Effects of Force Fitting on the Inductance Profile of a Switched Reluctance Motor

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Abstract - **The effects of compression on the magnetic properties of a steel alloy used in electromagnetic devices is investigated. The results of a case study on a switched reluctance motor are presented. It is demonstrated that compression affected the winding inductances profiles as well as the performance characteristics of the motor. The simulated performance results are verified by comparison to experimental data.**

I. Introduction

Electromechanical systems used in marine and aerospace applications are designed with very stringent requirements on weight and volume. Accordingly, electric machines used in these applications usually have relatively high values of airgap flux density to maximize the output with respect to the volume and are operated at high speeds to reduce the weight. In addition, the casing used to hold the stator of an electric machine is made from light weight material such as aluminum or magnesium. However, the force fitting of the casing around the stator could change the magnetic characteristics of the stator material due compression resulting from the difference in the temperature coefficients that exists between the casing and stator materials. In this work, the effects of compression on the magnetic properties of a steel alloy used in electromagnetic devices are investigated. The results of a case study on a 6/4, 0.15 hp switched reluctance motor are presented. The force fitting of an aluminum casing around the stator resulted in a change in the magnetic characteristics of the stator steel laminations due to compression. This, in turn, resulted in a change in the winding inductance profiles of the switched reluctance motor (SRM). The effects of compression on the SRM winding inductance profiles are shown as obtained from nonlinear magnetic field solutions and measurements. It is demonstrated that the exclusion of the compression effects on the magnetic characteristics of the steel laminations in the nonlinear field analysis could yield erroneous results. In addition, the effects of compression on the performance characteristics of the SRM drive system are investigated. In order to demonstrate the effects of compression on the performance characteristics of the SRM drive, two sets of parameters were determined. In the first set the effects of compression were excluded while the second set included these effects. Furthermore, the simulation results were compared to test data for verification.

II. Switched Reluctance Motor Drive System and State Space Model Description

The SRM utilized for the analysis is a 6/4 three-phase motor with a 0.15 hp rating at 5000 rpm. A cross section of the machine is shown in Figure (1). The coils of diametrically opposite stator poles are connected in series to aid each other and to form one phase of the machine. The motor consists of three phase windings designated as (a), (b), and (c). The inverter used for this study is shown in Figure (2). When a phase is 'on', the dc supply voltage is placed across the phase winding. When a phase is 'off', the energy stored in the motor phase winding is returned to the dc source through the antiparallel diodes.

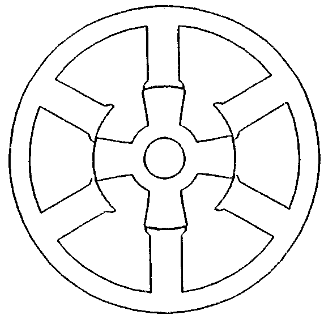

Figure (1): Motor Cross Section

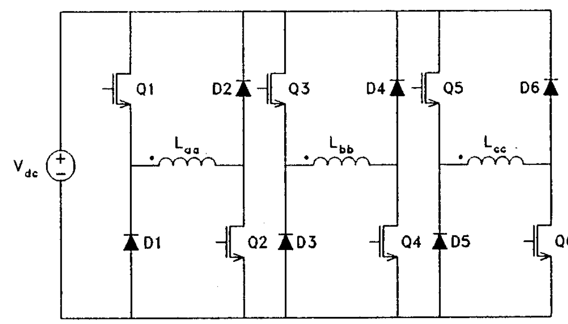

Figure (2): Inverter Schematic

Most of the efforts dealing with the modeling of switched reluctance motors have centered on the use of measured values of the motor inductances or flux linkages [1-4]. The drawback with these approaches is that it requires the construction of the actual device. In this work, a lumped parameter state space model in the natural abc frame of reference is derived and the the motor model parameters are determined from magnetic field solutions. Based on this approach, the terminal voltage of the j^{th} winding in the SRM system of three magnetically coupled coils can be expressed as follows [5,6]:

$$v_j = r_j i_j + (\sum_k [\frac{\partial \lambda_j}{\partial i_k}\frac{di_k}{dt}]) + [\frac{\partial \lambda_j}{\partial \theta}\frac{d\theta}{dt}] \qquad (1)$$

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Here j, k =a, b, and c. Also, r_j is the Ohmic resistance of the j^{th} winding, λ_j is the flux linkage of the j^{th} winding, and θ is the rotor position from a fixed reference. The first term on the right hand side of equation (1) represents the Ohmic voltage drop, the second term represents the transformer voltage, and the last term represents the rotational voltage. In addition, the term

$$\frac{\partial \lambda_j}{\partial i_k} = L_{jk}^{inc} \quad (2)$$

represents the incremental inductance. The superscript inc will be removed for simplicity. The term

$$\frac{d\theta}{dt} = \omega_m \quad (3)$$

represents the mechanical speed, ω_m, in radians per second. Equation (1) can be written in matrix form as:

$$\underline{V} = \underline{RI} + \underline{L}\frac{d\underline{I}}{dt} + \omega_m \frac{d\underline{L}}{d\theta}\underline{I} \quad (4)$$

where the matrix $\underline{L}$ is:

$$\underline{L} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \quad (5)$$

As shown in equation (5), the mutual inductances are accounted for in order to determine their effect on the device performance. The phase voltages $\underline{V}$ can be represented as:

$$\underline{V} = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^T \quad (6)$$

where the superscript T denotes the transpose of a matrix. The matrix $\underline{R}$ represents the phase resistances:

$$\underline{R} = \begin{bmatrix} r_a & 0 & 0 \\ 0 & r_b & 0 \\ 0 & 0 & r_c \end{bmatrix} \quad (7)$$

The array $\underline{I}$ represents the phase currents:

$$\underline{I} = \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^T \quad (8)$$

The values of the currents i_a, i_b, and i_c, of equation (4) can be determined numerically for any set of initial conditions and terminal voltages v_a, v_b, and v_c. As can be appreciated from equation (4), the main parameters of the state space model are the stator winding inductances of equation (5). The effects of compression on these parameters as obtained from nonlinear magnetic field solutions and measurements are discussed below.

III. Effects Of Compression On The Inductance Profiles

As mentioned previously, the force fitting of an aluminum casing around the stator of a SRM machine resulted in a change in the magnetic characteristics of the stator steel laminations due to compression. The effects of compression on the SRM winding inductance profiles are shown as obtained from nonlinear magnetic field solutions and measurements. It is demonstrated that the exclusion of the compression effects on the magnetic characteristics of the stator steel laminations in the nonlinear field analysis could yield erroneous results.

An energy and current perturbation approach applied to numerical magnetic field solutions provides the basis for the calculation of the machine self and mutual incremental inductances in this work. This approach has been developed and experimentally verified in earlier works [5,7].

In order to calculate a machine self inductance, L_{jj}, and a mutual inductance, L_{jk}, the global energy W at the operating point is first calculated. Next, currents through one or two coils are perturbed positively or negatively by an incremental value Δi with the remaining currents held constant. Using the resulting energy values as obtained from magnetic field solutions, the inductances are determined according to the following expressions:

$$L_{jj} = [W(i_j - \Delta i_j) - 2W + W(i_j + \Delta i_j)]/(\Delta i_j)^2 \quad (9)$$

$$\begin{aligned} L_{jk} = \ & [\ W(i_j + \Delta i_j, i_k + \Delta i_k) \\ & - W(i_j - \Delta i_j, i_k + \Delta i_k) \\ & - W(i_j + \Delta i_j, i_k - \Delta i_k) \\ & + W(i_j - \Delta i_j, i_k - \Delta i_k)]/(4\Delta i_j \Delta i_k) \quad (10) \end{aligned}$$

Equations (9) and (10) were utilized with the developed two-dimensional finite element model in order to determine the self inductances L_{jj} and the mutual inductances L_{jk}.

In order to study the effects of compression on the magnetic characteristics of the stator steel laminations, the stator winding inductance profiles were determined for two cases at no-load. In the first case, original B-H characteristics for the stator steel laminations, which do not account for compression effects and as supplied by the manufacturer, were used and are shown in Figure (3) by the solid line. Using a series of nonlinear magnetic field solutions over an entire electrical cycle in conjunction with the energy perturbation approach [5-7] resulted in all winding self and mutual inductances. This was performed by stepping the rotor by increments of 2^o and performing a nonlinear magnetic field solution at each rotor position. The profile of a stator phase self inductance is shown in Figure (4), while the stator phase mutual inductance is shown in Figure (5). In addition, Figures (4) and (5) show the corresponding measured values. An inspection of the two profiles in Figures (4) and (5) reveals the discrepancies between the predicted and actual values. In the second case, the stator steel lamination B-H characteristics were modified to account for the compression effects [6,8-10]. This resulted in the modified B-H characteristics shown in Figure (3) by the dashed line. Again, a series of nonlinear magnetic field solutions which account for the effects of compression in conjunction with the energy perturbation approach resulted in the stator phase self inductance profile shown in Figure (4) and the stator phase mutual inductance profile shown in Figure (5). A comparison of these values with measured data reveals the good agreement between the predicted and actual values of the inductances. It should be noted that the calculated inductance values should be slightly less in magnitude than the measured inductance values due to the fact that the end windings are not taken into account in the two-dimensional finite element analysis. Accordingly, it is demonstrated that in cases of high stress conditions due to force fitting, the compression effects on the magnetic characteristics of the stator laminations should be taken into account. To further demonstrate the effects of compression, the performance of the SRM drive system of Figure (2) was predicted using the state space model given in equation (4). The predicted performance characteristics were obtained using the two sets of inductance data described above.

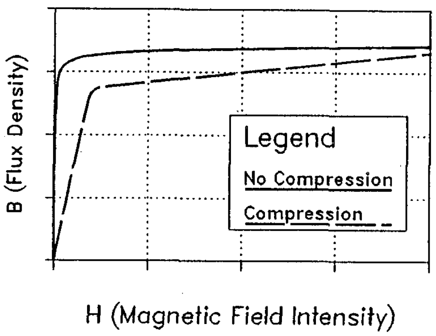

Figure (3): Original and Modified B-H Curves

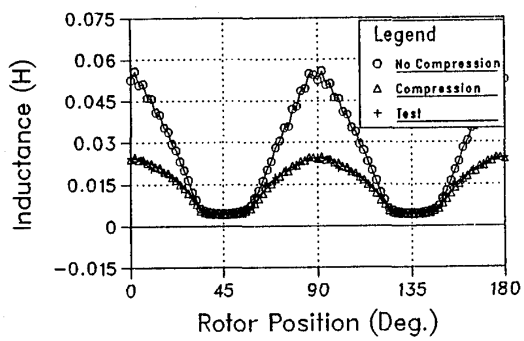

Figure (4): Measured and Calculated Phase Winding Self Inductances

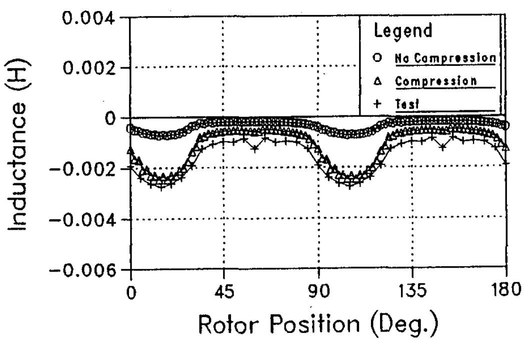

Figure (5): Measured and Calculated Phase Winding Mutual Inductances

IV. Effects Of Compression On The Performance Characteristics Of The Switched Reluctance Motor Drive System

The performance characteristics at no-load were predicted for the SRM drive system of Figure (2) for two cases. In the first case, inductance values which exclude the compression effects were used in the analysis. Meanwhile, in the second case, the inductance values which account for the compression effects were used.

The state model of equation (4) was used in conjunction with the computed values of the inductances to predict the dynamic performance of the SRM and the drive circuit of Figure (2). It should be noted that the three phases of the switched reluctance motor are shown and labeled as (a), (b), and (c) in Figure (2). Each of these phases has a self inductance and a resistance. Also, each phase is magnetically coupled through mutual inductances to the remaining two phases. In order to use the calculated inductances in the state model of equation (4), the self and mutual inductance data corresponding to the profiles as shown in Figures (4) and (5) was represented by Fourier Series type expressions of the form:

$$L_{jk} = a_o + \sum_{n=1}^{\infty}[a_n \cos(n\theta) + b_n \sin(n\theta)] \tag{11}$$

where a_o is the dc value of the inductance, and a_n and b_n are the coefficients for the cosine and sine terms of the n^{th} harmonic. It should be emphasized that the effects of space harmonics and magnetic nonlinearities were accounted for in the self and mutual inductance expressions of equation (11). Using the above models, the steady state performance of the SRM drive system was predicted. The analysis resulted in the current and voltage waveforms throughout the system.

Based on the above, the current waveform of a stator phase was predicted using the state space model and the inductance expressions which exclude the effects of compression and is given in Figure (6). Meanwhile, Figure (7) shows the predicted stator phase current as obtained from the model using inductances which account for compression effects. Finally, the measured current waveform at no-load is given in Figure (8) for comparison.

An inspection of the current waveforms of Figures (6) and (8) reveals the discrepancies between the measured data and corresponding simulated values based on inductance values which exclude the compression effects on the magnetic characteristics of the stator steel laminations. Meanwhile, a comparison of the current waveform of Figure (7), which is based on inductance data that accounts for compression effects, and the corresponding measured values of Figure (8) reveals the excellent agreement between the two waveforms. These results further demonstrate that in cases of high stress conditions due to force fitting, the exclusion of compression effects on the magnetic characteristics of the stator steel laminations in nonlinear field analysis could yield erroneous results.

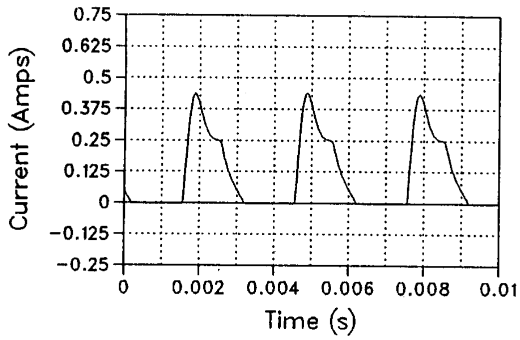

Figure (6): Simulated Phase (a) Current Excluding Compression Effects

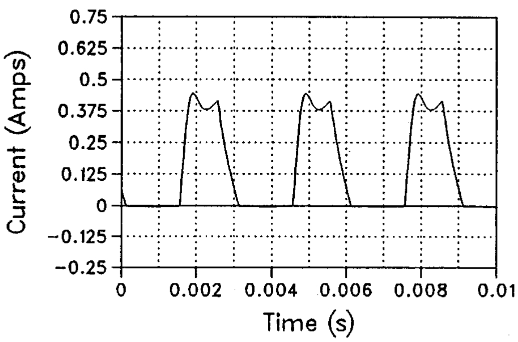

Figure (7): Simulated Phase (a) Current Including Compression Effects

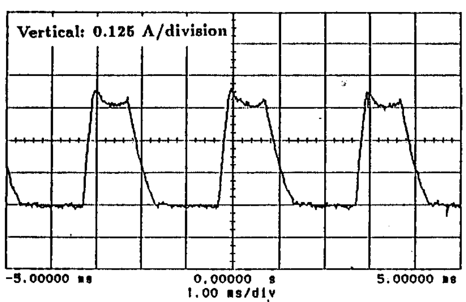

Figure (8): Measured Phase (a) Current

CONCLUSION

The results of a case study on the effects of compression on the winding inductance profiles of an example switched reluctance motor were presented. The switched reluctance motor winding inductances were determined from a series of nonlinear magnetic field solutions in conjunction with an energy perturbation approach. A comparison of the inductance values with measured data, as well as the performance characteristics of the machine, revealed that in cases of high stress conditions due to casing force fitting, the compression effects on the magnetic characteristics of the stator laminations should be taken into account.

V. REFERENCES

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