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Design Analysis and Performance Characteristics of Switched Reluctance Motor

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Abstract: Switched Reluctance Motor (SRM) is coming up as an alternative selection for variable speed drives in many automobile and industrial application. Its construction is simple and rugged. Its higher efficiency, high torque to inertia ratio and thermal toughness are some of the salient advantages of SRM. However, the SRM has not gained prominent importance in many practical applications, because of its few disadvantages like large torque ripple, acoustic noise and proper design. In this paper, the step by step design procedure of SRM is explained based on the previous literature available, for preliminary design. Finally the over all modifications and validations are carried out using finite element methods .Based on the design validations a proto type has been developed for automobile application .The experimental method verification of the motor winding inductance at different rotor positions from un-aligned to aligned position and ,the static flux linkage characteristics are also presented as they play an vital role in design verification and performance calculation of an switched reluctance motors (SRM's). The simulation results are having good conformity with the experimental results.

Keywords: Motor design optimization, Motor-CAD, ANSOFT MAXWELL, Static flux linkage characteristics, Inductance calculation.

I.INTRODUCTION

The concept of switched reluctance drives is not new to industry, it was established in 1838, but the SRM could not take in its full market in variable drive applications, until the modern era of power electronics [1]. The invention of power semi-conductor devices in the mid 1960's had given the S.R motor a new start and have raised its potential levels to compete with ac and dc drives. An SRM is an electric motor in which torque production principle is different from the conventional AC and DC motors. The torque production principle in SRM is by the tendency of its rotating part to move to a position of maximum inductance [4], which corresponds to the position of minimum reluctance. It will not work with AC or DC. It has salient poles on both rotor and the stator, but only the stator poles carry windings. Rotor is made up of stack of laminated steel. It is neither a permanent magnet nor does it carry any winding. Hence, SRM is a double salient, single excited motor. The principle of the motor is that, when current is sent through one of the stator phase, the rotor tends to align with the excited stator phase, which produces a torque tending to turn the rotor to a minimum reluctance area [3]. A sequence of torque strokes can be produced by properly exiting the stator phases, depending on the rotor position information.

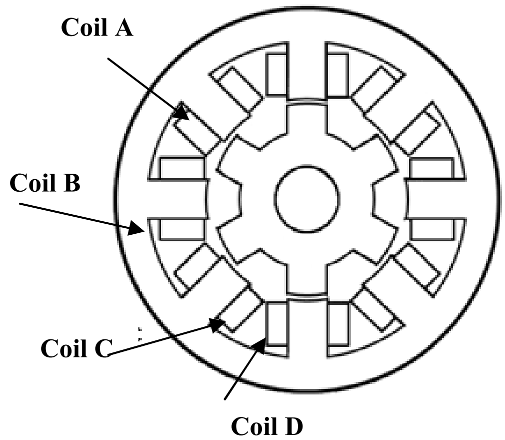

Fig. 1 Four Phase Switched Reluctance motor

The rotor tries to rotate along with the rotating magnetic field set up by stator currents and always be in synchronism with it. This present paper explains step by step procedural design for switched reluctance motor based on empirical and finite element method for automobile applications. The design procedure starts with the empirical formulas as obtained from the previous design experience and extracted from the technical publications .This involves the motor size, lamination geometry and winding dimension. However the method presents a relatively inaccurate design unless adequate design experience is accumulated. It therefore serves as a tool for preliminary design [9]. Hence final validations and fine tuning is carried out using finite element methods. The 8/6 -pole SRM structure to be designed for automotive applications is shown in Figure 1.

A satisfactory control strategy can be developed if true knowledge of flux-linkage characteristics of the machine is available. Hence knowledge of actual flux linkage versus current profiles is essential for design verification and performance prediction of switched reluctance motors[6]

This paper is organized on the following lines: Section II deals with the design aspects. Section III deals with experimental verification of main winding inductance and section IV deals with experimental set up for the determination of static flux linkage characteristics of an SRM.

A. Operational Principle

Fig. 1 shows the design structure of an *8/6* poles SR motor. It is doubly salient and has no rotor windings. The torque in this motor is due to the tendency of rotor poles to align with the poles of the excited stator phase[2]. The direction of the torque is independent of the direction of the phase current. The phases are constantly fed by uni-polar currents to get one-directional torque. Rotor position sensors are used to for turn on and turn off of the phase windings (position sensors can be eliminated with an indirect position sensing scheme).

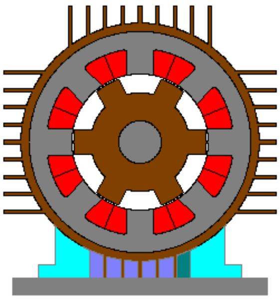

Fig. 1(a) Design Structure of SRM

Fig. 1(b) Prototype of Switched Reluctance Motor

II. DESIGN OF SRM[1][8][9]

The design of SRM is based on voltage equation and is given by:

i. Voltage per Phase:[9]

$$v = \frac{d\lambda}{dt} = \frac{\lambda_a - \lambda_u}{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

where $\boldsymbol{\lambda_a}$ is the aligned flux linkage,

$\boldsymbol{\lambda_u}$ is the unaligned flux linkage,

$\boldsymbol{\lambda}$ = Flux linkage = N φ Weber turns,

N is the number of turns & φ is the magnetic flux in webers

$$V = \omega_m * T_{ph} * B * \frac{D}{2} * L\left[1 - \frac{1}{\sigma_s \sigma_u}\right] \ldots\ldots\ldots\ldots 2$$

Where σ_s is constant and $\sigma_u = \frac{L_a}{L_u}$;

L_a is aligned inductance ,

L_u is unaligned inductance

If stator arc length $\beta_s = \theta = 15°$,

In radians i.e., β_s = 15 * π / 180

Then time taken for the rotor to move from aligned position to unaligned position, t=$\frac{\beta_s}{\omega_m}$ where wm is the rotor speed in radians /second.

ii. Specific Electric Loading: A_s[9]

$$A_s = \frac{2 * T_{ph} * i * m}{\pi * D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

T_{ph}= No. of turns per phase,

m=No. of phase excited at a time, for 8/6 m=1

iii. Duty Cycle Constant (K_d)

$$K_d = \frac{\theta_i * q * P_r}{360} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

θ_i is the current conduction angle, in the present case 15°

q is the number of phases ,given by Ps/2, where Ps is no. of stator poles, and Pr is no. of rotor poles, Here q=4;

Therefore K_d=1;for 8/6 SRM

iv. Power Equation[9]

Power developed per phase is given as

$$Pd = V * i$$
$$= V * i * m$$

Where V is the voltage and i is the rms current, m is the number of phases conducting at a time and m =1 in this case. If K_e is the efficiency of the motor and K_d is the duty cycle

$$P_d = K_e * K_d * K_1 * K_2 * B * A_s * D^2 * L * N_r \ldots\ldots 5$$

K_2 is a constant varying from 0.65 to 0.75

$$K_1 = \frac{\pi^2}{120}$$

D & L are calculated

Here the stack length is assumed to be as the multiple or submultiples of rotor bore diameter.

L=K*D

For non-servo applications the range of K can be

$0.25 < K < 0.7$

For servo applications it's usually the range given by

$1 < K < 3$

v. Stator Back Iron Thickness:

The stator back iron thickness, β_{sy} is determined on the basis of maximum flux density in it and by the additional factor of vibration minimization to reduce acoustic noise.

If ω_{sp} is the pole width given in terms of pole arc as follows:

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

Then the back iron thickness has to be minimum of $0.5\omega_{sp}$, Thus to considerations of mechanical robustness and minimization of vibration it could have a value in the range of:

$$\omega_{sp} > \beta_{sy} > 0.5\omega_{sp}$$

The design structure and prototype of Switched Reluctance Motor are shown in fig 1(a) and 1(b).

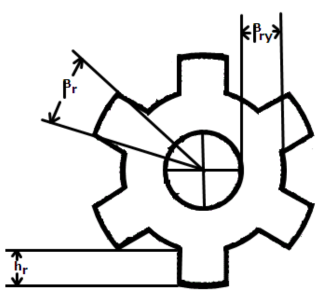

Fig. 1(c) Rotor of the 8/6 SRM

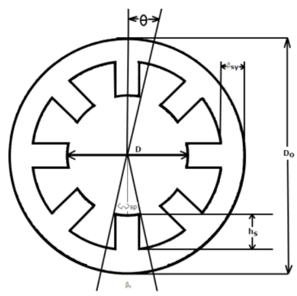

Fig. 1(d) Stator Pole Arc representation of SRM

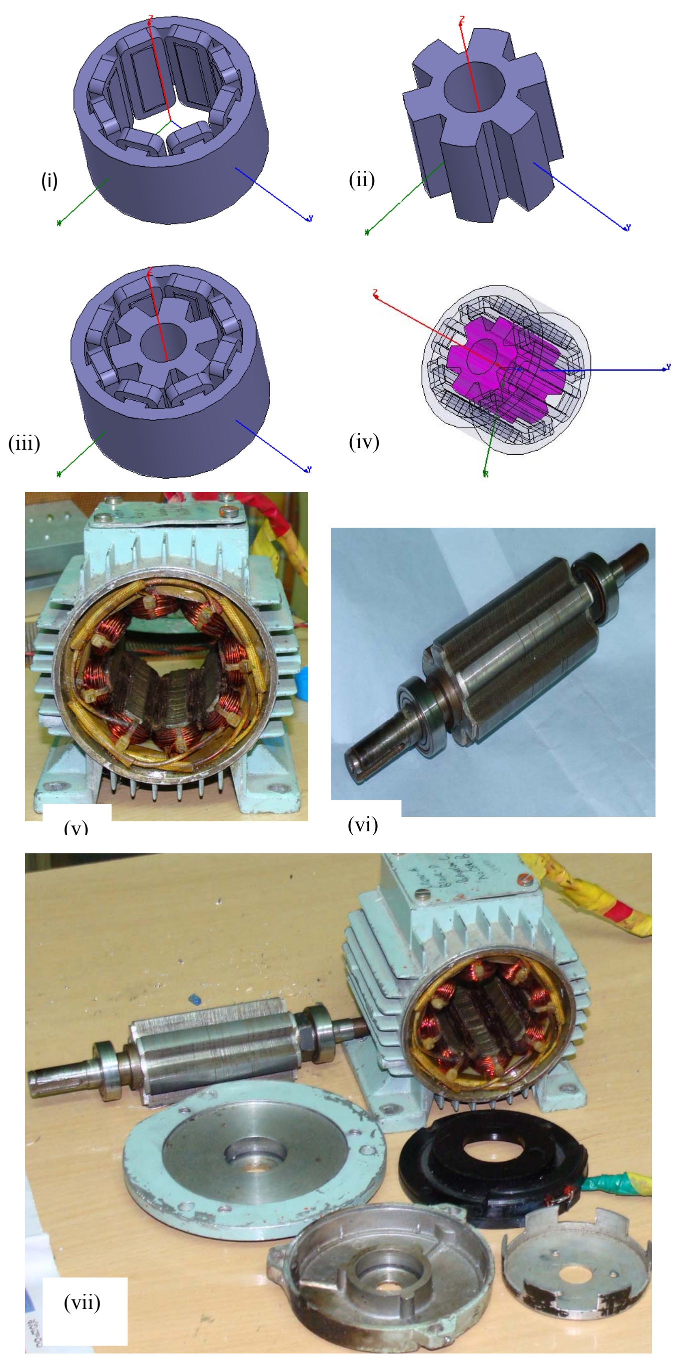

Fig 1(e) Construction details of 8/6 SRM
(i)Designed Stator (ii) Designed Rotor(iii) Both Stator &Rotor (iv)3-dimensional view of stator & rotor (v)Prototype Stator design
(vi) Rotor design (vii) Total Assembly

From Fig 2(a) it is seen that when stator current increases, flux linkage also increases and it saturates at point c and then it comes to L_s. Then it will be steady. L_s are the saturated inductance slope. The motor is already in saturation from starting then on increasing stator current, flux linkage will increase. Flux linkage increases indefinitely correspondingly to the stator.

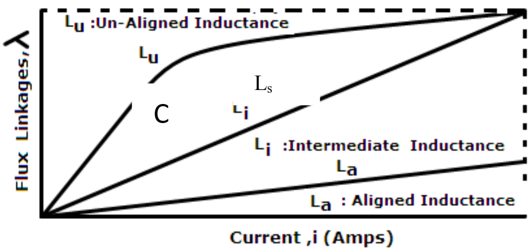

Fig. 2 (a) Flux-Linkages Vs Current for Different Values of Rotor Positions

III. EXPERIMENTAL VERIFICATION OF MAIN WINDING INDUCTANCE [1][3][5][10]

To verify the main winding inductance of SRM, a separate circuit was designed as shown in fig 3(a).In order to limit the peak value of current through the motor winding a resistance of known value is connected in series with the main winding and a switch (an electronic switch). A DC pulse voltage was applied to this combination consisting of external resistance and the motor phase winding, and current through this series combination is allowed to reach steady state current. The circuit can be treated as simple series RL, and the current raises exponential. The raise in current is decided by the time constant of the circuit. When the circuit is switched off, the current starts decaying[2]. From this decay rate of current, it was possible to determine the time constant of the RL circuit, hence from this; the inductance of the motor winding can be calculated. The main winding resistance was taken into account since the main winding was not a pure inductor. Each phase winding resistance of the motor was measured separately from a experimental set up and it was approximately 0.66 Ω per phase[1]

Fig 3(b) shows the single pulse view of the decay of the current. From this plot, the amplitude of the current was measured and then the 63.2 % value of the current was determined and found on the curve. This point was then shifted to the axis for a marker, and then time cursors were used to determine the time between the points where the current first started to decay to the point when it reached the 63.2 % value. This value of time is equal to the time constant of the RL circuit. Table 1 shows the time constants and inductances for DC currents ranging from one ampere to five amperes [8].

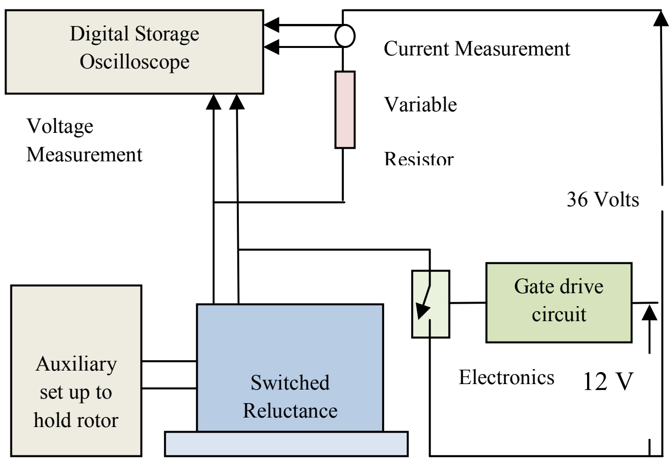

Fig 3 (a) Experimental set up for Inductance Calculation

Table 1: Inductance and Current Profile

I(A)	$I_{measured}$(A)	63.2%of $I_{measured}$(A)	$\tau = \frac{L}{R}$	L(mH)
1	0.99	0.632	1.5	1.2168
2	2.06	1.3	2.25	1.9386
3	3.05	1.927	2.5	2.016
4	4.07	2.572	2.33	1.91526
5	5.02	3.172	1.09	0.780876

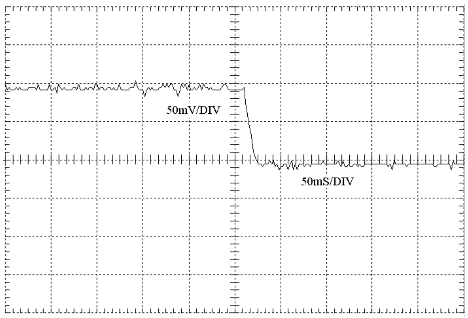

Fig: 3(b) Expanded Inductance Measurements at 2Amp DC

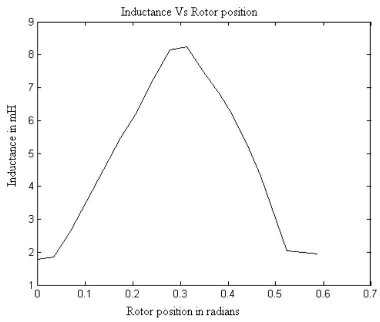

Fig. 3(c) Inductance Profile from the experimental results

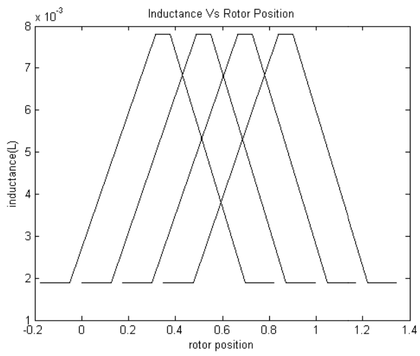

Fig. 3(d) Inductance Profiles for Specific DC Currents from simulation results

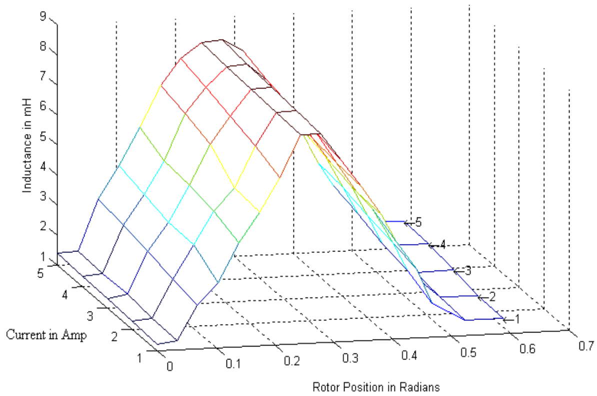

Fig. 3(e) Inductance Profile for different DC Currents in three dimensional views.

IV. FLUX-LINKAGE CHARACTERISTICS AND ITS MEASUREMENT [1][3][5][10]

The flux-linkage characteristic of the motor depends on the rotor location. Because of its doubly salient design, the motor is prone for saturation. The measure of saturation also depends on the rotor location. When a pair of rotor poles overlaps with the poles of a stator phase (aligned position), the inductance for the flux path is at its maximum level and the magnetic circuit gets saturated significantly. The flux-linkage characteristics in aligned position are represented by curve 1 in Fig 4. When the inter polar axis of the stator coincides with the rotor pole (when there is no overlap), (unaligned position), the magnetic circuit inductance will be minimum and it is not at risk for saturation as in aligned position [4]. The flux-linkage characteristics in the unaligned position is as shown in Fig.4 by curve 3. As the rotor position is changed from unaligned to aligned position, till the overlap of pole is approached the flux-linkage characteristics do not change appreciably. As the overlap begins, the flux path experiences local saturation in the pole tips and it spreads to the entire magnetic circuit with increase i_p current The flux-linkage characteristics in the intermediate position is as shown in Fig.4 by curve 2. The flux-linkage can be obtained simulation methods [2][1]

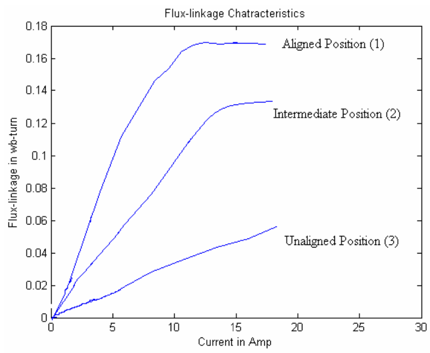

Fig. 4 Flux-linkage characteristics of SRM at different rotor positions

The theory of flux linkage characteristics is a given below: When one of the phases of motor is excited with a DC voltage pulse with all other phases kept open and with its rotor held in position by means of a mechanical arrangement , its voltage equation is given by

$$v = iR + \frac{d\psi}{dt} \qquad (1)$$

Where v is the phase voltage, R is the phase resistance, and i is its current. As all the other phases are kept open, the flux-linkage of the phase winding, **Ψ** will not be affected due to the mutual inductance between the phases. Neglecting the mutual inductance between the coupled conducting parts of the motor, the total flux-linkage of the phase winding can be considered to be due to its current, i. Therefore, the flux-linkage can be computed as,

$$\psi = \int (v - iR)dt \qquad (2)$$

For any given rotor position, the flux-linkage can be computed for different values of current using the Eq. (2). By moving the rotor to a set of equally spaced intervals between unaligned and aligned position and repeating the same procedure a set of flux-linkage vs. the current with rotor position as a parameter can be obtained.

A .Experimental Set up[10]

The flux-linkage characteristics of the laboratory SRM is obtained using the rising current method and the details are explained below[1][5]. The experimental setup for this is same as that for the inductance calculation as shown in figure 3(a). An auxiliary set up is used to hold the rotor in position against high torque produced during the experiment. By rotating the indexing head, the rotor can be taken to any desirable position. In this experiment, flux-linkage is measured for a set of rotor positions spanning from 0° to 30° at the step of 2°. Since the inductance profile is symmetrical with respect to the aligned position of a particular phase the flux-linkage characteristics of a phase will also be symmetrical with respect to the aligned position.

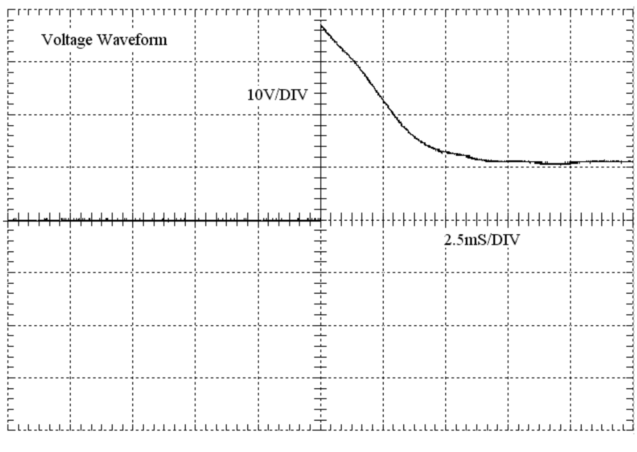

Fig. 5(a) Voltage Waveform

One of the motor phases is connected to a DC source, through an electronic switch as shown in the Fig 3(a) and the other phases are kept open. The rotor is fixed to the desired position by mechanical means and then a voltage pulse is applied to the phase winding by turning on the electronic switch. The duration of the voltage pulse is made sufficiently large to make the current reach nearly 15 to 30 more than the peak current. The raising current and the decay voltage drop across phase *a* winding at the selected positions are sampled at the same time right after turning on the electronics switch The voltage and the current waveforms recorded are shown in Fig. 5(a) and 5(b). A digital storage oscilloscope is used to acquire and store the current and voltage data digitally. The experiment is repeated for every 2 degrees of displacement of the rotor from the unaligned position to the aligned position (30 degrees). The flux-linkage characteristics will be symmetric after the aligned position. The results are shown in Fig. 4.

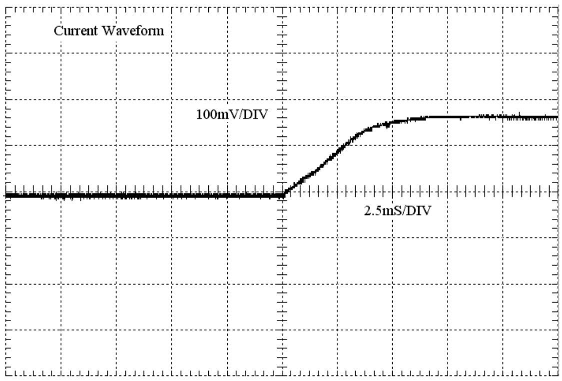

Fig. 5(b) Current Waveform

Like the flux-linkage characteristics, the torque in a machine is also a function of rotor position and excitation current. Once the whole set of flux-linkage characteristics are known, torque for each position and current can be computed through co-energy principle. The torque is produced due to the tendency of the rotor poles to align with excited stator poles. The rotor poles move from an unaligned position to an aligned position. The calculated values of torque from flux-linkage characteristics at different position is as shown in the figure 6

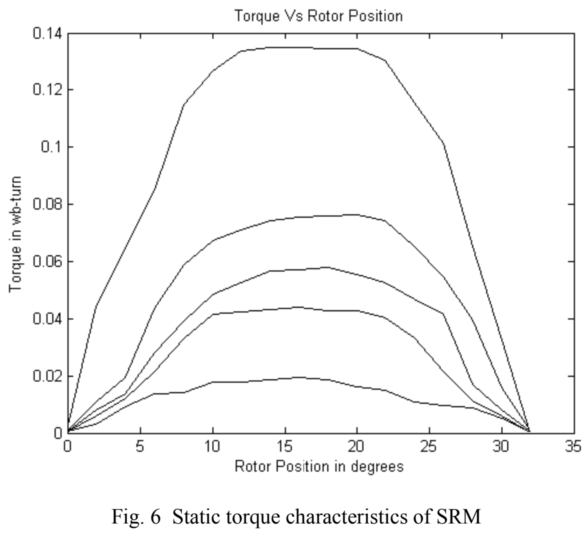

Fig. 6 Static torque characteristics of SRM

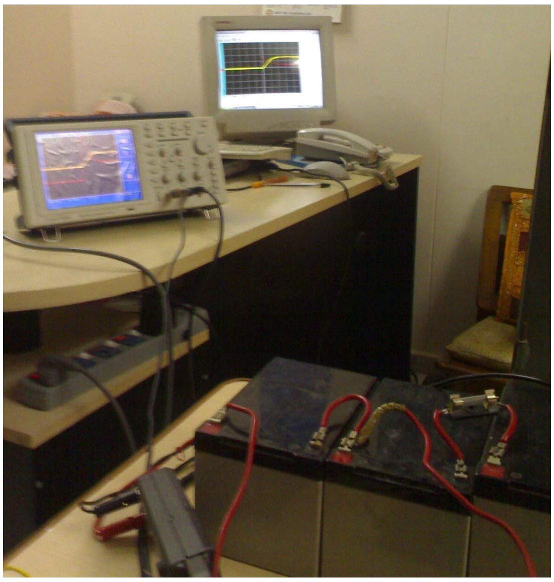

Fig.7 Test bench for flux linkage curve measurement

V CONCLUSIONS

The paper has described the design, construction and testing of a switched reluctance motor. The defining equations are presented. Based on this design aspects and equations a proto type of SRM was built. A major task in getting a good model for SRM is to get accurate flux-linkage characteristics. As the machine is doubly salient, the flux-linkage in SRM is a function of rotor position and stator current. The accuracy of the flux-linkage characteristics is very important for reliable performance prediction and control. The experimental setup and the procedure to compute the flux-linkage based on the terminal voltage and current measurements are given, and it is found that for higher currents the machine is prone to high saturation losses. Therefore it is recommended to use the motor for a rated current below the saturation current level.

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