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Analysis of a PM Motor Drive System by a Coupled Method with MATLAB and FEM

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Abstract - Finite element method (FEM) is a very powerful tool for the calculation of magnetic field of electromagnetic devices. MATLAB/Simulink is also well known as a very useful tool for control systems. This paper proposes a very promising method, where the FEM is coupled with MATLAB. We apply this method to analyze a permanent magnet (PM) motor drive system, and compare with results using MATLAB only.

Keywords: Finite element method, MATLAB, coupled problem, permanent magnet motor

1. Introduction

FEM is well known as a powerful tool for the analysis of electromagnetic field of electromagnetic devices. We can analyze the magnetic field, current, force and torque ripple of electric motors using FEM. As electrical motors are usually used with control systems, it is necessary to evaluate the motor drive control system. MATLAB/Simulink is well known as a very useful tool for the analysis and design of control systems. In order to analyze a motor drive system using MATLAB, the motor is usually represented by a d-q model. However, some factors are difficult to model in the d-q model, such as space harmonics of flux density, torque ripple and magnetic saturation. Then, a few papers have been published to couple the MATLAB and the numerical calculation of the magnetic field [1]. In these papers, the motor is analyzed by using FEM and the results are set as a MATLAB file, and then the MATLAB simulates the motor drive system using this file, that is, it is a series of magneto-static solutions. Therefore, there is as yet no fully integrated analysis environment for the system.

This paper proposes a new method for the evaluation of motor drive control systems [2]. The proposed method is composed of FEM and MATLAB, where a motor model using FEM is fully integrated into a drive control system using MATLAB/Simulink. We apply this method to analyze a permanent magnet motor drive system, and compare with results using MATLAB only.

2. Coupled Method Using MATLAB and FEM

Fig. 1 shows a typical block diagram for the simulation of a permanent magnet motor dive system, where a three-phase permanent magnet motor is fed by a PWM inverter, and two control loops are used; one is the inner loop to regulate the stator currents, and the other is the outer loop to control the motor speed. In this block, the block *PI* is a proportional and integral controller with a limiter for the motor speed. The block *dq2abc* translates d and q currents to three phase currents using rotor angle. A unit delay *1/z* delays signals one sample period, 200 μ sec in this paper. It corresponds to the sampling period of the digital control system. The block *PWM inv* is a PWM inverter with a proportional current controller. The block *PM* is a three-phase permanent magnet synchronous motor and can be utilized in the SimPower Systems, which is modeled in the d-q rotor reference with sinusoidal flux distribution [3]. The parameters in this block are resistance of the stator windings, q and d axis inductances, flux induced by magnets, inertia, friction factor and number of pole pairs. The input signals are three terminal voltages and mechanical load torque, and the output signals are three stator currents, rotor speed, rotor angle and electromagnetic torque.

This paper proposes to replace this *PM* block with a FEM model, which calculates the stator currents, motor speed, rotor angle and the torque using the terminal voltages and mechanical load torque. The model can be expressed by the following three equations, namely, a two-dimensional electromagnetic equation, voltage equations and the mechanical equa- tion.

$$\frac{\partial}{\partial x}\left(\nu\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial A}{\partial y}\right)=-J_0-\nu_0\left(\frac{\partial M_y}{\partial x}-\frac{\partial M_x}{\partial y}\right), \tag{1}$$

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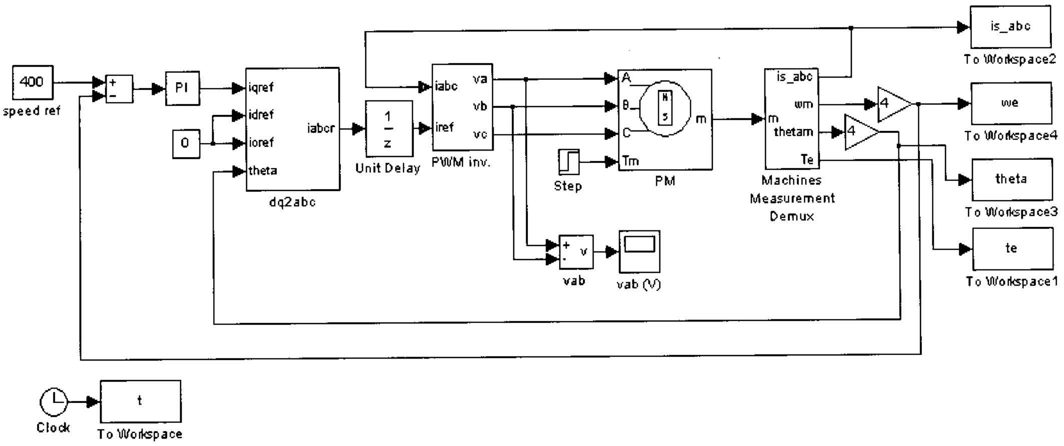

Fig. 1 Block diagram of permanent magnet motor drive system using MATLAB

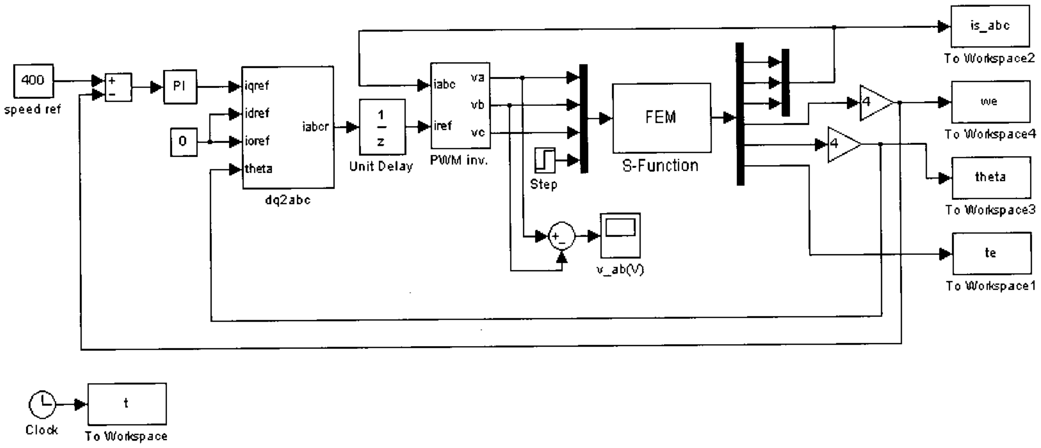

Fig. 2 Block diagram of permanent magnet motor drive system using MATLAB and FEM.

$$V_k = r\, i_k + l\frac{d\, i_k}{d\, t} + \frac{d\Phi_k}{d\, t} \ , \qquad (k = a,b,c)$$

$$\Phi_k = \frac{n}{S_k}\iint_{S_k} AL\ dxdy\ , \qquad J_{0k} = \frac{n}{S_k} i_k\ ,$$

$$J_m \frac{d\omega_m}{d\, t} + R_\omega \omega_m + \tau_l = \tau_e$$

where, $A, \nu, \nu_0, J_0, M, V, i, r, l, \Phi, n, S, L, \omega_m, J_m, R_{\omega,} \tau_l, \tau_e$ are magnetic vector potential, reluctivity, reluctivity of air, current density, magnetization, stator phase voltage, stator current, resistance of the stator winding, leakage inductance of the stator winding, flux linkage, number of turns of stator winding, cross section of the stator winding, stack length, motor speed, the combined inertia of rotor and load, viscous friction, load torque, and the developed torque, respectively.

Fig. 2 shows the block diagram coupled MATLAB with FEM. We can implement the FE algorithm in an S-function block in this figure. In the S-function block, the two-dimensional FE algorithm calculates three stator currents, motor speed, rotor angle and the developed torque using three stator voltages and load torque as input variables. We have developed the FE code written in a fortran-language, and then transferred to a c-language using a GNU compiler. This paper takes into consideration two PWM strategies, namely, a hysteresis comparator type and a type comparing a sine wave with a jagged wave.

3. Target Motor

Fig. 3 shows the cross section of a surface permanent magnet synchronous motor. The specifications of the motor are 1.0kW,

2000min^{-1}, 7.8A, and 8 poles. The number of turns of winding is 44, the stack length is 40mm, and the permanent magnet has 92300A/m. Fig. 4 shows the mesh partition, which has 4539 elements and 2347 nodes. Fig. 5 shows the torque, electromotive force and flux linkage, when the motor is running at the rated speed, and the stator current is zero or the rated one, subject that $i_d = 0$. In order to verify the model of the target motor, we compare the average torque and the

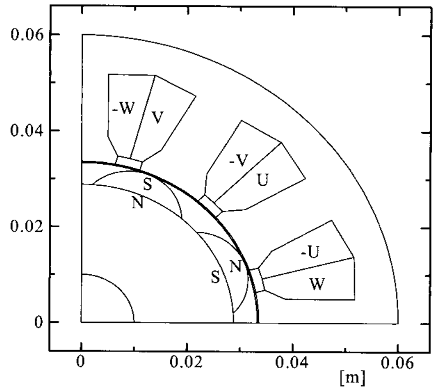

Fig. 3 Surface permanent magnet synchronous motor.

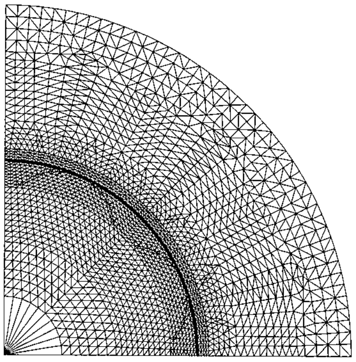

Fig. 4 Mesh partition.

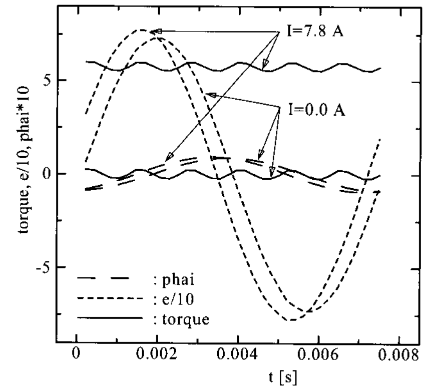

Fig. 5 Torque, current and electromotive force waveform when running at 2000min^{-1}.

electromotive force. The calculated results are 5.77N.m and 51.49V, and the catalog issued by a manufacturing company says that they are 5.93N.m and 52.4V, respectively. They show a very good agreement. It is well known that the MALAB can precisely simulate control systems. Then, the transient responses calculated by the proposed method will be compared with them calculated by the MATLAB only.

Fig. 6 shows the comparison between the nonlinear case and linear case. They shows the same results, because this motor is the surface permanent magnet type, where the gap length is very large, resulting in no magnetic saturation. Then, we use the linear calculation in the next chapter.

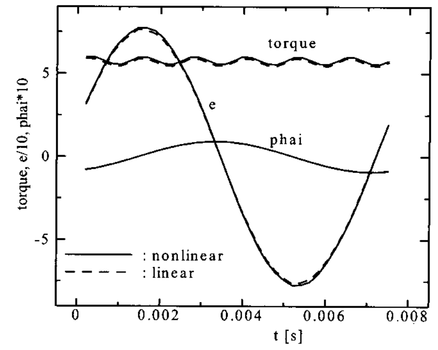

Fig. 6 Comparison of linear and non-linear cases.

4. Simulation Results

Transient response of stator current, electromagnetic torque, rotor speed and rotor electrical angle are calculated, when a speed reference of 400min^{-1} is set at t=0s and then a load torque is set to 2 N·m at 0.2s. Fig. 7 shows the responses calculated by MATLAB only, where PWM signals are generated with the hysteresis comparator. The parameters of the block *PM* are loaded from the catalog. Fig. 8 shows the responses calculated by the proposed method. Here, fig. 7 is calculated with a variable time step and fig. 8 is calculated with a fixed time step, 20 μ s. We can see from these figures that the stator currents and electromagnetic torque are approximately the same. A slice difference is shown in the torque, which has a ripple at a low speed in fig. 8. As the motor speed and rotor angle calculated by the proposed method are the same as those by MATLAB, they are omitted from fig. 8. The computational time of fig. 8 is 1.45 hours on the Pentium 4, 2.4GHz processor.

Fig. 9 shows the transient response calculated by MATLAB only, where PWM signals are generated by comparing the jagged waveform, and fig. 10 shows the responses calculated by the proposed method, where the fixed time step is set to 2 μ s in order to clearly show the torque ripple. We can see from these figures that the proposed method can take the torque ripple into account. The computational time of fig. 10 is 14.9 hours.

5. Conclusion

This paper has proposed the coupled method of FEM and MATLAB/Simulink. We have applied the proposed method to analyze the permanent magnet motor drive system, and have shown that it can take into consideration the torque ripple and space harmonics of the motor in the control system, which are not considered in MATLAB. In the case where the non-linearity is not significant, the simulation time is reasonable.

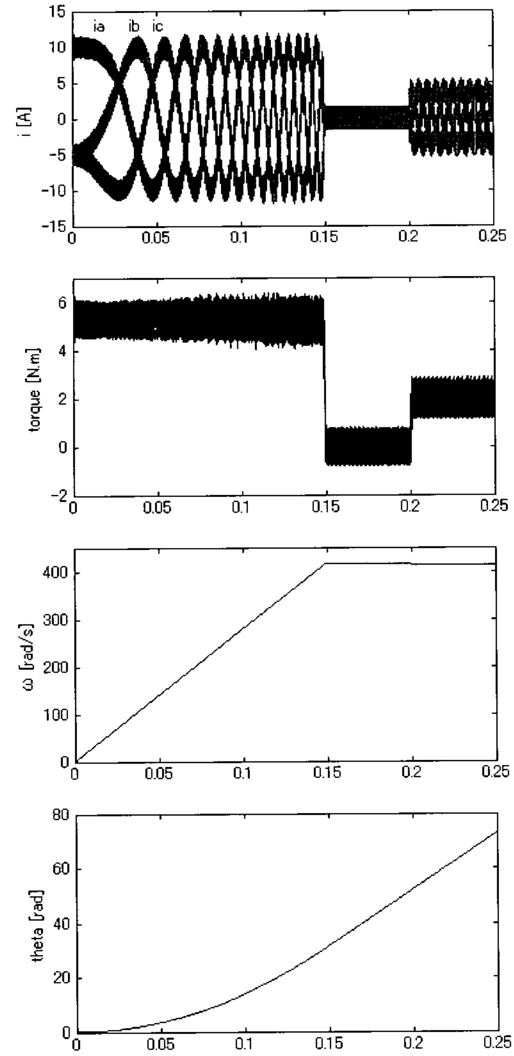

Fig. 7 Simulated responses using MATLAB only, where PWM is generated by the hysteresis comparator.

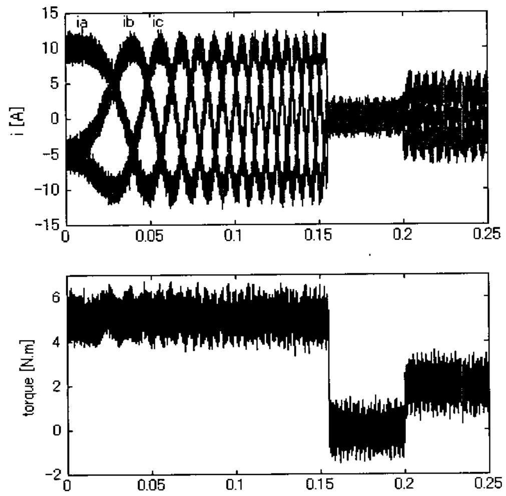

Fig. 8 Simulated responses using MATLAB and FEM, where PWM is generated by the hysteresis comparator and $\Delta t = 20\mu s$.

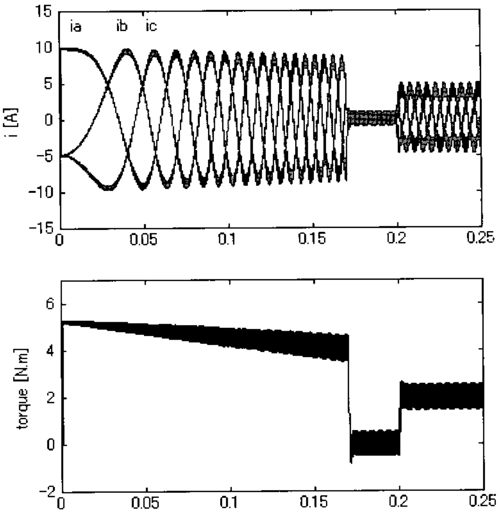

Fig. 9 Simulated responses using MATLAB only, where PWM is generated by the comparison with the jagged waveform.

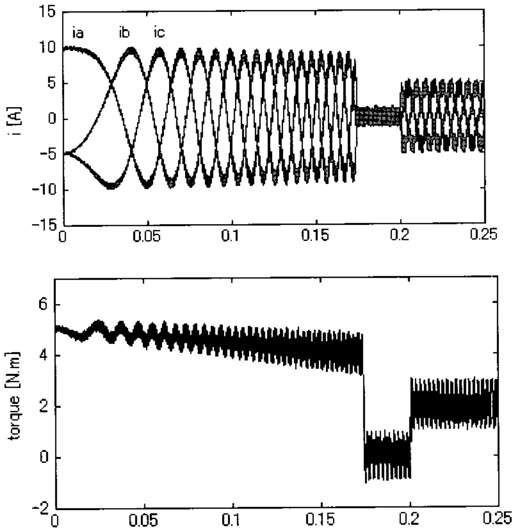

Fig. 10 Simulated responses using MATLAB and FEM, where PWM is generated by the comparison with the jagged waveform and $\Delta t = 2\mu s$.

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