Performance Analysis of Axially Laminated Anisotropic Synchronous Reluctance Motor

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Abstract: - Recent interest in the synchronous reluctance motor has increased with the advancement of its design. A high saliency ratio is the key factor to decide the performance of Synchronous Reluctance Motor (SRM). An axially laminated anisotropic (ALA) rotor was designed and fabricated to obtain high saliency ratio, using axially multiple C.R.G.O laminations interleaved with insulation sheets. This paper presents steady state performance analysis of SRM by developing mathematical model. Its performance was verified by experiment.

Key-Words: - Reluctance machine, Saliency ratio, axially laminated Anisotropic Rotor, Synchronous Reluctance Motor

1 Introduction

Synchronous reluctance motor can be traced back to the misty origin of electrical machinery and has been a subject in learned journals at least from last seven decades. The rotor of SRM was constructed with salient poles while the stator inner surface is cylindrical in shape and wound with three phase winding similar to an induction machine. Thus the machine typically retains all the benefits of variable reluctance machine while at the same time eliminating several of its disadvantages. The noise and torque pulsation problems, too difficult to overcome with variable reluctance motors, can be elegantly overcome in a SRM by simply winding the stator in the conventional manner so as to produce sinusoidal uniformly rotating air gap emf.

The SRM has attracted the attention many researchers from time to time. Since then, **Lawernson [4]** has intensively developed his segmental rotor design to secure optimum performance of reluctance motor for salient pole and segmental rotor construction.

A modern third generation type of motor was made by Cruickshank et al. [2]. Saliency ratios of three or more have been reported with this type of structure, which typically results in machine that competes favorably with an induction motor. This structure was considerably different from previous developments, namely to replace the usual radial laminations by axial lamination of anisotropic material with planes parallel to the axis of rotation, using essentially the technique of cut C cores machines.

The maximum synchronous output can be increased by high reactance ratios. But very high value will lead to instability. i.e. rotor oscillation about synchronous speed or about a steady synchronous speed. An analysis of stability of reluctance motors given by **Lipo and Krause** [3] with respect to certain motor parameters has clearly demonstrated this phenomenon. The essential polar characteristic of the rotor normally implies removal of rotor iron in some manner or another, with the attendant consequence of lowering power factor relative to that of induction motor. The proposal to use axial laminations of grain oriented material in place of normal radial laminations is an attempt to confer polar properties of the rotor by controlling both the external and internal anisotropy.

The main objective of this paper is to develop a mathematical model of three phase synchronous reluctance motor using park's transformation to simulate its dynamic performance. This model is utilized to obtain the performance of SRM.A prototype model of three phase SRM fitted with axially laminated an isotropic rotor has been fabricated in the given frame and rating of three phase induction machine. This machine is tested by performing the various experiments to obtain the steady state performance of SRM.

2 Problem of Operation

Electromechanical energy conversion involves the interchange of energy between an electrical system and a mechanical system through the medium of a coupling magnetic field. In case only stator winding is excited with salient pole rotor, the expression of torque is given by

$$T_{ri} = \frac{1}{2} i_s^{\,2} \frac{dL_{ss}}{d\theta} \quad \text{--- (1)}$$

Therefore, as long as the reluctance of the magnetic circuit, as viewed from the stator, varies for different positions of the rotor, a torque due this reluctance variation can exists. Inserting the general expression for the self inductance, into the above equation (1) permits us to write

$$T_{ri} = \frac{1}{2} i_s^2 \frac{dL_{ss}}{d\theta} = -\frac{1}{2}\phi^2 \frac{dR}{d\theta} \qquad \text{--- (2)}$$

Where $\Re$ is given by $\Re = \frac{\Re_q + \Re_d}{2} - \frac{\Re_q - \Re_d}{2}\cos 2\theta$

and ϕ denotes the instantaneous flux produced by the stator mmf Ni acting in the path of reluctance $\Re$. The negative sign indicates that the direction of the torque is such as to bring about a reduction in reluctance.

$T_r =$ average $T_{ri} = \frac{1}{2\Pi}\int_0^{2\Pi} T_{ri}\, d\omega t = \frac{1}{\Pi}\int_0^{\Pi} T_{ri}\, d\omega t$

If ω=ωr then the expression for the reluctance torque becomes

$$T_r = \frac{1}{8}\Phi^2 \left(\Re_q - \Re_d\right)\sin 2\delta \qquad \text{---- (3)}$$

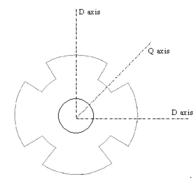
Thus we see that the machine is capable of producing an average reluctance torque, but only when the angular speed of the rotor is equal to the angular frequency of the stator line current. Furthermore, this torque varies with an argument that is double the torque angle δ. In contrast the electromagnetic torque has a fundamental variation with torque angle. The maximum reluctance torque occurs at δ=45 degrees. We define the direct-axis reactance x_d and the qudrature-axis reactance x_q as $x_d \equiv \omega L_d = \omega \frac{N^2}{\Re_d}$, $x_q \equiv \omega L_q = \omega \frac{N^2}{\Re_q}$ Where ω is the angular frequency of the stator current and N denotes the stator winding turns. Inserting the values of $\Re_d$ and $\Re_q$ in torque equation we get

$$T_r = \frac{1}{4}\frac{V^2}{\omega}\frac{x_d - x_q}{x_d x_q}\sin 2\delta \qquad \text{---- (4)}$$

It is interesting to note that for a machine with a uniform air gap, x_d and x_q is equal, which causes the reluctance torque to disappear.

3 Maximization of saliency ratio

The saliency ratio is the main factor which decides the performance of reluctance machine either as a generator or a motor. In the classical design, three phase reluctance motor analyzed and studied by various authors employed simple salient poles. The power factor and power density of three phase reluctance motor with this conventional salient pole(fig.1) rotor are lower than those for induction motor with an identical stator as the saliency ratio is very small (less than 2). Its efficiency is also very low. Manufacturing simplicity and mechanical strength were the major advantages. Recent design abandoned the traditional poles and various proposal of rotor configuration to increase saliency ratio have been cited in literature for the improvement of reluctance machine performance. The new segmental rotor (fig.2) reluctance motors gives significant improvement in its power factor, efficiency, and pull out power over conventional salient-pole rotor SRM.



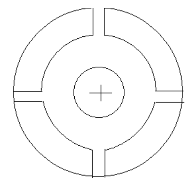
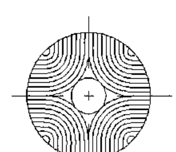


Fig.1 Salient rotor   Fig. 2 Segmental rotor

A new form of non segmented rotor which has single or multiple flux barrier for each pole pair is shown in the (fig.4). The new rotor is simple to make requires no special material. The synchronous performance of this SRM is at least equal to that of segmented rotor machines of existing design and its starting characteristics are appreciably superior. Single barrier rotor fall for short of full load performance that would compete with that of the induction motor as saliency ratio does not exceed 4.5 at full load. By using higher number barrier a saliency ratio around 9 is achievable which can give power factor sufficiently large with reduced torque ripple. Due to difficulty of constructing the multiple-barrier from a unitary lamination attention was given to replace the usual radial lamination by axial lamination of anisotropic material whose permeability was not only directional but which also followed a pattern corresponding to the natural shape of the flux lines. The ideal rotor is one which is infinitely permeable along the flux lines (fig.3) and completely impermeable across it. The axially laminated rotor approximates this arrangement. It has laminations shaped to follow the d-axis flux, and flux barrier which inhibit the q-axis flux.



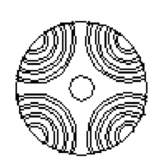


Fig. 3 ALA rotor   Fig. 4 Flux guided rotor

4 Modeling of SRM

In order to formulate the state equation for a synchronous reluctance machine, it is necessary to employ a mathematical model, which will represent the machine in the condition under study. For a two pole three phase synchronous reluctance machine the stator windings are identical, displaced by 120 degrees. Since stator windings are sinusoidally distributed, each with N_s equivalent turns and resistance r_s, flux harmonics in the air gap contribute only an additional term to the stator leakage inductance. Hence the equations which describe the behavior of SRM can be derived from the conventional equations depicting a conventional wound field synchronous machine that is Park's equation. In such machines, the excitation winding is

absent. The SRM can be started from rest to synchronous speed by proper inverter control. Hence eliminating both the field winding and damper winding equations from Park's equation forms the basis for the d-q equation for a SRM. The effect of the above transformation is to convert the stator quantities from phases a, b and c to new variables, the frame of which moves with the rotor. However since there are three variables in the stator, it is necessary to have three variables in the rotor for balance. The third variable is on a third axis i.e. the stationary axis. It is a stationary current proportional to the zero sequence current and it is zero under balanced conditions. Therefore a matrix P called Park's transformation is defined such that, $i_{0dq} = Pi_{abc}$ Park's transformation can also be used to convert voltages and flux linkages from abc quantities to 0dq quantities. The expressions are identical to the expressions for the current and are given by,

$v_{0dq} = Pv_{abc}$ and $\lambda_{0dq} = P\lambda_{abc}$ ---(5)

4.1 Voltage equation and winding inductance

$$v_{as} = r_s i_{as} + \frac{d\lambda_{as}}{dt}$$

$$v_{bs} = r_s i_{bs} + \frac{d\lambda_{bs}}{dt} \qquad v_{cs} = r_s i_{cs} + \frac{d\lambda_{cs}}{dt}$$

In matrix form

$V_{abcs} = r_s i_{abcs} + p\lambda_{abcs}$ Where p=d/dt -- (6)

$$r_s = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix}$$

$$\lambda_{as} = L_{asas} i_{as} + L_{asbs} i_{bs} + L_{ascs} i_{cs}$$
$$\lambda_{bs} = L_{bsas} i_{as} + L_{bsbs} i_{bs} + L_{bscs} i_{cs}$$
$$\lambda_{cs} = L_{csas} i_{as} + L_{csbs} i_{bs} + L_{cscs} i_{cs}$$

- In matrix form

$$\lambda_{abcs} = L_s i_{abcs}$$

$$L_s = \begin{bmatrix} L_{ls}+L_A+L_B\cos 2\theta_r & -\frac{1}{2}L_A+L_B\cos 2\left(\theta_r-\frac{\Pi}{3}\right) & -\frac{1}{2}L_A+L_B\cos 2\left(\theta_r+\frac{\Pi}{3}\right) \\ -\frac{1}{2}L_A+L_B\cos 2\left(\theta_r-\frac{\Pi}{3}\right) & L_{ls}+L_A+L_B\cos 2\left(\theta_r-\frac{2}{3}\Pi\right) & -\frac{1}{2}L_A+L_B\cos 2(\theta_r+\Pi) \\ -\frac{1}{2}L_A+L_B\cos 2\left(\theta_r+\frac{\Pi}{3}\right) & -\frac{1}{2}L_A+L_B\cos 2(\theta_r+\Pi) & L_{ls}+L_A+L_B\cos 2\left(\theta_r+\frac{2}{3}\Pi\right) \end{bmatrix}$$

Where L_{ls} is the leakage inductance, L_A is a constant magnetizing inductance, and L_B is the amplitude of the sinusoidal varying magnetizing inductance. For three phases SRM, the stator magnetizing inductances are defined as one and half times the magnetizing inductance of a two phase machine.

$$L_{mq} = \frac{3}{2}(L_A - L_B) \; L_{md} = \frac{3}{2}(L_A + L_B) \qquad \text{---- (7)}$$

The relation between phase inductances and d-q inductances in rotor reference frame is given by

$$L_d = L_{ls} + \frac{3}{2}(L_A + L_B) = L_{md} + L_{ls}$$

$$L_q = L_{ls} + \frac{3}{2}(L_A - L_B) = L_{mq} + L_{ls} \qquad \text{--- (8)}$$

4.2 Machine equation in rotor reference frame

Substituting the change of variables into stator voltage equation yields

$$\left(P_s^r\right)^{-1} V_{qdo} = r_s \left(P_s^r\right)^{-1} L_{qdo}{}^r + P\left[\left(P_s^r\right)^{-1} \lambda_{qdos}{}^r\right]$$

The nonlinear differential equations model of synchronous reluctance motors in rotor reference frame is

$$\frac{di_{qs}}{dt} = -\frac{r_s}{L_q} - \frac{L_d}{L_q} i_{ds}\omega_r + \frac{1}{L_q} V_{qs},$$

$$\frac{di_{ds}}{dt} = -\frac{r_s}{L_d} - \frac{L_q}{L_d} i_{qs}\omega_r + \frac{1}{L_d} V_{ds},$$

$$\frac{d\omega}{dt} = \frac{P}{2J}\left[T_e - T_l - B_m\left(\frac{2}{P}\right)\omega\right] \qquad \text{… (9)}$$

and $\frac{d\delta}{dt} = \frac{P}{2}(\omega_r - \omega_s)$

4.3 Steady state performance

The resolution of the phase current I into direct and quadrature axis components I_d and I_q is preferred for reluctance machines since the mmf of I_d acts directly along an axis through a pole center or the d-axis and the mmf of I_q acts directly along an axis placed between poles(q axis).All reluctance machines have physical poles , and so the just mentioned resolution of current or MMF is entirely natural not only for the immediate purpose but also for other purposes, such as the calculation of the direct and quadrature axis reactance's X_d and X_q respectively. The construction of the phasor diagram depends upon the conditions that the stator currents produce a synchronously rotating MMF wave varying sinusoidally in space and that the voltages and currents vary sinusoidally in time. These conditions are nearly true for the reluctance machine operating at a steady state.The phase current I and the axis currents I_d and I_q are relatable to the phase voltage V ; I lags V by the power factor angle ϕ and I_q is specified to lag V by angle δ , which is the torque angle. Each axis current I_d, I_q flows, respectively ,through impedances Z_d and Z_q, so that two phasors are formed : viz., $I_d Z_d$ and $I_q Z_q$.Since at synchronous speed there are no induced rotor current or phasors from other sources , it follows that the vector sum of $I_d Z_d$ and $I_q Z_q$ equals the applied phase voltage V . The impedances Z_d and Z_q are

$$Z_d = \sqrt{x_d^2 + r_a^2} \; ; \; Z_q = \sqrt{x_q^2 + r_a^2} \quad \ldots. \; (10)$$

It is difficult now to orientate the four phasors $I_d X_d, I_d r_a, I_q X_q$ and $I_q r_a$ with respect to voltage. This is done in fig.5 which represent the phasor diagram of reluctance motor. The direct and quadrature axis locations are also indicated in fig.5.These axes are exactly what their names imply; they are axes and not phasors. However, the d and q axes being fixed in the synchronously rotating rotor define the rotor position with respect to another synchronously rotating axis.

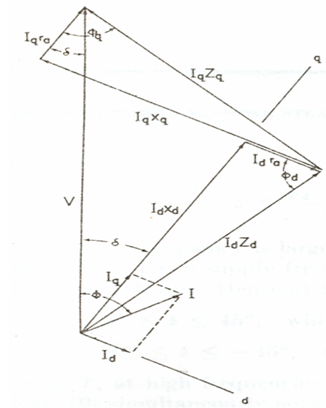


Fig.5 Phasor diagram for SRM

4.4 Determination of currents

The I_d, I_q currents are found by projecting the voltage V on the d and q axes from which $V\cos\delta = I_d X_d + I_q r_a$ . . . (11)

$V\sin\delta = I_q X_q + I_d r_a$ … (12)

Solving for the currents we obtain

$$Iq= \frac{VZ_d \cos(\phi_d - \delta)}{x_d x_q + r_a^2} \quad \ldots (13)$$

$$Id= \frac{VZ_q \sin(\phi_q - \delta)}{x_d x_q + r_a^2} \quad \ldots (14)$$

Where δ = Torque angle

$$\phi_d = \tan^{-1}\frac{x_d}{r_a} \qquad \phi_q = \tan^{-1}\frac{x_q}{r_a} \quad \ldots (15)$$

The rms current to each phase is I= $\sqrt{I_d^2 + I_q^2}$. … (16)

4.5 Power and torque

The input power $mVI\cos\phi$ to all phases is found by projecting the I_d, I_q currents along the Voltage axis of fig.5 thus obtaining

$P_i = mV(I_q \cos\delta - I_d \sin\delta)$ ... (17)

The term δ is eliminated by using (1) and (2), yielding

$$P_i = mI_d I_q (X_d - X_q) + mI^2 r_a \; \ldots. (18)$$

The developed electrical output power P_e is the input power minus the ohmic losses

$P_i - mI^2 r_a$, or $P_e = mI_d I_q (X_d - X_q)$ …. (19)

The relation of power to torque is $P_e = T_e \omega_m$ where ω_m is the angular velocity in mechanical radians per second, in terms of electrical radians, $P_e = T_e (2/P)\omega$ .Hence the developed electrical torque is

$$Te = \frac{mPI_d I_q (L_d - L_q)}{2} \quad (20)$$

From equation (13) and (14) for steady state currents, the product of Id Iq is

$$I_d I_q = \frac{V^2 f_{\omega 0}}{\omega^2 L_d L_q} \sin(\phi_q - \delta)\cos(\phi_d - \delta) \quad (21)$$

Where

$$f_{\omega 0} = \frac{\sqrt{1+(r_a / x_d)^2}\sqrt{1+(r_a / x_q)^2}}{\left[1+(r_a^2 / x_d x_q)\right]^2} \quad (22)$$

By substituting equation (22) in (21), the electrical developed torque T_e for m phases is obtained.

$$Te = \frac{mPV^2}{2\omega^2}\left(\frac{1}{L_q} - \frac{1}{L_d}\right) f_{\omega 0} \sin(\phi_q - \delta)\cos(\phi_d - \delta) \quad (23)$$

5 ANALYSIS OF STEADY STATE MODEL

Load angle or torque at any load can be calculated using the torque by equation (23). By this load angle direct and quadrature axis current can be calculated by equation (13) and (14). To calculate value direct axis inductance by using function L_d in terms of direct axis current I_d .Since load angle δ also depends upon L_d . Final value of L_d and I_d can be obtained by iteration. The input and output power for SRM can be obtained using the value of load angle, direct and quadrature axis current by the equation (17) and (19). The power factor and efficiency can also be calculated by equation (17) and (19) for steady state model of SRM.

6 Experimental set up

A standard stator frame initially used for a three phase squirrel cage induction motor rated 1 kw 400/230 V, 50 Hz and 4-pole was employed for constructing the SRM (Fig.6). Its rotor was replaced with an axially laminated anisotropic rotor. Basic data of this prototype are given in Appendix. Four sets (one per pole) of “sandwiches”, consisting of magnetic and insulation layers alternately, were formed and attached to the shaft using nonmagnetic bolts with nonmagnetic pole holders.

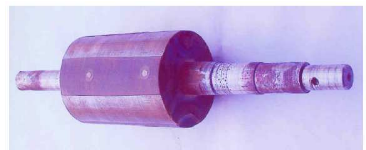


Fig.6 axially laminated anisotropic Rotor for SRM

7 Results and Discussion

The steady state performance of axially laminated anisotropic synchronous reluctance motor has been carried out experimentally and compared with simulated results. Its parameters have been determined by performing synchronous running test, and ac standstill test. The presence of harmonics was analyzed at two different load conditions, one at no load and another at on load.

The magnitudes of X_d, X_q, r_a and W_0 were computed and then the machine performance was estimated for no-load and pull-out conditions. The steady state performance of SRM was evaluated in MATLAB environment Fig.7, Fig.8. The experimental results for power factor and efficiency show good agreement with the calculated values (Fig.9, Fig.10, and Fig11).

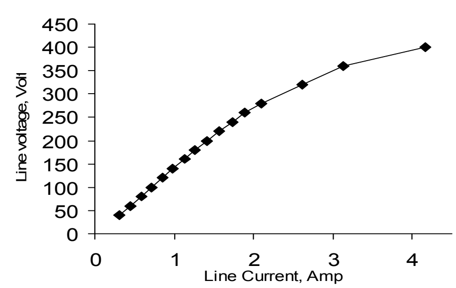


Fig.7 Saturation Effect in prototype SRM

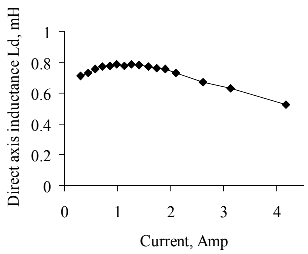


Fig.8 Variations of direct axis inductance with phase current.

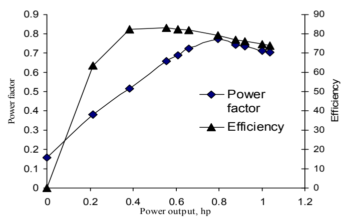


Fig.9 Variations of PF and η of prototype SRM with power output.

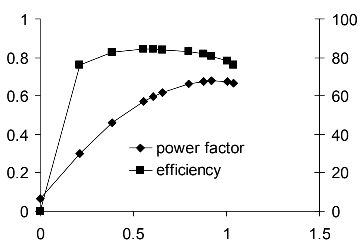


Fig.10 Variations of PF and η of steady state model with power output.

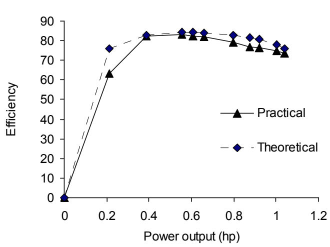


Fig.11Comparison of theoretical and practical efficiency of SRM

8 CONCLUSION

The steady state analysis performed on simulated motor as well as experimentally on test motor is found to be in close agreement. It is also shown that the reluctance machine can be cheap, reliable and robust alternative to induction motor.

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