Determination of Saturated Reactance in PMSM with Time-stepping Finite Element Simulation and Experiment

Li Heming, Zhang Jian, Liu Mingji, *Member*, *IEEE*, and Luo Yingli
North China Electric Power University, Beijing, 102206, China
zhjian@ncepu.edu.cn

Abstract —It's difficult to get the steady parameters of permanent magnet synchronous motor (PMSM), for its complicated magnetic circuit and heavy saturation. It is common to assume for the current X_d and X_q test of PMSM based on phasor diagram method that the EMF induced by permanent magnet only has *quad*-axis component and is constant despite of the different saturation level, which does not comply with the actual situation. This paper proposed an improved parameter calculation method, which researched the phenomenon due to cross-saturation effect which *direct*-axis magnetic field generates not only *quad*-axis EMF but also *direct*-axis EMF. Then, the paper improved the traditional phasor diagrams and got the new X_d and X_q. calculation method. There is considerably large difference between the calculation result and the normal test result using constant E_{pm}. The new method is significant to exactly calculate the saturated parameters of PMSM taking the variation of magnet circuit saturation level and cross-saturation effect into account.

I. Introduction

The precise knowledge of parameters is very necessary for the correct performance calculation and motor-driven control of permanent magnet synchronous motor (PMSM). The magnetic circuit analysis approach to getting the parameters cannot meet the requirements, for the magnet circuit of PMSM is more complex [1], especially for line-start PMSM with starting squirrel cage bars in rotor.

In recent years, the finite element method (FEM) has been widely used to calculate the steady-state parameter of PMSM. The methods of magnetic energy storage and separately applied direct quad-axis current based on phasor diagram have been already studied to get the steady-state parameter by using FEM [2]-[7]. But these methods take less the effect of cross-saturation into account [3].

Therefore, this paper presents an improved steady-parameter calculation method based on phasor diagram taking into account of effects of cross-saturation and difference leakage reactance.

II. Calculation Tool: T-S FEM

The FEM based on the Maxwell equations has been used in many commercial software. In this paper, we will use a self-developed time-stepping FEM (T-S FEM) program, in which we can easily define the excitation, save the instantaneous values of any intermediate variables while calculating the field distribution, such as voltage and current, speed and torque, permeability of every element, etc.

III. Traditional Phasor Diagram Method

Load phasor diagram method is a reliable method to calculate the steady-state parameters of PMSM [7]-[9].

To calculate Xq and Xd in a given work condition, it is necessary to get the resistance R_1 of stator winding, phasors of U, I and E_0. The prototype was tested on a test platform which was shown in Fig. 1. The structure parameters of the prototype were ignored in this digest.

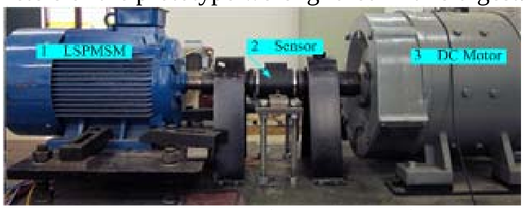

Fig 1. LSPMSM multi-function test platform.

Firstly, the PMSM is driven by the DC motor to the synchronous speed as a no-load generator. A high-speed data acquisition system is used to record the waveform of EMF E_{pm} in PMSM and the rotor position pulse, which is one pulse per revolution. Then, the PMSM operates as a motor, ensuring that the rotating direction is as the same as former. The PMSM is loaded and the waveforms of supply voltage and rotor position pulse are recorded synchronously.

Using the rotor position pulse signals as sign, the phase that the supply voltage waveform is ahead of EMF waveform is the power angle.

Then, the parameters of X_d and X_q can be calculated according to the traditional phasor diagram. A series of X_d and X_q with load are shown in Fig. 2.

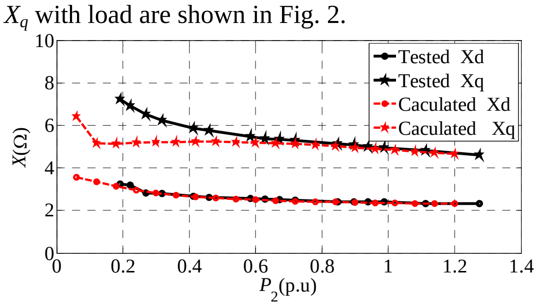

Fig. 2 T-FEM calculated and Measured X_d X_q Compare

It is shown from Fig. 2 that the test and the calculated results match well especially while the motor operating with heavy loads. Surely, in the slight load conditions, the difference of X_q is larger, which may be due to the singularity of some equations to calculate the parameters. The results indicate that the calculation method is reliable.

IV. Improved Phasor Diagram Method

In the tradition phasor diagram, it's assumed that the EMF due to permanent magnet (PM) only has quad-axis component and keeps constant. The saturation effect is ignored.

The EMF induced by PM in load conditions is specifically calculated in this paper. Due to the saturation of magnetic circuit, the magnetic field solution is a nonlinear iterative process. After the completion of the calculation of load field at each step, the permeability of every finite element keeps unchanged, and the excitation is changed as PM independently. The PM magnetic field can be calculated. The time derivative of the stator winding cross-linked flux is the actual E_{pm}.

It must be stressed that the saturation state under which the E_{pm} by PM only is calculated is as the same as that the motor operating with load. Due to the cross-saturation effect, although the direction of PM MMF is on direct axis, the EMF by PM is not exactly coaxial with *q*uad-axis, the E_{pm} exists *d*- and *q*- axis component, viz. E_{pmQ} and E_{pmD}. As shown in Fig. 3.

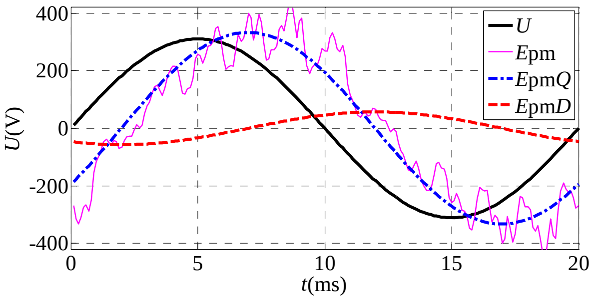

Fig. 3 Relationship of EMFs, Voltage

Consequently, the traditional phasor diagram should be improved as Fig. 4.

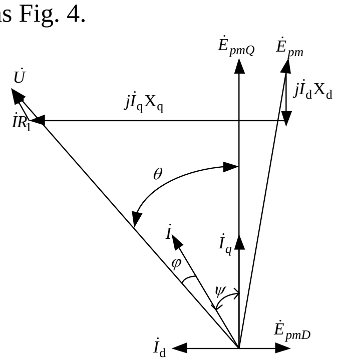

Fig 4. Phasor diagram of PMSM

The parameters of X_d and X_q can be calculated according to the phasor diagram shown in Fig. 4. A series of X_d and X_q with varying load can be calculated with the above steps, as shown in Fig. 5.

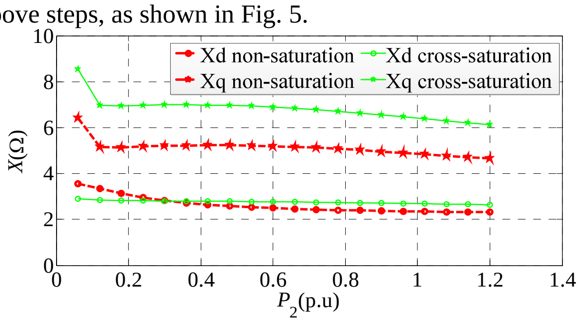

Fig. 5 Calculated X_d and X_q versus load.

The calculated parameters taking cross-saturation effect into account are the X_d and X_q considering the condition that the direct axis magnetic field induces *d*-axis and *q*-axis EMF. Obviously, the result is different after taking the cross-saturation effect into account. It is also proved that ignoring the cross-saturation effect will introduces a large calculation or measurement error.

V. Conclusion

This paper researched how to calculate the steady-state parameter of PMSM taking the cross-saturation effect into account. Firstly, the T-S FEM was used to simulate the measurement proceeding. The calculate result matched the test result well. Secondly, the paper studied the existence of cross-saturation effect, and identified the shortage of the traditional phasor diagram method. Then the parameter calculation method based on improved phasor diagram was proposed. The method is a good reflex of the actual cross-saturation effect. Then we calculated a series of saturated parameters X_d and X_q with the load varying.

Note that: this paper has 6 figures and 13 references, including 7 of references are from the *IEEE Transactions on Magnetics*.

VI. Acknowledgement

This work is supported by National Natural Science Foundation of China (50777018)

VII. Reference

[1] J. F. Gieras, E. Santini and M. Wing, "Calculation of synchronous reactances of small permanent-magnet alternating-current motors: comparison of analytical approach and finite element method with measurements," *IEEE Transactions on Magnetics*, vol.34, pp. 3712-3720, 1998.

[2] M. A. Rahman and Z. Ping, "Determination of saturated parameters of PM motors using loading magnetic fields," *IEEE Transactions on Magnetics*, vol.27, pp. 3947-3950, 1991.

[3] M. A. Rahman and T. A. Little, "Dynamic Performance Analysis of Permanent Magnet Synchronous Motors," *IEEE Power Engineering Review*, vol.PER-4, pp. 40, 1984.

[4] F. Fernandez-Bernal, A. Garcia-Cerrada and R. Faure, "Determination of parameters in interior permanent-magnet synchronous motors with iron losses without torque measurement," *IEEE Transactions on Industry Applications*, vol.37, pp. 1265-1272, 2001.

[5] T. Marcic, G. Stumberger, B. Stumberger, M. Hadziselimovic and P. Virtic, "Determining Parameters of a Line-Start Interior Permanent Magnet Synchronous Motor Model by the Differential Evolution," *IEEE Transactions on Magnetics*, vol.44, pp. 4385-4388, 2008.

[6] A. N. Wignall, A. J. Gilbert and S. J. Yang, "Calculation of forces on magnetised ferrous cores using the Maxwell stress method," *IEEE Transactions on Magnetics*, vol.24, pp. 459-462, 1988.

[7] R. Dutta and M. F. Rahman, "A Comparative Analysis of Two Test Methods of Measuring d- and q-Axes Inductances of Interior Permanent-Magnet Machine," *IEEE Transactions on Magnetics*, vol.42, pp. 3712-3718, 2006.

[8] J. F. Gieras and M. Wing, *Permanent Magnet Motor Technology - Design and Applications*, New York: Marcel Dekker INC ., 2002.

[9] H. P. Nee, L. Lefevre, P. Thelin and J. Soulard, "Determination of d and q reactances of permanent-magnet synchronous motors without measurements of the rotor position," *IEEE Transactions on Industry Applications*, vol.36, pp. 1330-1335, 2000.