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Abstract

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Keywords

composite, claw, magnet, motor, influence, variation, magnetic, pole, soft, permanent, performance, inductance

Disciplines

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Influence of inductance variation on performance of a permanent magnet claw pole soft magnetic composite motor

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Winding inductance is an important parameter in determining the performance of electrical machines, particularly those with large inductance variation. This paper investigates the influence of winding inductance variation on the performance of a three-phase three-stack claw pole permanent magnet motor with soft magnetic composite (SMC) stator by using an improved phase variable model. The winding inductances of the machine are computed by using a modified incremental energy method, based on three-dimensional nonlinear time-stepping magnetic field finite element analyses. The inductance computation and performance simulation are verified by the experimental results of an SMC claw pole motor prototype. © *2008 American Institute of Physics*.
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I. INTRODUCTION

Soft magnetic composite (SMC) materials and their application in electrical machines have achieved significant development in the past decade, thanks to the materials' unique properties such as magnetic isotropy, very low eddy current loss, and relatively low total core loss at medium and higher frequencies, and prospect of very low cost net-shape fabrication by using the well-developed powder metallurgical molding techniques.[1] The major advantage may be with the isotropic magnetic property, which provides great benefits to electrical machine design. The constraints imposed by the conventional laminated steel, such as that the flux must flow within the lamination plane, can now be ignored, so that electrical machines with radically different topologies can be exploited to acquire the best performance.[2] Typical examples of SMC application include claw pole and transverse flux motors, in which the magnetic field is really three-dimensional (3D).[3] In such machines, it is very difficult or almost impossible to construct the core by using the laminated steel because the magnetic flux has significant component in any direction and the flux component perpendicular to the lamination plane may cause excessive eddy current loss. SMC offers an ideal solution to these machines.

To investigate the application potential of SMC in electrical machines, the authors of this paper have designed, fabricated, and tested several SMC motor prototypes, including a three-phase three-stack claw pole motor with SMC stator core.[4,5] The motor employs an interior stator made by SMC and an exterior rotor with 20 NdFeB permanent magnets (PMs) per phase on the inner surface of the mild steel rotor yoke. Three phases of the motor are stacked axially on the stator shaft with an angular shift of 120° electrical to each other. Each phase has a single concentrated winding around a SMC core, which is molded in two halves. The major dimensions are 80 mm for the stator outer diameter, 93 mm for the stator effective axial length, and 1 mm for the main air gap. The prototype has operated successfully with a sensorless brushless dc (BLDC) scheme, delivering an output power of 500 W at 1800 rpm when the stator current is 4.1 A.[5]

Based on nonlinear time-stepping magnetic field finite element analysis (FEA), the authors have previously studied the accurate computation of key motor parameters at various loads, considering the nonlinearity of magnetic materials and effects of armature reaction.[6–8] In such a machine with 3D flux structure and single concentrated winding, the inductance value and the inductance variation are generally large. This paper investigates the influence of the winding inductance, particularly its variation with respect to rotor position, on the performance of the claw pole motor.

II. INDUCTANCE COMPUTATION

The self-inductance of one phase winding is computed at various rotor positions by using a modified incremental energy method,[6] which consists of the following steps: (1) A nonlinear FEA is conducted with the excitations of PMs (assuming the magnetic field of PMs is dominant). (2) Both the apparent and incremental permeabilities of each element are stored, which correspond to B/H (flux density/field strength) and $\Delta B/\Delta H$ at the operating point (B,H) of the nonlinear magnetization curve, respectively. (3) The coercive force of

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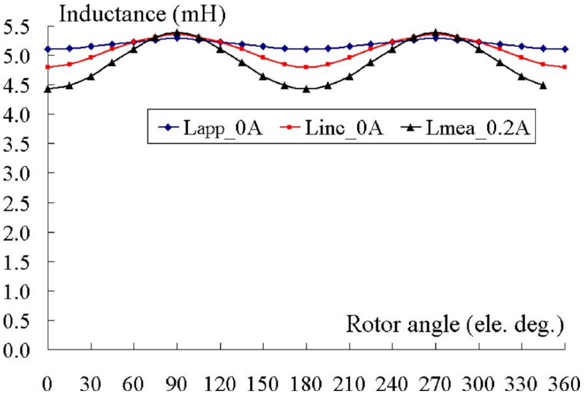

FIG. 1. (Color online) Computed and measured phase inductance.

PM is set as zero and a linear FEA is conducted with a perturbation current i to find out the variation of magnetic coenergy $\Delta W'_f$. (4) The winding inductance can then be computed by

$$L = 2\Delta W'_f / i^2. \tag{1}$$

It should be noted that the stored apparent permeability is used for apparent inductance computation and the incremental permeability for incremental inductance. Figure 1 illustrates the computed apparent and incremental phase inductances without the effect of armature reaction. The apparent inductance is generally larger than its incremental counterpart. This agrees with the fact that apparent inductance corresponds to the slope of the secant line between the origin and the operating point of *B-H* curve, and incremental inductance corresponds to the slope of the tangential line at the operating point.

For verification, the measured inductances are also plotted in the figure, which are obtained by using the common *V-I* method with a small ac current (500 Hz, 0.2 A). The error may be due to the eddy current caused by the measuring current.

The magnetic circuits of three phases are almost independent to each other, so the mutual inductance between phase windings can be considered as zero.

III. MOTOR PERFORMANCE ANALYSIS

The characteristic of the electrical circuit of one phase winding is governed by the voltage equation written as

$$v_j = r_j i_j + d\lambda_j/dt + e_j \quad (j = a,b,c), \tag{2}$$

where v, r, i, λ, and e are the phase voltage, resistance, current, flux linkage, and back electromotive force (emf), respectively. The flux linkage can be written in terms of apparent inductance as

$$\lambda_j = \sum_{k=a}^{c} L_{jk} i_k. \tag{3}$$

Because the flux linkage is a function of stator currents and rotor position, the second term of Eq. (2) can be expanded as

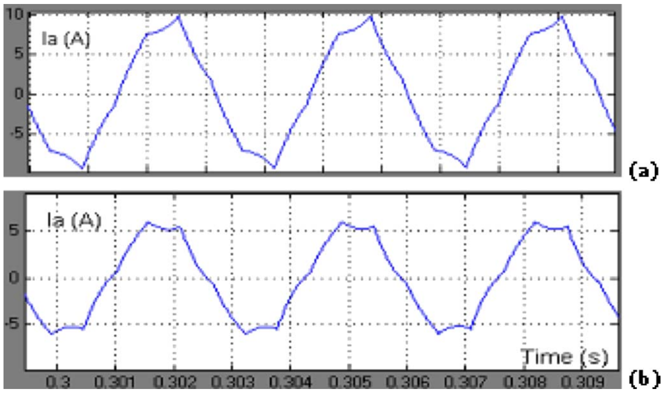

FIG. 2. (Color online) Current of a phase winding at steady state: (a) considering the effect of inductance variation and (b) with constant inductance.

$$\frac{d\lambda_j}{dt} = \sum_{k=a}^{c} \frac{\partial \lambda_j}{\partial i_k}\frac{di_k}{dt} + \frac{\partial \lambda_j}{\partial \theta_r}\frac{d\theta_r}{dt} = \sum_{k=a}^{c}\left(L'_{jk}\frac{di_k}{dt} + \frac{dL_{jk}}{d\theta_r} i_k \omega_r\right), \tag{4}$$

where L_{jk} is the apparent inductance, L'_{jk} the incremental inductance, θ_r the rotor mechanical angle, and ω_r the rotor angular speed in mechanical rad/s.

Substituting Eq. (4) into Eq. (2), the voltage equation of the jth phase winding becomes

$$v_j = r_j i_j + \sum_{k=a}^{c}\left(L'_{jk}\frac{di_k}{dt} + \frac{dL_{jk}}{d\theta_r} i_k \omega_r\right) + e_j. \tag{5}$$

The electromagnetic torque (under optimum BLDC control) and motion equation are

$$T_{\text{em}} = \left(\sum_{j=a}^{c} e_j i_j\right) \Bigg/ \omega_r + T_{\text{cog}}, \tag{6}$$

$$J\frac{d\omega_r}{dt} = T_{\text{em}} - \frac{P_{\text{Fe}}}{\omega_r} - T_L - \delta\omega_r, \quad \frac{d\theta_r}{dt} = \omega_r, \tag{7}$$

where T_{cog} is the cogging torque, J the total inertia of rotating parts, P_{Fe} the core loss, T_L the load torque, and δ the friction coefficient.

From Eqs. (2)–(7), it can be seen that both the apparent and incremental inductances and their variations affect the stator current and hence the electromagnetic torque and mechanical characteristics. To include this effect in the motor performance prediction, the phase variable model can be employed.[9]

For the symmetrical three-phase windings, which are star-connected without central line, one has

$$r_j = r_k, \quad L_{jk} = L_{kj}, \quad \sum_{j=a}^{c} i_j = 0 \quad (j,k = a,b,c). \tag{8}$$

The above equations [Eqs. (2)–(8)] constitute the so-called phase variable model. The profiles of the inductances as well as the back emf, core loss, and cogging torque are obtained in advance by nonlinear time-stepping FEAs, in which magnetic saturation and rotor position dependence are considered. All the data are stored in lookup tables and will be retrieved during the motor performance simulation.

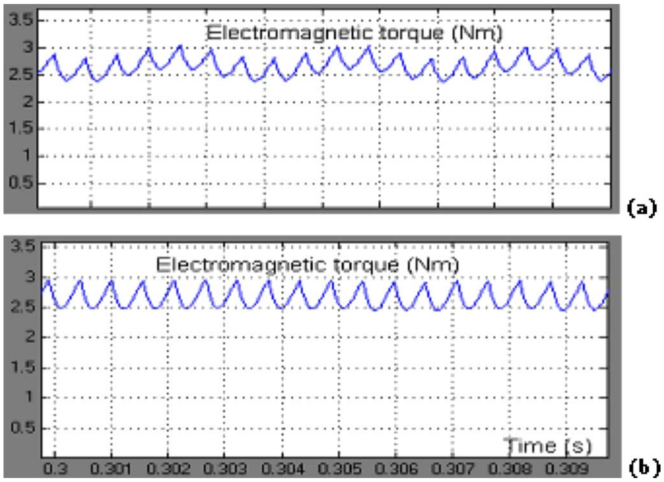

FIG. 3. (Color online) Electromagnetic torque at steady state: (a) considering the effect of inductance variation and (b) with constant inductance.

In a PM motor with BLDC control scheme, there always exists a phase winding which is open-circuited and the input voltage of the phase is immeasurable, so the equation-based model cannot be applied directly and an alternative model, composed of several circuit components, had to be used.[9] Based on a pure mathematical approach, the authors of this paper developed an improved phase variable model in which the voltage of the central point of Y-connected three-phase windings is mathematically obtained and hence the equation-based simulation model can be directly applied to BLDC motors.[10]

According to Eqs. (2)–(8) and the mathematical approach for determining the voltage of the central point of three-phase windings, a Simulink-based simulation model is built.

By using the model, various motor performances can be predicted. For example, Fig. 2 illustrates the phase current at steady state when the inverter voltage is 165 V dc and the load torque is 2.65 N m. For comparison, the simulated current with constant inductance (averaged value) is also given. It can be found that both the magnitude and waveform of the phase current are affected by the inductance variation, and the effect can also be observed in the electromagnetic torque, as shown in Fig. 3.

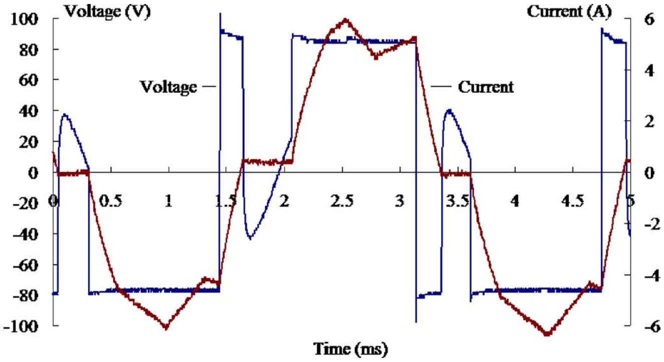

FIG. 4. (Color online) Measured phase current with a load of 2.65 N m at 1800 rpm

Experiments have been carried out for both the steady state and dynamic performances.[5] As an example, Fig. 4 shows the measured phase current. The line voltage of the same phase with respect to the negative dc link terminal is also plotted. The simulated current agrees generally with the measurement.

IV. CONCLUSION

This paper presents the influence of inductance variation on the performance of a permanent magnet claw pole motor by using a Simulink-based improved phase variable model. Simulation results show that the phase current and the electromagnetic torque are significantly affected by the variation of winding inductance. It is therefore important to include the effect of inductance variation in advanced design and analysis of electrical machines, particularly those with large inductance values and variations. Both the inductance computation and motor performance prediction are verified by the experimental results on the motor prototype.

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