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DESIGN AND IMPLEMENTATION OF SWITCHED RELUCTANCE MOTOR

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Abstract—*In this paper, the switched-reluctance motor uses an electronic position sensor to determine the angle of the rotor shaft and solid state electronics to switch the stator windings, which also offers the opportunity for dynamic control of pulse timing and shaping. This differs from the apparently similar induction motor which also has windings that are energized in a rotating phased sequence, in that the magnetization of the rotor is static (a salient pole that is made 'North' remains so as the motor rotates) while an induction motor has slip, and rotates at slightly bellow synchronous speed. This absence of slip makes it possible to know the rotor position exactly, and the motor can be stepped arbitrarily slowly.The proposed method is implemented on a 100W, 48V, 8/6, 4 phase SRM drive for validation purposes.*

***Keywords**-Switch Reluctance Motor (SRM), Electronic Position Sensor*

I. INTRODUCTION

In recent years, the switched reluctance motor (SRM) has received considerable attention for variable-speed drive applications. The basic concepts of SRM and fundamentals of control were introduced by Lawrenson PJ, Stephenson JM, Blenkinsop PT, Corda J, Fulton NN [1].Compared to induction and synchronous motors, switched reluctance motor drives are simple in construction, therefore, gained popular recognition in electric drives market due to power density, speed range, efficiency, torque/inertia ratio, manufacturing cost, and reliability and its converter has a minimum number of switching devices due to the unidirectional current requirement [2-3]. Their combination with power electronic controllers may yield an economical solution [4]. The structure of the motor is simple with concentrated coils on the stator with no presence of windings and brushes on the rotor. The Switched Reluctance Motor drives are advantages in terms of torque/inertia ratio with four-quadrant operation, making it an attractive solution for variable speed applications especially in electronic vehicles. [5-6] SRM technology offers an impressive list of advantages that is making industrial users seriously looking at switched reluctance drives [7]. The torque/inertia ratios of SRMs are also high.

This paper proposes the design of switched reluctance motor to obtain high motor efficiency. The first step of design makes the principle improving motor efficiency clear. Next the cross sections and axial shapes of rotor and stator cores.The switched reluctance motor (SRM) drives for industrial applications are of recent origin. This paper introduction to SRM, its principle of operation and design considerations.Key to an understanding of any machine is its torque expression. The implications of machine operation and its salient features are inferred from the torque expression. The torque expression requires a relationship between machine flux linkages or inductance and the rotor position. The machine operation in all of its four quadrants of torque vs. speed is derived from the inductance vs. rotor position characteristic of the machine, and the dynamic equivalent circuit for SRM is formulated.

II. BASIC OF S R MOTOR

It has wound field coils of a dc motor for its stator windings and has no coils or magnets on its rotor. Both the stator and rotor have salient poles, hence the machine is referred to as a doubly salient machine. Such a typical machine is shown in Figure 1(a), and a modified version with two teeth per pole is shown in figure 1(b).

The rotor is aligned whenever diametrically opposite stator poles are excited. In a magnetic circuit, the rotating member prefers to come to the minimum reluctance position at the instance of excitation. While two rotor poles are aligned to the two stator poles, another set of rotor poles is out of alignment with respect to a different set of stator poles. Then, this set of stator poles is excited to bring the rotor poles into alignment. Likewise, by sequentially switching the currents into the stator windings, the rotor is rotated. The movement of the rotor, hence the production of torque and power, involves switching of currents into stator windings when there is a variation of reluctance; therefore, this variable speed motor drive is referred to as a switched reluctance motor drive.

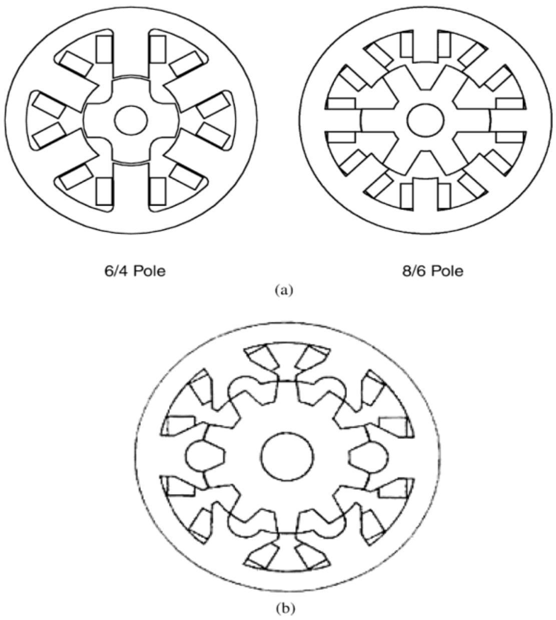

Figure 1. Switched reluctance motor configurations. (a) One tooth per pole. (b) Two teeth per pole (12/10 poles).

Switched Reluctance Motor is based on the principle that converts the reluctance torque into mechanical power. Both rotor and stator have a salient-pole structure, which produces a high output torque. The torque in the switched reluctance motor is produced by alignment tendency of poles. The rotor will shift to a position where reluctance is to be minimized and thus the inductance of excited winding is maximized [8].

The switched reluctance motor has a doubly salient structure; rotor is made of steel laminations without windings or permanent magnets. The rotor is basically made of steel shaped to form salient poles, so it is only motor type with salient poles in both the rotor and stator. As a result of its inherent simplicity, the switched reluctance motor promises a reliable and low manufacturing cost and will undoubtedly take the place of many drives now using the cage induction motor, permanent magnet motor, and DC motor in the short future.

III. BLOCK DIAGRAM OF PROPOSED S R MOTOR

Figure 2 shows the block diagram of SRM. Here, shaft position encoder block is connected to the shaft. It feeds back the position of rotor with respect to stator poles to the processor.
Signal processor block processes the signal according to the rotor position and rotation
i.e. clockwise or anticlockwise and then feeds the signal to invertor.

Set speed block adjusts the speed if varied from the rated speed and ultimately gives signal to invertor through processor. Invertor also has current sense which limits the current. These pulses are then finally fed to the motor and corresponding speed variation is achieved.

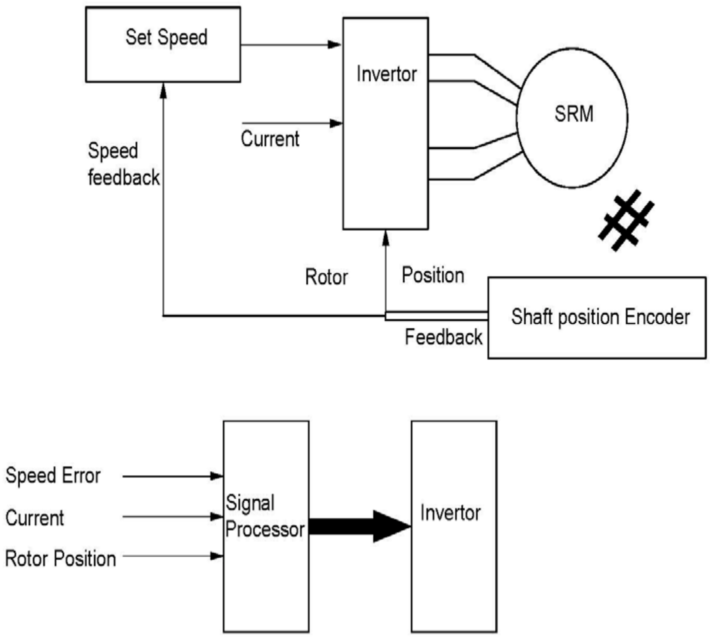

Figure 2. Block diagram of Switched Reluctance Motor and Drive circuit

CIRCUIT DIAGRAM AND DESCRIPTION

Figure 3 shows the circuit diagram of SRM. As shown, every winding gets excited when the diode corresponding to it is made ON. This happens with the help of opto-isolator in which transistor generates a high pulse for excitation. Thus, sequential turning ON of the LEDs give sequential pulses which excite the windings and rotor motion is achieved.

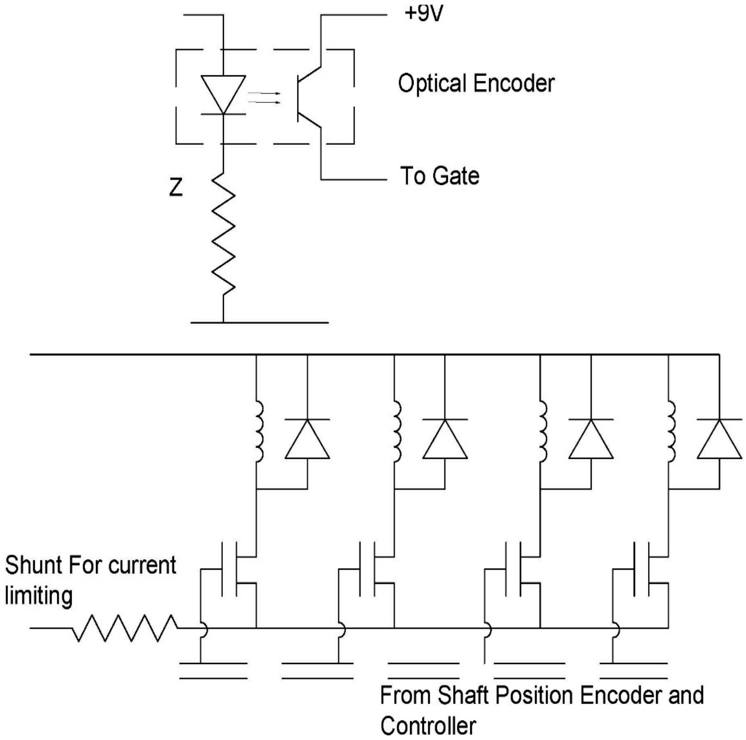

Figure 3 Circuit diagram of Switched Reluctance Motor and optical encoder

IV. DESIGN OF SRM

Performance analysis of the SRM requires the dimensions for stator and rotor laminations, winding details, pole numbers, and pole arcs. An approximate sizing of the SRM is obtainable using a power output equation familiar to machine designers. The resulting machine dimensions form the starting point in design evaluation, and final design is achieved through an iterative process of steady-state performance calculations described in this chapter. This chapter contains the derivation of the output equation and selection of various machine variables such as number of poles, rotor and stator pole arcs, core length, bore diameter, back iron thickness, number of turns in each phase, and air gap for rotary switched reluctance machines. The design trade-offs emerging from conflicting requirements are discussed in great detail.

A procedure to calculate resistive and core losses is presented. Flux densities at various parts of the machine are derived from first principles. Measurement of winding inductance is crucial to the validation of machine design and is briefly described here. The computation of torque for ideal and practical currents is developed, and the procedure is equally applicable to both steady-state and dynamic processes.

A step-by-step design of linear motion SRMs is considered in detail. In order to utilize the knowledge base of the rotary SRM, the linear machine design is achieved using the rotary SRM design process developed in this chapter. In order to accomplish it, the design specifications of the linear machine are converted to rotary machine design specifications. Then, an equivalent rotary SRM is designed and the design outcomes are translated into linear machine dimensions and variables by simple algebraic relationships. The design verification with analysis using magnetic equivalent circuits, finite element method, and experimental measurements is developed in detail. The procedure for inductance and force measurements is also described in this chapter for the linear SRM.

DERIVATION OF OUTPUT EQUATION

The output equation relates the bore diameter, length, speed, and magnetic and electric loadings to the output of a machine. In general, the conventional machines are designed starting from the output equation. A similar development of the output equation for SRM will make its design systematic. Moreover, the experience of the machine designers can be effectively used in the design of these new machines, as they could use the commonality between these and the conventional machines to start with. While the output equation of SRM will be significantly different from that of the conventional machine, the emphasis here is placed on their similarities.

The power developed is given by p_d

$$p_d = k_e k_d k_1 k_2 B A_s D^2 L N_r \qquad (1)$$

Where K_d is the duty cycle, K_e is the efficiency

$$K_d = \frac{\theta_i q P_r}{360} \qquad (2)$$

Where θ_i is the current conduction angle for each rising inductance profile, q is the number of stator phases given by $P_s/2$, P_s is the number of stator poles, and P_r is the number of rotor poles.

$$k_d \approx 1$$

$$P_r = 6$$

$$\theta_i = \frac{1*360}{4*6} = 15^0$$

$$k_1 = \frac{\pi^2}{120} = 0.08$$

In general, at the rated operating point, the range of k_2 is given by

$$0.65 < k_2 < 0.75$$

Inner diameter, D = 0.0508m.

Since the SRM is normally used as a variable-speed device, it is appropriate to have a base speed specification. At the base speed, the motor is expected to deliver the rated torque and hence the rated output power. To correspond to the rated power output and keeping the stack length as a multiple or submultiples of rotor bore diameter, the following is obtained

Where,

$$L = kD$$

$$0.25 < k < 0.70$$

$$L = 0.4 * 0.0508 = 0.0203m.$$

Assuming,

Rotor speed, N_r = 3000 rpm and efficiency, K_e = 95%

The values of B for the aligned position can be taken as the allowable maximum for the core material. The specific electric loading in amp-conductors per meter is usually in the range of:

A_s = 13,000 – 16,000

B = 0.35 – 0.5

Now,

$P_d = k_e k_d k_1 k_2 B A_s D^2 L N_r$

$=0.95*1*0.08*0.7*16,000*(50.8*10^{-3})^2*(20*10^{-3})*3000*0.5$

∴ P_d = 65.89 W.

Now,

Torque, $T = k_d k_e k_3 k_2 B A_s D^2 L$

$=1*0.95*\pi/4 *0.7*0.5*16,000*$

$(50.8*10^{-3})*(20*10^{-3})$

= 0.2153N-m.

Note that the torque and power output are proportional to the product of specific electric and magnetic loadings and bore volume given by (πD2L)/4. k2 is the only variable dependent on the operating point of the motor and is determined by the stator phase current, magnetic characteristics of the core materials, and dimensions of the motor. For a given operating point, k2 is a constant. Hence, to extract the maximum output power from the SRM, k2 needs to be calculated at the maximum stator current. For that matter, the flux linkages vs. current for the aligned and unaligned positions are to be estimated for various values of stator currents. For k_d= 1, the power developed is maximum for a given stator current. It is usual to find that themaximum possible duty cycle is less than one. Furthermore, torque and power control areexercised by the duty cycle similar to a chopper-controlled dc motor. The speed is controlled by the frequency of switching of the phases resembling that of a synchronous motor

NUMBER OF TURNS:

As per space consideration, size of conductor is chosen to be 26 gauge.

And 26 gauge → D = 0.457mm.

Cross Sectional Area = $\pi\pi DDLL$ = 0.1644

Current density, J = 7.5A/mm2

Now, to find current, $P_d = k_e\ k_d\ V\ i\ m$

65.89 = 0.95*1*80*i*1

∴ Current, i = 0.866A.

Now to find T_{ph},

$A_s = \frac{2\,Tph\ im}{\pi D}$

$\therefore T_{ph} = \frac{As\ \pi D}{2im}$

=

$$\frac{16000 * \pi * 0.0508}{2 * 2.5 * 1}$$

… [considering maximum current]

$\therefore T_{ph} = 510.69$

Thus, considered $T_{ph}$is 500 because of space constraints.

STATOR BACK IRON THICKNESS (BSY):

The stator back iron thickness, b_{sy}, is determined on the basis of maximum flux density in it and by the additional factor of vibration minimization to reduce acoustic noise. The flux density in the stator back iron is approximately half that of the stator poles. An allowance is given to have a slightly greater share of the pole flux. The stator pole arcs have to be chosen to accommodate the pole flux density. If ω_{sp} is the pole width given in terms of pole arc as follows

$\omega_{sp} = D\sin(\beta_s/2)$

Where, ω_{sp} = pole width

$= 0.0508 \sin(23^o/2)$

$= 0.0101$

Where, β_s= stator pole arc and,

then the back iron thickness has to be a minimum of $0.5\omega_{sp.}$ Due to considerations of mechanical robustness and minimization of vibration it could have a value in the range of $0.5\omega_{sp} \leq b_{sy} < \omega_{sp}$

$5.06*10^{-3} \leq b_{sy} < 0.0101$m

We get,

$b_{sy} = 5.6*10^{-3}$ m.

Stator pole arc and rotor pole arc: Length of arc = β_s *2πr./360

$\therefore \beta_r = 10.9*360/\pi*0.0505$

$= 24.73^o$

≈ 0.43 rad.

STATOR COIL DIMENSIONS:

The stator coil dimensions given by its width, ω_c, and length, h_c, emerge from the area of cross section of the conductor, ac, determined by the current density and the number of turns per phase, T_{ph}. Let ω_{cs} is the width or gap to be left between the two adjacent coils in a slot at the bore including the slot liners. A stator coil area is given, in terms of number of turns and area of cross section of the conductor, by

$$h_c\omega_c = \frac{a_c T_{ph}}{2} = \frac{0.164 * 500}{2}$$

$h_c\omega_c = 41.0$

Considering space factor as 2.2,

$h_c\omega_c = 41.0*2.2$

∴ Total area of coil = 90.2
Now,
$\omega_c = \frac{area\ of\ coil}{h_c} = \frac{90.2}{14}$

… [actual 16, 14 because of wedge]

= 6.44mm.

STATOR POLE HEIGHT:
The minimum stator pole height is approximately equal to the coil height, but the coil has to be held in place and for that a small space is required near the pole face. The coil seating at theroot of the pole is not usually tight fitting; therefore, some additional space is lost which mustbe accounted for to calculate the stator pole height. Taking into consideration all these factors and the need for a smaller length of the pole, the pole height in terms of the coil height h_c is given by
$h_c < h_s < 1.4h_c$
Where,
h_s = stator pole height h_c = coil height
We have taken $h_c = 14$
∴ h_s should be between 14 - 19.6
∴ $h_s = 16$

OUTER DIAMETER OF STATOR LAMINATION:
If the outer diameter is pre-specified, the design is carried out from the outer to inner dimensions. Machines used in special variable-speed applications may not fall under frame numbers categorized by NEMA and other agencies and organizations. In that case, design details may start from bore diameters and then work their way up to determine the outer diameter of the stator lamination by adding to it the pole heights and back iron thickness. It then is given by:
$D_o = D+2b_{sy}+2h_s$

$= (50.8*10^{-3}) + (2*5.6*10^{-3}) + (2*16*10^{-3})$

$= 94*10^{-3}$ m.

Whereas, we have taken it as 96 mm.

ROTOR BACK IRON THICKNESS:
The rotor back iron thickness, bry, is based on structural integrity and operating flux density. It need not be as much as the stator back iron thickness and neither has to be equal to the minimum value equal to half the stator pole width. The range of values to be chosen from has to accountfor the larger inter-polar air gap to provide a high ratio between the aligned and unaligned inductances, but at the same time it is desirable to have shorter rotor poles to generate minimum vibration in the rotor. Based on these considerations, the rotor back iron thickness in terms of stator pole width is
$0.5\omega_{sp} < b_{ry} < 0.75\omega sp$

$5.05*10^{-3} < b_{ry} < 7.57*10^{-3}$

But our b_{ry} comes out to be $12.55*10^{-3}$ m.

ROTOR POLE HEIGHT:
Given the bore diameter, air gap length, l_g, rotor back iron thickness, and rotor shaft diameter, the rotor pole height is written as

$h_r = \frac{D-2l_g-D_{sh}-2b_{ry}}{2}$

$= \frac{50.8-2*(0.15)-12.9-2*(12.55)}{2}$

= 6.25 mm.

Where D_{sh} is the rotor shaft diameter

STATOR COPPER LOSSES:

If Rs is the per-phase resistance of the stator winding, the total copper losses for non- overlapping currents in the stator is given by

$P_{cu} = qI_p^2 R_s$

Where q is the number of stator phases, and I is the RMS value of the current given by Where,

I_p = peak value of phase current

= 2.5 A.

R_s = resistance per phase

= 7.2Ω

$\therefore P_{cu} = (2.5)^2 * 7.2$

P_{cu} = 45 W. … [For 100% duty cycle.]

24 steps needed per rotation i.e. each phase gets excited six times per rotation.

$\therefore P_{cu}$ = 45/6 = 7.5 W/phase

…[maximum loss for 100% duty cycle]

7.5 W gets reduced to lower value again for lower duty cycles.

SELECTION OF NUMBER OF PHASES

The number of phases is usually determined by the following factors:

1. Starting capability: For example, a single-phase machine cannot start if the rotor and stator poles are aligned. It usually requires a permanent magnet on the stator at an intermediate position to the stator poles to keep the rotor poles at an unaligned position.

2. Directional capability: Whether the machine needs to run in one or two directions dictates the minimum number of stator phases. For example, a 4/6 machine is capable of only one direction of rotation, whereas a 6/4 is capable of two-direction rotation. The former case is a two-phase machine and the latter case is a three-phase SRM.

3. Reliability: A higher number of phases means higher reliability because a failure of one or more phases will still allow the running of the machine with the remaining healthy phases. Thisfactor may be highly relevant in critical applications where safety of human beings or successful mission completion is the predominant factor. Examples are an aircraft generator, a defense mission, actuators in nuclear power plants, and icebreakers for research missions.

4. Cost: A higher number of phases requires a corresponding number of converter phase units, their drivers, logic power supplies, and control units. All these are likely to impact the cost and packaging size and therefore have to be considered concurrently with the machine design.

5. Power density: A higher number of phases tends to give higher power density (say, three- phase compared to two-phase) in many applications.

6. Efficient high-speed operation: Efficiency is enhanced by reducing the core loss at high speed by decreasing the number of stator phases and lowering the number of phase switching per revolution.14 Three phases is preferred over four phases in an aircraft starter/generator SRM because of its high-speed operation and the need to keep the size smaller, which requires a great reduction in losses to maintain thermal robustness.

SELECTION OF POLES

It is preferred to have the ratio between stator and rotor poles be a non-integer even though some at integer values have been attempted. Based on this guideline, the stator and rotor pole combinations common in industrial designs are given below:

Table No.1 Guidelines for selecting stator and rotor pole combination

	POLES		
STATOR	6	8	12
ROTOR	4	6	8

The limiting factors in the poles selection are the number of converter power switches and their associated cost of gate drives and logic power supplies and the control requirement in terms of small rise and fall times of the phase currents. Note that a 12/8 SRM is a three-phase machine with four stator poles per phase. If the maximum speed of the machine is ω_{rm} rad/sec, then the stator frequency for a phase is

$$f_r = \frac{(\omega_{rm})}{2\pi} P_r \text{ Hz}$$

Therefore, increasing the rotor poles increases the stator frequency in proportion, resulting in higher core losses and more importantly greater conduction time to provide the rise and fall of the current compared to that of an SRM drive with a smaller number of rotor poles. The latter contributes to higher copper losses and to larger phase conduction overlaps. Due to increased switching frequency, the commutation torque ripple frequency is also increased, thus making its filtering easier. Further due to the overlapping phase conductions and their effective control, note that the commutation torque ripple magnitude could be attenuated very significantly, leading to a quiet operation. It should be understood that this comes at the expense of efficiency and simplicity in control. In many applications such as fans or pumps and even in off- and on- highway vehicle propulsion this may not be necessary, as they can stand higher commutation torque ripples, for example, as compared to position servos.

The cost of motor production rises with higher pole numbers due to increased winding insertion costs and terminal costs and most of all due to the increased cost of the converter, with its greater number of power switches and diodes and cost of packaging.

V. THE CONTROLLER

For controlling the Ton & T_{off} time following Flowchart algorithm is used which is shown in Figure. we have used concept of Pulse Width Modulation (PWM) for changing Ton and T_{off} time which ultimately helps to achieve speed control of the motor.The lesser is Ton time, lesser will be the speed and the more is Ton time, more will be the speed.

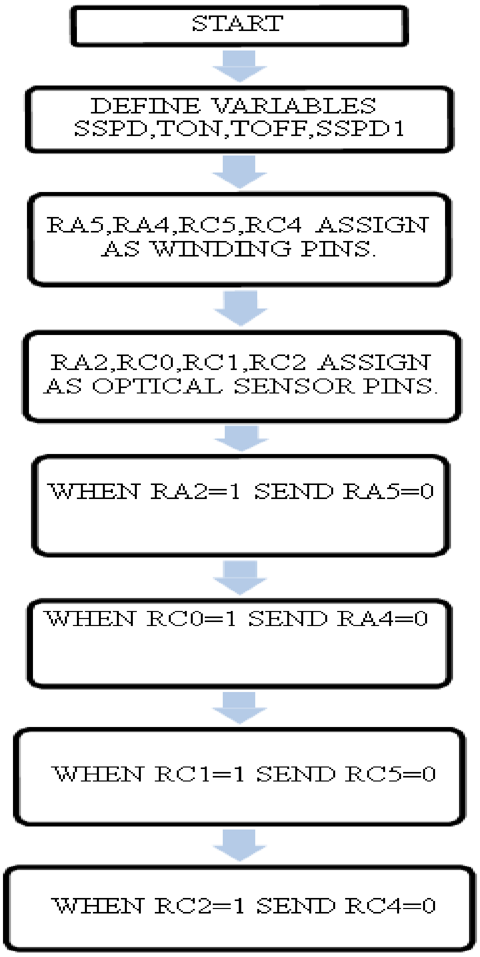

Figure. 4 Flowchart of the program for motor operation

Execution of program for generation of gate pulses is used PIC device16F684.Figure 5 shows PIC simulator main window. PIC 16F684 is amongst the most basic microcontrollers. Program has specific duty and time set. On toggling four of the pins rotation is achieved in a step fashion. This program is then fed to the IC using MPLAB.

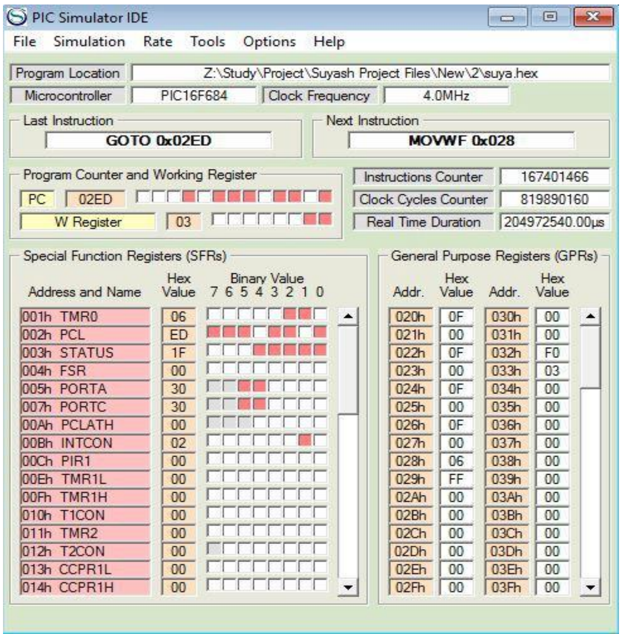

Figure5. PIC Simulator main window

VI. HARDWARE RESULT

A ready made stator of 100W is used. Rotor dimensions are fixed according to stator and on the same basis further calculations are done. Circuit components such as resistors, transistors, capacitors, MOSFETS, zener diodes, IC and voltage regulators are used.

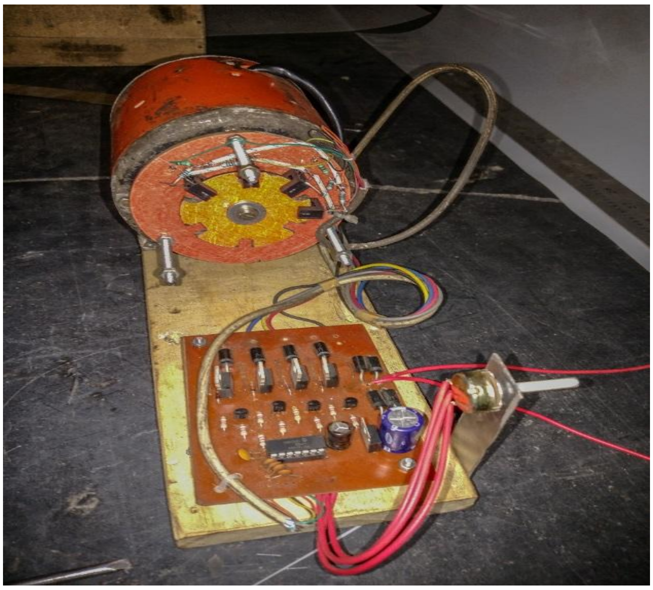

Figure 6. Hardware Implementation of SRM

Following table no. 2 shows the readings of voltage & speed taken for SRM. This characteristics speed Vs Voltage is plotted & shows in figure 7.

Table No. 2

Voltage	speed
0.6	190
1	417
2	1100
5	1360
7.5	1560
8	1720

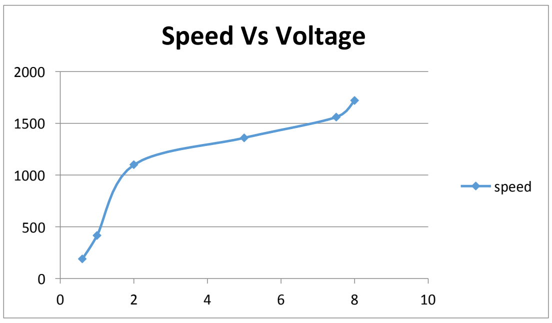

Figure 7. Speed v/s Voltage graph

Total Costing of switch reluctance motor assembly is approximately4615-6260 Rs.

VII. CONCLUSION

Thus from this setup we can say that the Switched Reluctance Motor is more efficient and highly reliable. SRM is robust, has high starting torque, good running torque. Hence most of the disadvantages of Induction Motor are overcome by SRM. SRM has simple construction, low maintenance and very high speed.SRM has applications where high speed and high power is required and is majorly used in upcoming electrical vehicles.

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