Computation of Incremental Inductances for Nonlinear Dynamic Analysis of a PM Claw Pole SMC Motor

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Proper determination of winding inductances is a key factor for design and performance simulation of electrical machines. This paper presents the computation of the incremental inductances of a three-phase three-stack permanent magnet (PM) claw pole motor with soft magnetic composite (SMC) stator by using magnetic field finite element analysis in combination with energy and current perturbation technique. The magnetic saliencies due to both the motor's structure and magnetic saturation are included in the inductance profile. The theoretical computations are validated by the measurements on the motor prototype.

Key Words: Incremental inductance, Soft magnetic composite (SMC) material, Permanent magnet (PM) claw pole motor, Finite element analysis, Nonlinear dynamic performance.

1. Introduction

Effective and accurate determination of winding inductances is a crucial factor for design and optimization of high performance motors. This is especially true for newly-developed electrical machines with new materials and new topologies because the conventional approaches, based on equivalent magnetic circuit, empirical formulae or previous experiences, cannot provide correct computation. An example is a three-phase three-stack permanent magnet (PM) claw motor employing soft magnetic composite (SMC) stator [1]. By taking advantage of the unique properties of SMC [2], such as the magnetic isotropy, the magnet was chosen both axially and circumferentially longer than the claw pole to increase the specific torque. The magnetic flux in the motor path is really complex and three-dimensional (3D).

In such a 3D flux machine, numerical techniques such as finite element analysis (FEA) should be performed for proper determination of the magnetic field distribution. This paper presents the computation of winding inductances of the PM claw pole SMC motor by employing 3D magnetic field FEA in combination with a modified incremental energy method (MIEM) [3].

Secant (apparent) inductance, which is defined as the ratio of the winding flux linkage over winding current, is usually employed. However, this is not correct when the nonlinear characteristic of the magnetic core is considered in dynamic performance analysis [4]. For nonlinear analysis, the incremental (differential) inductances should be used. In this paper, the incremental inductance profile of the claw pole motor is computed by using the MIEM. The effects of both structural and magnetic saturation saliencies are included in the inductance profile, enabling the nonlinear dynamic performance analysis of the motor [5].

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2. Incremental Inductances

2.1 Definition of incremental inductance

Generally, the dynamic performance of a motor can be analyzed by the following equations:

$$u_j = R_j i_j + \frac{d\lambda_j}{dt}, j=1,2,\ldots,m \tag{1}$$

where m is the number of phases, u_j, R_j, i_j and λ_j are the applied voltage, resistance, current and flux linkage of the j-th phase winding, respectively. Due to the magnetic saturation, the flux linkage, contributed by both the stator currents and PMs, varies with stator currents and rotor position θ as

$$\lambda_j = \lambda_j(i_{PM}, i_1, i_2, \ldots, i_j, \ldots, i_m, \theta) \tag{2}$$

where i_{PM} is the equivalent current of PMs, which can be considered as a constant. By substituting (2) into (1), the voltage equation of the j-th phase winding can be rewritten using the chain rule as:

$$\begin{aligned} u_j &= R_j i_j + \sum_{k=1}^{m} \frac{\partial \lambda_j}{\partial i_k}\frac{di_k}{dt} + \frac{\partial \lambda_j}{\partial \theta}\frac{d\theta}{dt} \\ &= R_j i_j + \sum_{k=1}^{m} L_{jk}\frac{di_k}{dt} + e_j \end{aligned} \tag{3}$$

where $L_{jk}=\partial\lambda_j/\partial i_k$ is the incremental inductance, and e_j is the rotational electromotive force (*emf*).

When the magnetic circuit is saturated, the motor performance should be analyzed with the incremental inductance, along the tangential line at the operating point of the flux-linkage versus current curve. The secant inductance, *i.e.* the slope of the linearized characteristic through the origin and the operating point, is not appropriate when dealing with an electrical machine with non-linear magnetic properties.

2.2 Modified incremental energy method

In a PM motor, the magnetic field is dominated by the field produced by the PMs. Since the field and energy generated by the winding currents are considerably smaller than those generated by PMs, large computational errors may happen during the numerical field solution. This may be avoided by using the MIEM [3], which is developed based on the energy/current perturbation method [6]. Firstly, a nonlinear magnetic field FEA is conducted at the motor's normal operating state to find out the magnetic property of each element. The differential permeability of the elements can then be obtained according to the known *B-H* curve of the nonlinear magnetic material. Next, the motor is reconfigured to a linear system by assuming that each element is made of a linear material with the previously determined permeability and that the PM remanence is set to zero. Finally, a linear magnetic field FEA is performed to acquire the magnetic co-energy, W_c, at a specified winding current, i. The incremental self-inductance can then be calculated by

$$L_{inc} = \frac{2W_c}{i^2} \tag{4}$$

To consider the effect of magnetic saturation caused by both PMs and stator current, the first step of MIEM is to perform a nonlinear analysis with both the excitations.

3. Computation of Incremental Inductances of a PM Claw Pole SMC Motor

3.1 Motor prototype

To investigate the application potential of SMC in electrical machines, a three-phase PM claw pole SMC motor has been developed by the authors [1]. The three phases are stacked axially with a circumferential shift of 120° electrical to each other. The major dimensions and parameters include: 80 mm for the diameter of the inside stator, 1 mm for the main airgap length, 31 mm for the axial length of each stack, 75 turns for each winding, and 20 poles.

Considering the structural symmetry and the negligible magnetic coupling between stacks, only one pole region of one stack is required for the FEA solution, as illustrated in Fig. 1, where *A* is the SMC stator core, *B* the rotor PMs, *C* the mild steel rotor yoke, and *D* the steel shaft. Each phase has a single coil winding (not shown for clarity) around an SMC core, which is molded in two halves.

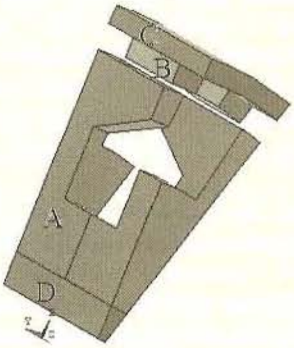

Fig. 1. Motor structure and FEA solution region

3.2 Computation of incremental inductances

Due to the variations of structure and magnetic saturation (the latter is mainly caused by rotor PMs), the winding inductance is a function of rotor position. At the normal operating state, the total winding flux is composed of the rotor flux produced by the PMs, as well as the stator flux produced by the stator current. Due to the stator flux, the magnetic core becomes more saturated at some parts and less saturated at other parts. Therefore, the winding inductance computation should also take into account the effect of the stator current.

When the motor operates in the steady state synchronous state, the stator flux, or the resulting flux of both the stator and rotor fluxes, leads or lags the rotor flux by a fixed spatial angle. Referred to the rotor, the stator current can be seen as a DC at a specified load. Therefore, the inductance pattern versus various stator currents and rotor positions are very useful information for design and performance analysis of the motor under various control schemes. Here, the inductance is computed with various DC offsets, which emulate the effect of the stator current. The inductance pattern can then be used as a look-up table for simulating the motor performance under a particular control scheme and load [5].

Fig. 2 illustrates the computed self incremental inductances of one phase winding considering both structural and magnetic saturation saliencies, with the zero rotor position where the rotor PMs line up with the stator claw poles, as shown in Fig. 1. The curves with DC bias reflect the effect of the stator flux. The mutual inductances between phases can be considered as zero due to the almost independent magnetic circuit of one phase.

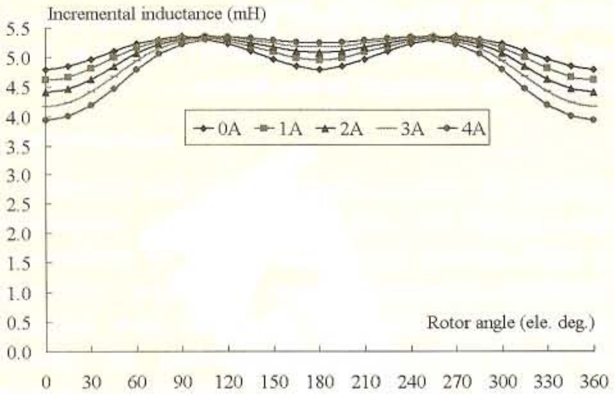

Fig. 2. Computed self incremental inductances of one phase winding considering both structural and magnetic saturation saliencies

3.3 Inductance measurement

Fig. 3 illustrates the experimental setup for measuring the self-inductance by using a small high frequency AC current (500 Hz, 0.2 A) while the rotor is locked at a specified rotor angle [7].

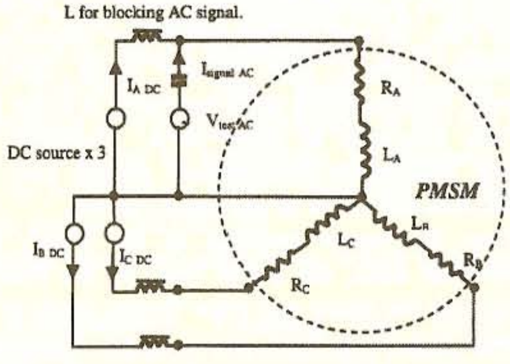

Fig. 3. Experimental setup for inductance measurement

A DC current is input into one phase winding for simulating the effect of stator flux and a small AC signal is superimposed upon the same phase for measuring the inductance. The AC voltage across the two terminals, V_1, and the AC current following the winding, I_1, are measured. The phase winding inductance can be calculated by

$$L_1 = \sqrt{(V_1 / I_1)^2 - R_1^2} / (2\pi f_1) \qquad (5)$$

where f_1 is the frequency, and R_1 is the resistance of the phase winding. The inductance is measured with rotor positions from 0° to 360° electrical at 15° intervals, and bias current levels of 0 A, 2 A and 4 A, as shown in Fig. 4. For comparison, the computed inductances are re-plotted in the figure, revealing that they basically agree with the experimental ones. The error may be caused by the measuring current, which causes a small loop in the vicinity of the saturation point in the B-H curve. Another possible reason is the eddy current caused by the measuring current. Although the particles of SMC materials have been coated by a thin electrical insulation, the eddy current might be non-negligible due to the possible insulation damage during the high-pressure compaction process. Ideally, the measuring current should be as close to zero as possible but the reading error could be large.

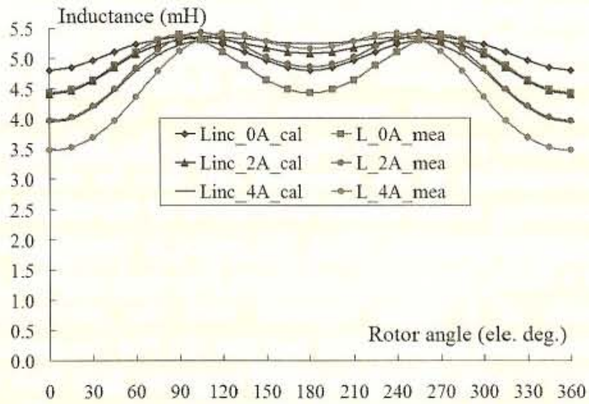

Fig. 4. Computed and measured inductances with DC bias in the stator winding

4. Dynamic Performance Analysis

The inductance profile, in combination with other key parameters such as back *emf*, cogging torque and core loss [1], the phase variable model can be built for the dynamic performance analysis of the PM motor under a brushless DC control scheme [8], [9], including (3) and the motion equations below:

$$T_{em} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} \quad (6)$$

$$\frac{d\omega_r}{dt} = \frac{T_{em} - T_L - T_{cog} - \delta_0 \omega_r}{J} \quad (7)$$

$$\frac{d\theta}{dt} = \omega_r \quad (8)$$

where T_{em} is the electromagnetic torque, ω_r the rotor angular speed, T_L the load torque, T_{cog} the cogging toque, δ_0 the friction coefficient, and J the total inertia of the rotating parts.

As an example, simulation is conducted to investigate if the motor can reach the required steady-state speed of 1800 rpm with the rated torque of 2.65 Nm, when the applied voltage of the inverter is 165 VDC, and the simulated results are shown in Figs. 5 and 6. It is found that the performance requirements can be met.

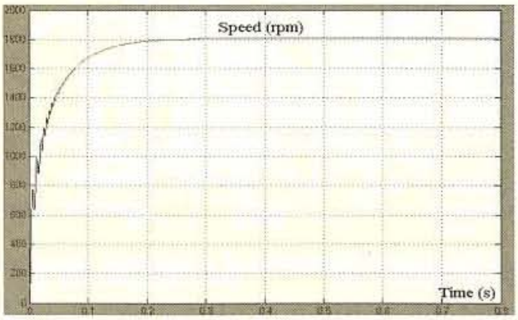

Fig. 5. Speed curve during the start-up with a load of 2.65 Nm when the inverter voltage Vdc=165 V

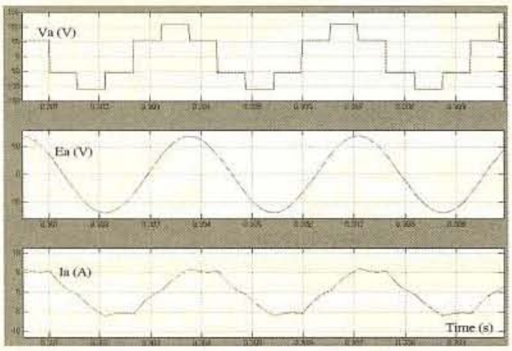

Fig. 6. Voltage, back *emf* and current of a phase winding at the steady state

5. Conclusion

This paper presents the computation of the incremental inductances of a PM claw pole SMC motor. To consider the effect of both structural and magnetic saturation saliencies, the inductance is computed with different rotor positions and bias DC currents. The computation of inductances has been verified by the experiments on the motor prototype.

The inductance, in combination with other key parameters, enables the dynamic performance of the PM motor under different certain control scheme. Furthermore, the inductance pattern, which can be obtained by computation and/or experiment, can provide a method to determine the initial rotor position of surface mounted PM motors under sensorless control schemes.

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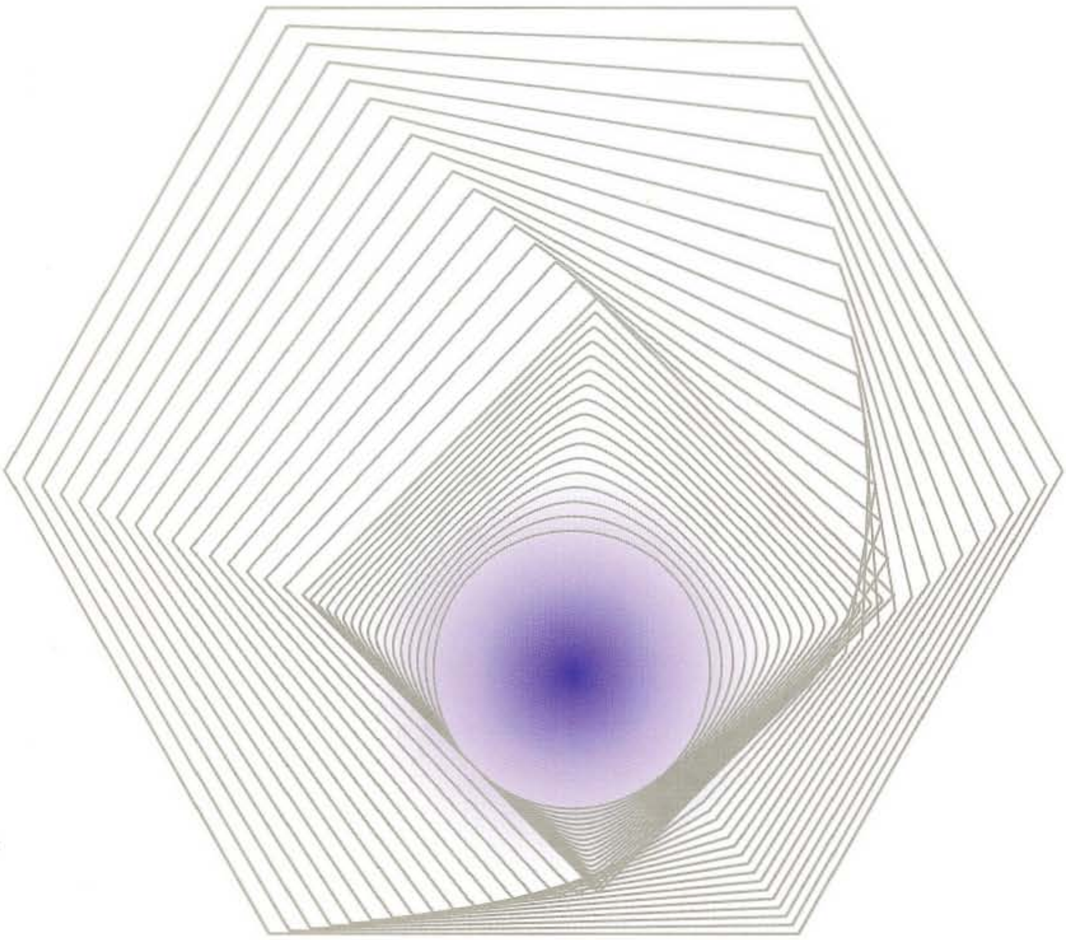

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