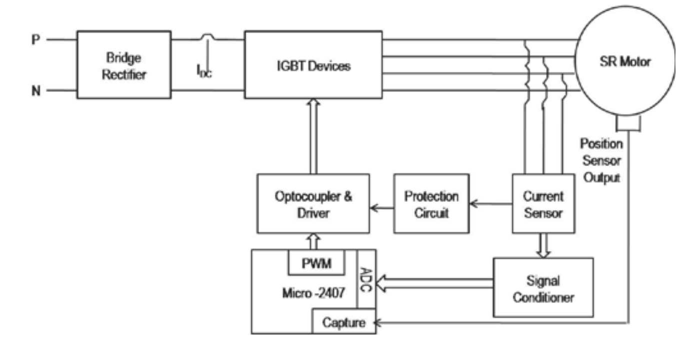

Fig. 18. Schematic for experimental setup

hardware includes the following components: The IGBT device used is 1MBH60D-090A. The rotor position is sensed using a hall sensor placed inside the motor. The rotor position is sensed once in 15^0, i.e the rotor position changes for each 15^0. Since the experimental results are obtained for a commercially available switched reluctance motor of 8/6 four phase, with a maximum speed of 4000 rpm, a scaling of the obtained values are done before comparison with simulated values. Fig. 19 shows the experimental setup of SRM Drive. The experimental setup has a maximum speed limitation of 4000 rpm. Table 6 shows a comparison of the performance of SRM obtained by analytical method, simulation and experiment. It is clear that the experimental results are in close agreement with the simulated values.

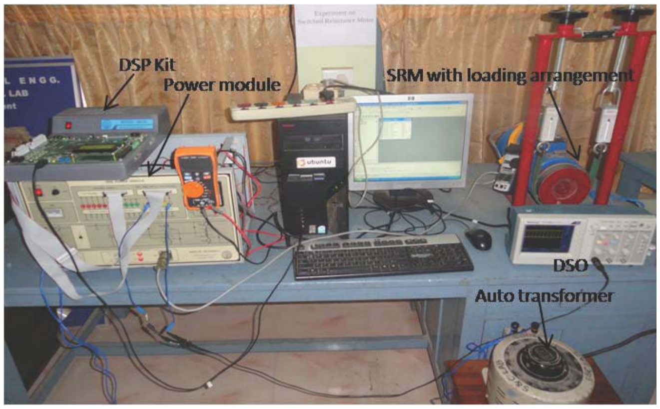

Fig. 19. Eexperimental setup

TABLE 6
SUMMARY OF THE ANALYTICAL, SIMULATED AND EXPERIMENTAL SRM OPERATING DATA AT RATED CONDITION

Parameters	Analytical	FEM	Experimental
Frictional and Windage	11.12	10.08	17
Total Loss (W)	43.12	40.59	57.84
Output Power (W)	370	369.98	362.66
Input Power (W)	413.12	410.57	420.50
Efficiency (%)	89.56	90.11	86.244
Rated Speed (rpm)	2850	2837	2850
Rated Torque (N-m)	1.24	1.239	1.22

7 CONCLUSION

This paper discusses the possibility of using a machine like Switched Reluctance Motor with high efficiency in domestic appliances. The Analytical and 2-D FEM analysis show that the efficiency of SRM is as high as 90.11% whereas the SPIM provides only an efficiency of 72.22% under similar operating conditions, thereby establishing the superiority of SRM over SPIM. The experimental investigation validates the above results. Hence higher efficiency, rugged construction, ability of extremely high speed operation of the SRM may be used in domestic appliances. The advent of various new semiconductor devices can take care of the drives to be used with SRM and hence this investigation holds relevance in the present scenario.

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