Construction of Permanent Magnet Synchronous Motor Variable-Parameter Model

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Abstract: Permanent magnet synchronous motor output characteristics can be expressed with its voltage equation, torque equation and motion equation. Parameters including inductance, resistance, flux linkage, damping coefficient and moment of inertia is regarded as constant in traditional motor models. However, the presence of magnetic saturation, cross-coupling and harmonics make the parameters variables. This paper analyzes causes and effects of the phenomena. Based on the constant parameter model of permanent magnet synchronous motor, the paper presents functions of flux linkages on d-axis current, q-axis current and rotor position angle. Building a motor model with the functions, permanent magnet synchronous motor variable-parameter model is constructed.

1. Introduction

The traditional permanent magnet synchronous motor (PMSM) model is based on the equivalent resistance of the stator, the equivalent inductance in the d-axis and q-axis, and the equivalent flux linkage of the permanent magnet. The introduction of the two-phase rotating coordinate system eliminates the complexity of the control on AC variables in the motor, and the double-reaction theory eliminates the inductance variation caused by the air gap non-uniformity in the salient-pole motor, and thus obtains a compact PMSM constant parameter model [1]. However, the PMSM constant parameter model is based on certain assumptions as follows.

1) The three-phase windings of the stator and the magnetic field generated by the permanent magnet are spatial sinusoidal distribution, and the induced electromotive force waveform in the windings is a sine wave during the steady-state operation.

2) The influence of stator slots on the air gap reluctance and magnetic field distribution is ignored.

3) The magnetic permeability of the stator core and rotor core is infinite, and the winding inductance of the motor does not change with the working conditions.

The above assumptions are different from the actual operating conditions of motors, especially motors in vehicle electric drive systems. In order to pursue high power density, the stator core generally works in a high magnetic saturation state, and a better sinusoidal distribution of the motor magnetic field in the air gap cannot be guaranteed in load conditions [2]. Therefore, to accurately simulate the voltage and current excitation-response rules under operating points of a motor, phenomena including the magnetic saturation and cross-coupling, rotor magnetic field harmonics, motor loss and temperature rise should be considered, which affects parameters of the motor, such as the inductance, flux linkage and resistance.

The motor models in Electric Machine Emulators in previous publications generally focus on the discretization realization method of various numerical integration methods in solving the motor model, not the variations of parameters [3-5]. In publications [6] and [7], the inductance parameters of permanent magnet synchronous motor under magnetic saturation state are obtained by finite element simulation, and the electromagnetic model of permanent magnet synchronous motor is constructed based on this. In [8], the concept of differential inductance is proposed. The stator flux linkages of d-axis and q-axis is used to obtain partial derivative of d-axis and q-axis axis currents, and the d-axis and q-axis self-inductance inductance and cross-coupling inductance value are obtained respectively, but the process of determining the differential inductance value is cumbersome, which increases the calculation of the motor model. In [9], when identifying the motor parameters, the stator flux linkage value of the motor is mainly identified, and the inductance value is obtained according to the flux linkage value considering that the stator flux linkage contains rotor magnetic field harmonics and switching harmonics. The above means of obtaining the parameters under saturated magnetic conditions are not appropriate for analytic calculation in Electric Machine Emulators. Therefore, a variable parameter PMSM model needs to be constructed.

2. Saturation and Harmonics Effects on PMSM

In a motor, the ferromagnetic material that acts as a stator core and a rotor core is used to shape the magnetic field to achieve the desired torque and electrical characteristics. There are many magnetic domains inside the ferromagnetic material, and the magnetic moments of all the atoms in the magnetic domains are parallel, and thus the net magnetic moment is generated in the magnetic domains. When no external magnetic force is applied to the material, the magnetic moments of the magnetic domains in the material are randomly oriented, and the magnetic moments in different directions cancel each other out, so the net magnetic flux in the material is 0, and the material is macroscopically shown as non-magnetic. When an external magnetizing force is applied to the material, the magnetic moments of the magnetic domains tend to align along the applied magnetic field, and the material macroscopically exhibits magnetism. The magnetic moment generated by the magnetic domain is superimposed on the original magnetic field, and the magnetic flux density value generated is larger than the magnetic flux caused by the applied magnetic field alone. The effective magnetic permeability at this time is equal to the magnetic flux density value and the applied magnetic field. The ratio of the intensity is greater than the permeability in free space. The larger the external magnetization force, the more magnetic domains are uniformly oriented inside the material, and the stronger the magnetization of the material. However, this growth is not infinite. When the applied magnetic field force increases to a certain value, the orientation of all magnetic domains is aligned along the direction of the applied magnetic field, the magnetization of the material is no longer increased, and the value of the magnetic flux density will no longer rises for the effect of the magnetic domain, at which point the material is said to be fully saturated.

In the two-phase rotating coordinate system, the d-axis and the q-axis are orthogonal to each other. Therefore, the d-axis and q-axis parameters have no influence on each other. But this law only applies to current and voltage, not to flux linkages. In the stator yokes of motors, the d-axis flux and q-axis flux share the same flux paths. At different locations, the d-axis and q-axis fluxes operate in the same or opposite directions. If the magnetic lines of force in d-axis and q-axis run in the same direction, it will cause magnetization of the stator yoke segments. If they run in the opposite direction, it will cause demagnetization. Due to the nonlinear magnetization characteristics of the stator core, the effects of magnetization and demagnetization do not cancel each other out, resulting in the d-axis and the q-axis being magnetically coupled. For example, if the q-axis magnetic path becomes severely saturated with a large q-axis current, the magnetic path of the d-axis will change accordingly, and vice versa. This coupling mechanism is called cross-coupling.

In the fixed-parameter model of the permanent magnet synchronous motor, the permanent magnet flux linkage value is fixed, that is, the rotor magnetic field is considered to be an ideal sinusoidal distribution in the air gap. However, the permanent magnet synchronous motor in practical application has a large harmonic content in the rotor magnetic field generated by the permanent magnet, due to factors like the shape of the magnetic pole, the distribution of the winding, the existence of the cogging, and so on. Therefore the actual rotor magnetic field is not ideally sinusoidal.

There are a large number of odd-numbered harmonics superimposed on the fundamental wave in the rotor magnetic field of the motor. The main causes of these harmonics are as follows.

1) In the surface-mount permanent magnet synchronous motor, the permanent magnets of the rotor are spaced along the surface of the rotor to make the air gap non-uniform, thereby forming a non-sinusoidal magnetic field.

2) The stator tooth part of the motor is composed of a plurality of teeth and grooves, and the presence of these grooves distorts the magnetic field in the air gap along the circumference.

3) The windings of the motor are discretely distributed in one or more grooves. When the rotor is at different positions in the region, the electromagnetic conditions of the region where the windings are located change, causing the flux linkage variety of the winding to be not sinusoidal when the rotor rotates.

4) Due to the limitation of the manufacturing process, the manufacturing surfaces of the permanent magnet and the stator core are not completely smooth, causing unevenness of the air gap.

3. PMSM Variable Parameter Model

Permanent magnet synchronous motor constant-parameter model is built first based on its equivalent model in Fig. 1. The motor mathematic model is expressed with the following voltage equation (1) and torque equation (2).

$$\begin{cases} u_{\mathrm{d}} = R_{\mathrm{s}} i_{\mathrm{d}} + \dfrac{d\psi_{\mathrm{d}}}{dt} - \omega_{\mathrm{e}} \psi_{\mathrm{q}} \\ u_{\mathrm{q}} = R_{\mathrm{s}} i_{\mathrm{q}} + \dfrac{d\psi_{\mathrm{q}}}{dt} + \omega_{\mathrm{e}} \psi_{\mathrm{d}} \end{cases} \tag{1}$$

$$T_{\mathrm{e}} = \frac{3}{2} p \left(\psi_{\mathrm{d}} i_{\mathrm{q}} - \psi_{\mathrm{q}} i_{\mathrm{d}} \right) \tag{2}$$

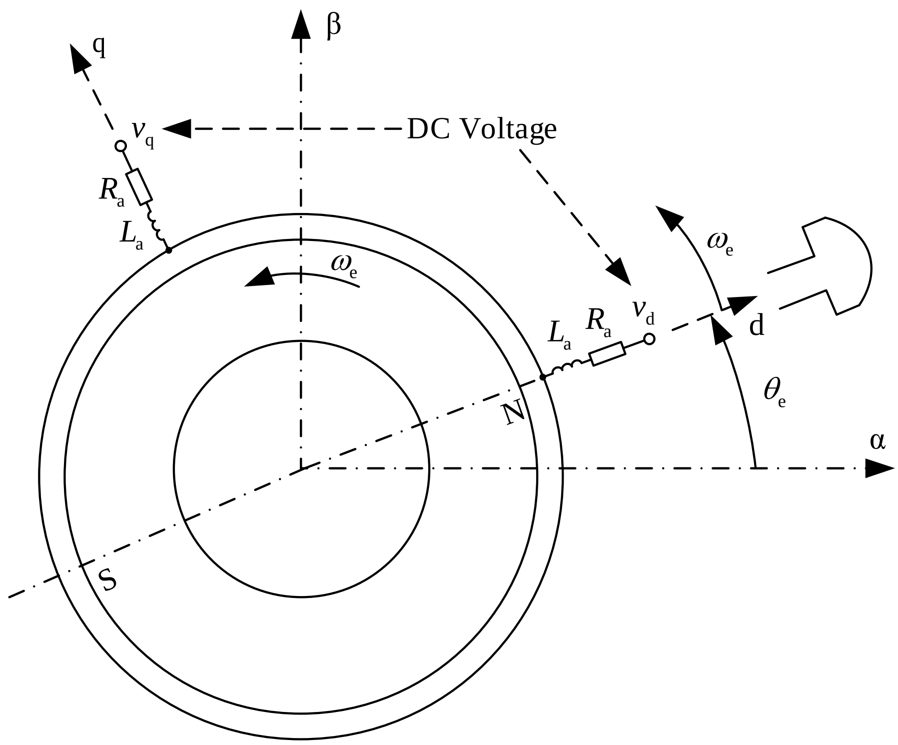

Figure 1. Equivalent Model of Pmsm in Two-Phase Rotating (D-Q) Coordinate System.

The existence of magnetic saturation and cross-coupling effect makes the inductance values of the motor not a fixed value, but a value that changes with the motor output currents in real time. Therefore, the d-axis and q-axis stator flux linkage values of the motor is no longer a linear function of the dq-axis current, but a binary nonlinear function. The stator flux linkages are fully differentiated by the d-axis and q-axis currents to obtain the self-inductance and mutual inductance values shown in the formula (3), collectively referred to as differential inductances. However, building a mathematical model of the motor based on equation (3) will require determining four inductance values, so the calculation process is complicated. Therefore, this paper ignores the explicit determination of the differential inductances and directly obtains the binary function of the motor stator flux linkages on the d-axis and q-axis currents.

$$\begin{cases} \psi_{\mathrm{d}} = f_1\left(i_{\mathrm{d}}, i_{\mathrm{q}}\right) \\ \psi_{\mathrm{q}} = f_2\left(i_{\mathrm{d}}, i_{\mathrm{q}}\right) \end{cases} \tag{3}$$

The binary function of the d-axis and q-axis currents with respect to the d-axis and q-axis stator flux linkages by calculating the inverse function of f_1 and f_2, as shown in formula (4).

$$\begin{cases} i_{\mathrm{d}} = f_3\left(\psi_{\mathrm{d}}, \psi_{\mathrm{q}}\right) \\ i_{\mathrm{q}} = f_4\left(\psi_{\mathrm{d}}, \psi_{\mathrm{q}}\right) \end{cases} \tag{4}$$

The magnetic pole shape, winding distribution, stator cogging and other factors of the permanent magnet synchronous motor make the rotor magnetic field have obvious harmonic characteristics. The presence of harmonic characteristics causes the motor rotor flux to be the function of the rotor position angle. The rotor flux linkage contains 6kth harmonics and the rotor flux linkage values generate harmonic components in the d-axis and q-axis respectively. Through the coordinate transformation, the motor d-axis and q-axis stator flux linkages all become the function of the rotor position angle.

The stator flux linkage expressions including the 6kth harmonic are obtained as shown in formula (5). Since the amplitude of the higher harmonics is small, only 5th, 7th, 11th, and 13th harmonics are taken in this paper, and higher harmonics are ignored.

$$\begin{cases} \psi_{\mathrm{d}} = L_{\mathrm{d}} i_{\mathrm{d}} + \psi_{\mathrm{f,1}} + \left[\left(\psi_{\mathrm{f,5}} + \psi_{\mathrm{f,7}}\right)\cos 6\theta + \left(\psi_{\mathrm{f,11}} + \psi_{\mathrm{f,13}}\right)\cos 12\theta + \cdots\right] \\ \psi_{\mathrm{q}} = L_{\mathrm{q}} i_{\mathrm{q}} + \left[\left(-\psi_{\mathrm{f,5}} + \psi_{\mathrm{f,7}}\right)\sin 6\theta + \left(-\psi_{\mathrm{f,11}} + \psi_{\mathrm{f,13}}\right)\sin 12\theta + \cdots\right] \end{cases} \tag{5}$$

4. Conclusion

Parameters including inductance, resistance, flux linkage, damping coefficient and moment of inertia in permanent magnet synchronous motor is influenced by the presence of magnetic saturation, cross-coupling and harmonics and become variables. Based on the analyses of their causes and effects, functions of flux linkages on d-axis current, q-axis current and rotor position angle are presented. Building a motor model with functions of parameters, permanent magnet synchronous motor variable-parameter model is constructed, which performs better than constant-parameter model on simulating the output characteristics of permanent magnet synchronous motors.

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