STATIC ANALYSIS OF MUTUALLY COUPLED SWITCHED RELUCTANCE MOTOR WITH FINITE ELEMENT METHOD

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ABSTRACT

This paper introduces the concept of fully pitched winding in a switched reluctance motor. It is demonstrated that such a winding configuration results in more efficient use of electric circuit. In contrast to the conventional switched reluctance motor (SRM) with short-pitched winding, the new configuration produces torque by exploiting the rate of changing mutual inductance between phases. So, it is called Mutually Coupled Switched Reluctance Motor (MCSRM). Compared with the conventional type, each phase contributes to positive torque production for two-thirds of cycle of rotation. Consequently, this paper shows that the new winding configuration resulted in increased torque production for the same amount of copper and magnetic material.

I. INTRODUCTION

Switched reluctance motor has been developed around the concept of short pitching each phase winding, generally around a single stator tooth. By employing such a winding configuration, coupling between machine phases is completely eliminated, so that torque is generated due to the rate of change of self-inductance of the excited phases.

Utilization of electric circuit is poor since each phase winding can only contribute to positive torque for a maximum of half electrical cycle. In other words, each phase contributes positive torque production while its inductance rises during motor operation.

In contrast to conventional SRM, the new winding configuration allows to produce entire torque from changing mutual inductance between phases. Because of the fundamental discrepancies in operating principles, each phase of the machine can contribute to torque production for considerably greater than half electrical cycle, leading to more efficient utilization of the winding.

II.FUNDAMENTAL OPERATING PRINCIPLE OF CONVENTIONAL SRM

In order to explain the basics principles of operation, an example of a three-phase 6-4 SRM will be used. The main principles of operation will remain same in the machines having different stator-rotor pole configuration. Figure 1. shows a conventional short-pitched SRM with single phase excited. It is clear that the other two phases will not contribute the magnetomotive force (MMF) which drives flux through stator teeth S1 and S4 and produces anticlockwise torque on the rotor teeth R_1 and R_3. So it is concluded that each phase will contribute to the torque production for only one-third of each electric cycle. Furthermore, complete decoupling between phases assures that mutual inductance is not a function of rotor position. .

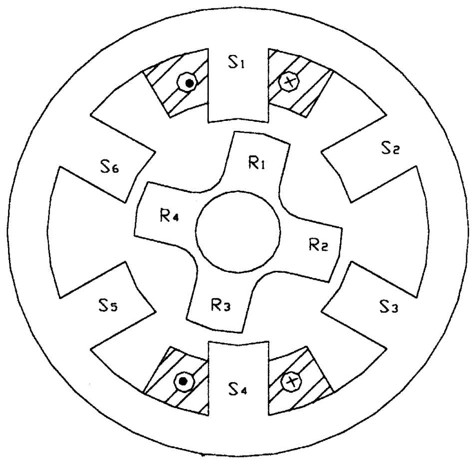


Figure.1 Conventional Switched Reluctance Motor.

In conventional switched reluctance machines, the produced torque can be directly determined from the area enclosed by the flux linkage/current locus of each phase. The self inductance of any phase rises as rotor teeth come into alignment with the excited stator teeth and consequently the torque is produced according to

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

The more general expression for torque in three-phase reluctance machine is given in equation 2 as follows,

$$\begin{aligned} T = {} & \frac{1}{2} i_a^2 \frac{dL_a}{d\theta} + \frac{1}{2} i_b^2 \frac{dL_b}{d\theta} + \frac{1}{2} i_c^2 \frac{dL_c}{d\theta} + \\ & \frac{1}{2} i_a i_b \frac{dM_{ab}}{d\theta} + \frac{1}{2} i_b i_c \frac{dM_{bc}}{d\theta} + \frac{1}{2} i_c i_a \frac{dM_{ca}}{d\theta} \end{aligned} \qquad (2)$$

where, in a conventionally wound SRM, the last three terms are generally ignored because of complete decoupling between phases. In conventional SRM, the self inductance of phase winding consists of a constant leakage value plus a much larger component as follows,

$$L_{phase} = L_l + \mu_0 \frac{N^2 \alpha \beta_L}{2G} \qquad (3)$$

where L_{phase} is total inductance of a phase, L_l is the leakage inductance per phase, N is the number of turns per phase, α is the machine axial length, G is the air gap length, β_L is the length of overlap between stator and rotor teeth through which flux generated by the phase current will flow. As seen from Figure.2 β_L is made up of the sum of the overlapping lengths x and y of two rotor teeth with stator teeth.

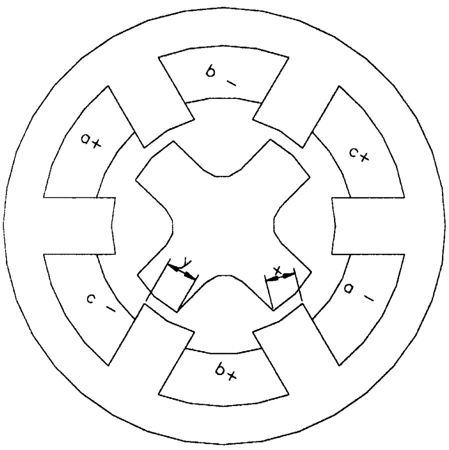


Figure 2 The length of overlapping tooth for self and mutual inductance.

It can be seen from Figure 2 that β_L is independent of rotor position for fully pitched winding configuration since one rotor tooth comes into alignment as the other rotor tooth comes out of alignment. This result means that the first three terms of equation 2, which are only torque producing components in conventional switched reluctance motor, are zero [1-4].

III. FUNDAMENTAL OPERATING PIRINCIPLE OF MCSRM

The mutual inductance between phases can be deduced in a similar way to self inductance. Using the same assumptions for Figure. 2 ,

$$M_{ab} = \mu_0 \frac{N^2 \alpha \beta_M}{2G} \qquad (4)$$

where, β_M = x-y.

As stated before, the new machine produces torque solely due to the mutual inductances rather than self inductances. This requires two phases be conducting at any instant. For example, when phases a and b are on, the derived torque is as follow,

$$T = i_a i_b \frac{dM_{ab}}{d\theta} \qquad (5)$$

In contrast to the conventional case in Figure 1, Figure 3 shows the same machine with fully pitched winding. Two phases are now excited with unipolar current excitation in order to produce the same excitation pattern as in Figure 1. S_2, S_3, S_5 and S_6 stator teeth remain unexcited. Although the magnetic circuit remains the same for both winding configurations, the twice area of copper is available for excitation when fully pitched windings are employed. Compared with the conventional short pitched machine, far better utilization of the electric circuit is achieved since each phase conducts two-thirds of one electric cycle. For a given peak instantaneous phase current, not only back emf is doubled but also the torque output is increased significantly.

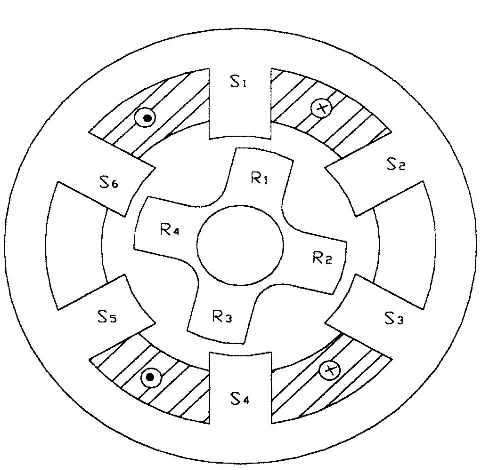
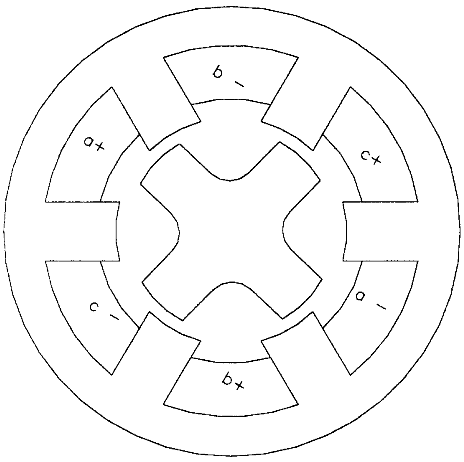


Figure 3. The excited winding area around stator teeth S_1 and S_4.

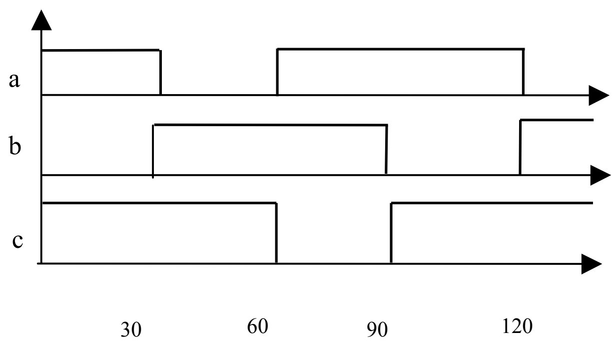
In order to compare the new machine with conventional machine it would be useful to consider eqn. 1 and eqn.5. In eqn. 5 , the rate of change of mutual inductance is twice that of the rate of change of self inductance in eqn.1. Hence, for a given current level, the new machine will provide four times higher torque than conventional machine in an unsaturated machine. [1-4]

IV. THE MCSRM MODEL WITH FINITE ELEMENTS METHOD

The examined model of the switched reluctance motor is 3-phase, 6/4 motor, which has 6 stator and 4 rotor poles[5,7]. The three phase winding arrangement of the examined mutually coupled switched reluctance motor and its excitation pattern with unipolar current are illustrated in Figure 4.



(a)



(b)

Figure 4. The winding arrangement and excitation pattern.

The finite element model of SRM and MCSRM have been built to predict their performances by using ANSYS™.[10] Material properties defined as BH magnetizing curve are shown in Figure 5. Since the core material properties of MCSRM is the same as core material properties of conventional SRM, the model of MCSRM has nonlinear characteristics as well.

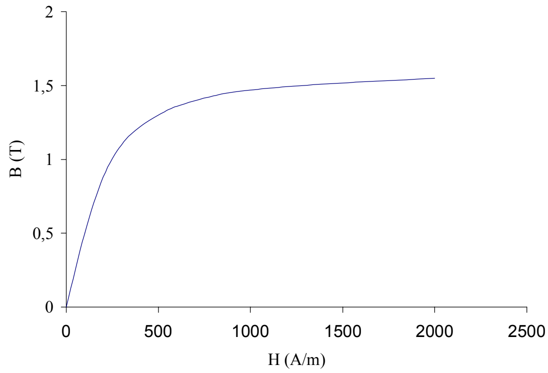


Figure 5. Magnetizing curve of the core materials.

The element defined by eight nodes for 2-D model has been used in the finite element model of MCSRM. The element type has three degrees of freedom per node; magnetic vector potential (AZ), current (CURR), electromotive force (EMF) [8].

Modelling in the air gap of MCSRM is very important to obtain a good field solution. The air gap ($g=0.2286\cdot10^{-3}$ m) between the radial pair of stator and rotor poles has been designed quite accurately. The finite element method of MCSRM consists of approximately 6000 elements and 16000 nodes. Basic principle of magnetic solution of MCSRM is based on the Poisson expression which is given as follows;

$$\frac{\partial}{\partial x}\left(v\frac{\partial A_z}{\partial_x}\right)+\frac{\partial}{\partial x}\left(v\frac{\partial A_z}{\partial_y}\right)=-J_0 \qquad (6)$$

A_z = The z component of the vector potential, A,
J_0 = The z component of the density of current, J,
v = The magnetic reluctivity.

In order to obtain static torque curves of MCSRM and SRM, the rotor poles were rotated in 5° increments over a sufficiently long angular displacement. The windings were excited by unipolar currents 3, 5, 7, 10, 15 and 20 A. Only the data for 10 A current level were used to compare torque outputs of two machines.

The finite element method is used to obtain the magnetic vector potential values throughout the motor. These vector potential values can be processed to determine the field distribution, flux linkage and torque. The static analysis has been performed using the finite element model of SRM. The solution includes neither time nor velocity vector.

V. CALCULATION OF TORQUE

The torque characteristic has been derived using the Maxwell stress-tensor method. In this method, torque is computed from the force produced by the Maxwell stresses over a closed surface enclosing the entire rotor. The mathematical expression of the torque can be given as,

$$T = v_0 \cdot Z \cdot R \int_S B_r \cdot B_\theta \cdot dS \qquad (7)$$

v_0 : reluctivity of air,
Z : length of SRM,
R : radius of cylindrical surface in the middle of airgap,
B_r : radial component of the flux density,
B_θ : tangential component of the flux density.

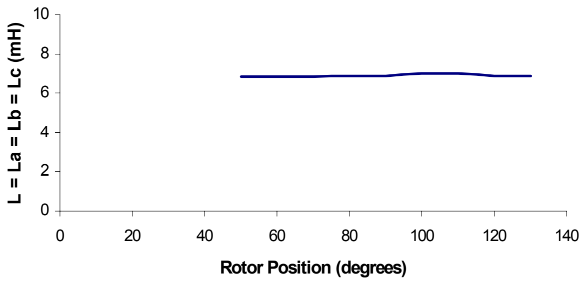


Figure 6. Angular variations of self inductances.

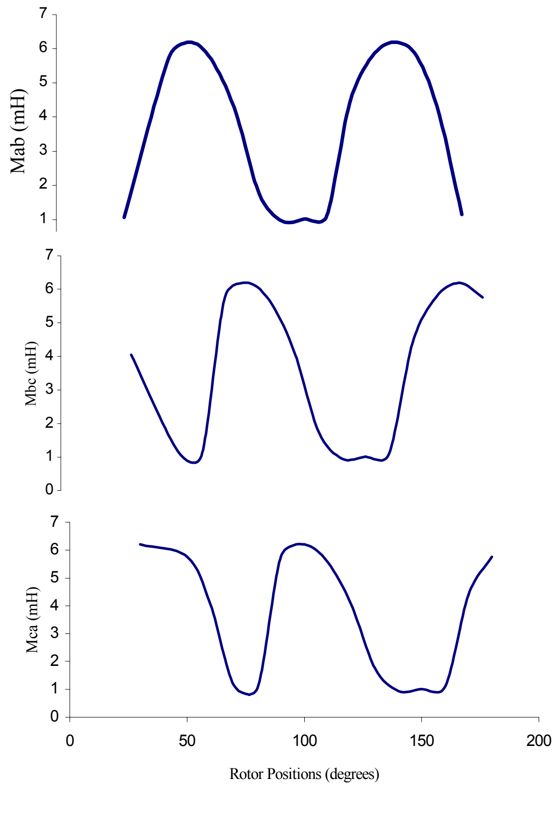


Figure 7. Angular variations of mutual inductances.

The angular variations in self inductances were obtained as shown in Figure 6. It is clearly concluded from this figure that the first three terms in equation 1 will be zero and all of the torque will be produced by virtue of mutual inductance variation.

The angular variations in mutual inductances are illustrated in Figure 7. These self and mutual inductance profiles are somehow interesting when we compare them with inductance profiles of conventional machine. It is a well known fact that a conventional SRM has position dependent self inductance profile and position independent mutual inductance profile [6,8,9].

Torque derived in terms of changing mutual inductances is shown in Figure 8.Positive torque is produced by rising side of mutual inductances with unipolar excitation. However, it can be produced by falling side of mutual inductance when the windings are excited with bipolar current.

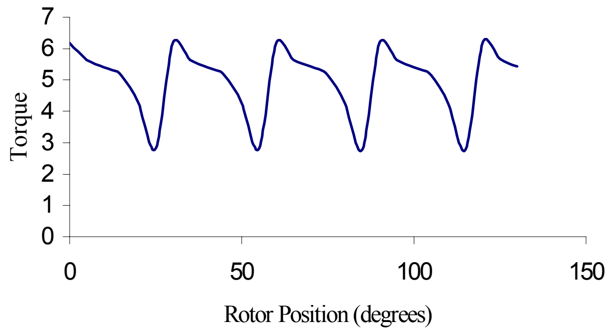


Figure 8. The torque curves of mutually coupled switched reluctance motor.

When the torque output of MCSRM shown in Figure.8 is compared with the torque output of conventional machine shown in Figure 9, it is clearly concluded that new winding configuration provides higher torque output for the same amount of copper and magnetic material.

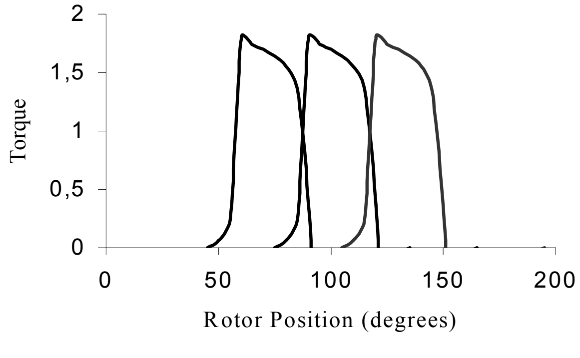


Figure 9. The torque curves of conventional type switched reluctance motor.

Since two phases are conducting at any instant, there is strong coupling between conducting phases. This fact is the cause of a major drawback in MCSRM which is the torque produced by any phase is not only dependent on rotor position and current level but also it is dependent on the current level of other phases. This situation makes the analysis of he machine more complicated.

CONCLUSION

In this paper, a switched reluctance motor with fully pitched winding has been introduced. It has been shown that the variation of self inductances is constant and is independent from rotor position. The torque has been produced entirely by virtue of the variation in mutual inductances. For this reason this new machine is referred to as mutually coupled switched reluctance motor.

Compared with conventional type, an increase in torque output has been achieved. The mutually coupled switched reluctance motor has considerably higher end-winding losses. To make an ideal comparison, it is needed to take end-winding losses into account and to compare these motors in equal iron and copper losses.

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