Physical Modeling Study of Electrical Machinery

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Abstract— Conventional dq-model is based on the assumption of having the sinusoidal flux and back emf waveforms. It also assumes that the mutual inductances and balanced, symmetric and vary sinusoidally. When these assumptions fail, the dq-model becomes mathematically incorrect. The terminology, physical motor model refers to the model whose working flux as well as the back emf contains all the possible harmonic components due to saturation and slotting effects. Two types of physical motor model and their coupling with external circuits are studied in this paper. One is the FE model while the other is the phase variable model. Its circuit parameters are calculated based on FE analysis. As an example, the FE model and physical phase variable model of a PM synchronous machine are established. The Coupling of the external circuits directly with the FE motor model is carried out. The physical phase variable model of PM synchronous motor is proposed and implemented in Simulink. The rotor position dependence of inductances is obtained through nonlinear transient FE analysis and energy perturbation method. The rotor position dependence of flux linkage contributed by the permanent magnet only is obtained from transient FE analysis. In addition to the electromagnetic torque component produced by the interaction between the armature field and the permanent magnetic field, the cogging torque due to the permanent magnet field and slotting is taken into account in the physical model. It is evaluated through FE analysis. The established physical motor models are applied in integrated motor drive systems.

I. INTRODUCTION

The ideal air gap flux density and back emf waveform of rotating machines is assumed to be sinusoidal. In real machines, however, they can’t be sinusoidal because of the pole shape, the existing slots and the saturated magnetization property. Theoretically the working flux can be reached through the pole shape design. In practical, this can’t be done perfectly. The slots are necessary for embedding windings. They superpose high order harmonics on the flux waveform. Dq-model is an idealized model. It ignores the effects of the saturation, the pole shape as well as the existing slots.

AC machines design follows the assumption of having sinusoidal working flux and back emf. Furthermore, many analytical methods for the machine analysis are based on the sinusoidal assumption. Sinusoidal assumption is not sufficient for extensive analysis, optimization design as well as fault analysis. Two examples are given below.

An increase in the number of poles can be utilized for increasing the machine power density or obtain lower velocity. This means in turn the reducing of the number of slots per pole per phase. As a result, more harmonic components will be contained in the working flux and back emf waveforms. Our research group investigated the effects of decreasing the number of slots per pole per phase on the working flux by using Fourier filter operation [1] and wavelet transformation [2].

The idealized dq-model behaves effectively for most of the normal operating conditions. However, it is inaccurate under some fault conditions due to the ignorance of the ferromagnetic saturation as well as the eddy current effects. This is especially significant for short circuit fault conditions because both the current density and its frequency of some phase can be probably very high. In this case, the operating point of magnets will move to the saturation part of the magnetization curve. Consequently, the inductances will drop and become asymmetric.

Therefore, finding a better way to simulate the above situations is needed. FE motor model coupled with external circuit can be considered as one solution. The FE model is a field model and it carries the structure information, like the pole shape and slotting, and can takes into account the nonlinear material property. The problem of FE modeling is the expensive time cost. This leads to the establishment of physical phase variable models. The details about building the FE model and the physical phase variable model of a synchronous PM motor are presented.

II. FE MODEL

A. Transient magnetic field equation

The transient FE analysis is adopted for the magnetic field calculation of the motor. The potential formula involving both the electrical and magnetic potentials is written below:

$$\nabla \left( \sigma \frac{\partial A}{\partial t} - \sigma \nabla \times (\nabla \times A) + \sigma \nabla V - J^e \right) = 0$$

(1)
Where, \( \sigma \) is conductivity, \( A \) is vector potential, \( v \) is the velocity of the modeled object, \( V \) is electrical potential. \( J^e \) is external current density. \( \mu \) is relative permeability. \( M \) is magnetization.

The constitutive relation is:

\[
B = \mu_0 (H + M) \tag{3}
\]

Where \( B \) is the flux density, \( H \) is the field strength, and \( \mu_0 \) is the air permeability.

From (1) to (3), one can see that both the eddy current effect and the nonlinear material property are considered. And, as a field analysis method, FE itself catches structure information of the object analyzed. Moving air gap technique is necessary for the correct torque profile output. A 2hp 6-pole PM synchronous motor is analyzed. Fig. 1 shows the one pole structure, the excitation currents, the mesh, as well as the obtained vector potential lines.

### III. Phase Variable Model

#### A. Equations

The physical phase variable model of PM synchronous motors is as follows [3]:

\[
V_{abc} = R_{abc}i_{abc} + d\psi_{abc}(i_{abc}, \theta)/dt \tag{5}
\]

\[
\psi_{abc}(i_{abc}, \theta) = L_{abc}(i_{abc}, \theta)i_{abc} + \psi_{rabc}(\theta) \tag{6}
\]

\[
T_m = p\left(0.5i_{abc}^T T_{abc} (i_{abc}, \theta)/d\theta i_{abc} + i_{abc}^T d\psi_{rabc}(\theta)/d\theta\right) + T_{cog}(\theta) \tag{7}
\]

\[
J d\omega/dt = T_m - B_0 \omega - T_L \tag{8}
\]

\[
d\theta/dt = \omega \tag{9}
\]

Where, \( V_{abc} \cdot i_{abc} \cdot \psi_{abc} \) are vectors of the phase voltages, currents and fluxes respectively. \( \psi_{rabc} \) is the flux linkage contributed by the permanent magnet. \( p \) is the number of pole pairs; \( T_m \) is the produced torque; \( T_L \) is the load torque; \( T_{cog} \) is the cogging torque. \( J \) is the moment of inertia and \( B \) is the friction constant. The rotor position angular \( \theta \) and angular velocity \( \omega \) are measured in electrical radians and \( rad/s \) respectively. \( R_{abc} \) and \( L_{abc} \) are the stator resistance and inductance matrices.

#### B. Parameter determination and Simulink implementation
FE analysis is used to calculate the magnate field and the energy perturbation method [4] is adopted to calculate the self and mutual inductances. The inductance of permanent magnet machine is current-independent. The cogging torque and the winding flux linkage $\psi_{rabc}$ produced by the permanent magnet are evaluated through transient FE analysis also [5]. The inductance, flux linkage from PM, and cogging torque of a 2hp 6-pole PM motor are shown in Fig.3. The data are stored in three separate tables in Simulink implementation. Thus, the slotting and saturation effects are included in the phase variable model.

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IV. SIMULATION RESULTS

The FE model, phase variable model and the conventional dq model of the 2hp PM motor are respectively applied to an voltage supplied integrated drive system. The winding voltage, current, and output torque profiles obtained from the phase variable model are shown in Fig. 6. The slotting effects can be seen clearly from the fluctuations on them. The corresponding results from FE model are given in Fig. 7. For the comparison purpose, simulations of a PWM speed regulation system are performed using the three types of motor models. The output torque profiles are shown in Fig. 8. The slotting effect can not be reflected by dq modeling. The phase variable model performs almost the same as the FE model with much faster simulation speed.
V. CONCLUSIONS

Compared with the conventional dq motor model, the FE model and the proposed physical phase variable model can simulate the machines much closer to the real situations. They can be used as a testing platform for machine performance optimization as well as its driving system design. Hopefully, it can replace the costly laboratory experiments the near future.

REFERENCES


Figure 6. Simulation results using phase variable model

Figure 7. Simulation results using FE model

Figure 8. Torque profile comparison: (a) by phase variable model, (b) by FE model, (c) by dq model