Parameter Estimation for Universal Motor Module of Vehicle Simulator

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Abstract : This paper deals with the determination of parameters in the motor module of vehicle simulator. In the general vehicle simulator, the traction motor of Hybrid Electric Vehicle is defined by efficiency map, maximum torque/speed curve and so forth. Due to the prevalence of Interior Permanent Magnet Synchronous Motor (IPMSM), this paper mainly focuses on the calculation of efficiency map of IPMSM considering magnetic nonlinearity. Firstly, by means of numerical methods, the inductance and iron loss resistance are calculated. Next according to equivalent circuits, the motor characteristics including speed, torque and efficiency are investigated. Finally, the calculated efficiency result is verified by the experiment data. And all parameters are loaded and implemented in ADVISOR which is an advanced vehicle simulation software for testing.

Key words : Interior Permanent Magnet Synchronous Motor, efficiency map, iron loss resistance, motor module, ADVISOR

Nomenclature

A : power, kW
B : length, mm
C: inductance, mH
D: resistance, Ohm

1. INTRODUCTION

These years, Hybrid Electric Vehicle (HEV) and Fuel Cell Vehicle have been paid more attention because of the environmental and economic benefits. In their design process, however, due to the complex integrate system, it is difficult to determine the specification of each component and estimate the overall performance. Based on these difficulties, many vehicle simulators were developed by institutes and companies. Such as a vehicle simulator called ADVISOR, it dose not only offer the practical vehicle and components model for selection, but also support self-specified parameters of each components. Despite there have been many literatures [1] to introduce the establishing methods, none of them mentions how to estimate the required parameters. Therefore, this paper will focus on the determination of parameters of motor module used in general vehicle simulators. Owing to the prevalence, the Interior Permanent Magnet Synchronous Motor (IPMSM) is chosen as the analysis and simulation model. The parameters of motor module employed in vehicle simulator mainly are efficiency map, maximum torque/speed curve, mass of motor and inverter, moment of inertia and so on. Here the efficiency map and maximum torque/speed curve are the dominant factors, which require an accurate and relatively easy estimation method to get them. This paper presents a series of methods, which consists of Finite Elements Analysis (FEA) and equivalent circuit analysis. The FEA is used to calculating the nonlinear parameters such as d- and q-axis armature self inductance and iron-loss resistance. And the equivalent circuit analysis takes charge of calculating the characteristics including the maximum torque/speed curves

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and efficiency map with these nonlinear parameters. Finally, the calculated efficiency map is compared with the measured results to verify these methods. And the total calculated parameters are loaded and implemented in ADVISOR for testing.

2. MOTOR SIMULATION MODULE IN GENERAL VEHICLE SIMULATOR

Due to the complication, the vehicle simulator system usually focuses on power transmission and distribution rather than transient data of each component. Be a part of this system, the traction motor module hence is established based on efficiency map of motor and controller [2]. In the motor module, the efficiency map usually is converted to a 2-D look-up table, and indexes it via torque and speed. The general implement process of this motor module is:

-Step 1: input requirement of torque and speed;

-Step 2: calculate possible torque and speed according to maximum torque/speed characteristics;

-Step 3: calculate required input power according to efficiency map;

-Step 4: compare required power with available power. If the required is larger than the available, the available torque is output. Otherwise, the required torque is output.

In addition, in order to describe the dynamic of motor, the moment of inertia and mass of motor are required. And the motor controller module needs maximum current and minimum voltage.

3. ANALYSIS MOTOR MODEL

3.1 Motor Specifications

In this paper, a 12 kw soft-type IPMSM which is designed to be traction motor in a parallel-type HEV is analyzed. The specification of this motor is described in Table I. The half cross-section of this motor is showing in fig. 1.

3.2 Equivalent Circuits and Equations

On the basis of Clark-Park theory, 3-phase AC motor usually is transformed to 2-phase d-q model. The equivalent circuits of d-q model of IPMSM are shown in Fig. 2 [3].

Table I
Specifications of IPMSM

parameters	Values	
stator outer diameter	270.0	mm
rotor outer diameter	198.0	mm
rotor stack length	35.0	mm
air gap length	0.9	mm
size of permanent magnet	14.2x4.8x35	mm^3
number of poles/ slots	16 / 24	-
DC link Voltage	130	V
material of iron	S18	-

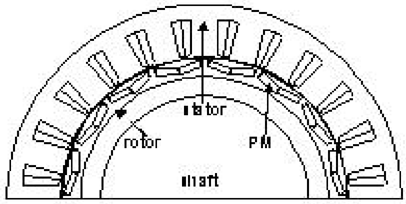


Fig. 1 The half cross-section of the analyzed motor model

Based on the equivalent circuits, the IPMSM dynamic mathematic model is described by (1)-(3).

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1 + \frac{R_a}{R_c}\right) \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + p \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \quad (2)$$

$$T = P_n \left[\psi_a i_{oq} + \left(L_d - L_q \right) i_{od} i_{oq} \right] \quad (3)$$

where, ψa is the flux linkage generated by permanent magnet, Ld is d-axis inductance and Lq is q- axis inductance, Ra is armature winding resistance per phase, and Pn is pole pair number. Additionally, the copper loss and iron loss equations with d-q current and frequency are described in (4) and (5).

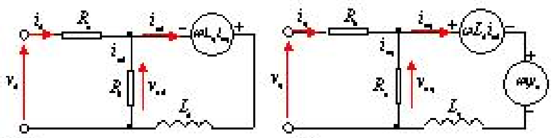
$$W_c = R_a I_a^2 = R_a(i_d^2 + i_q^2) \tag{4}$$

$$W_i = \frac{V_o^2}{R_c} = \frac{\omega^2((L_d i_{od} + \psi_a)^2 + (L_q i_{oq})^2)}{R_c} \tag{5}$$

4. PARAMETERS CALCULATION USING FEA

4.1 Inductance Calculation

In this paper, the inductance calculation method is based on a synchronous d-q frame of reference as shown in Fig. 3, which is used to describe the vector relationship of motor parameters. In Fig. 3, it is observed that there are the relationships as expressed in (6) and (7).



(a) (b)

Fig. 2 Equivalent circuits: (a) d-axis equivalent circuit; (b) q-axis equivalent circuit

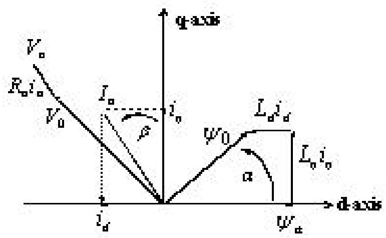


Fig. 3 Synchronous d-q frame of reference of IPMSM

$$L_d = \frac{\psi_0 \cos\alpha - \psi_a}{i_d} \tag{6}$$

$$L_q = \frac{\psi_0 \sin\alpha}{i_q}$$

(7)

where ψ0 is the flux linkage generated by permanent magnet and excited armature winding. The process to calculate the Ld and Lq in FEA is listed as follow:

-Step 1: For the different current and current phase angle, the permeability of each element is calculated and saved at operating point in nonlinear analysis.

-Step 2: Setting the ψa to zero and using the permeability obtained in Step 1, the linear magnetic analysis is performed. Here the current phase angle is fixed at 90o in the d-axis inductance calculation, and at 0o in the q-axis inductance calculation. The magnitude of phase current is set to 1A for non-saturation calculation.

-Step 3: The phase inductance is calculated by the effective inductance equation which is defined as twice the energy stored in the magnetic filed divided by the square of the current in the device winding. According to the Clark-Park Transformation, the d- and q-axis inductance is 2/3 times of phase inductance, which is described in (8).

$$L_{d/q} = \frac{2}{3}\left(\frac{2W_s}{i^2}\right) \tag{8}$$

where Ws is the stored energy obtained in d-axis inductance calculation or q-axis inductance calculation in Step 2.

4.2 Iron Loss Resistance Calculation

The dominant loss in IPMSM usually consists of copper loss, iron loss and mechanical loss. The copper loss is determined by coil resistance which is constant in a given temperature. In this paper, the phase resistance is calculated by the conductivity and the wire geometric with considering turn number and parallel circuit. And the mechanical loss is assumed to be 1.5% over the motor output according to IEEE112.

The iron loss usually is separated into two components: the hysteresis loss Ph and eddy current loss Pe, both in W/Kg as shown in (9) [4].

$$P_c = P_h + P_e = k_h f B_m^n + k_e f^2 B_m^2 \tag{9}$$

Usually, there are harmonic components in current waveform. And hence, same frequency components are caused in flux density. However, (9) only can be used for sinusoidal variation. In this paper, an improved method which consists of Time-stepping FEA and harmonic analysis is used to calculate iron loss.

4.3 Time-stepping FEA

In order to take into account the harmonic components, the temporal and the spatial variations of magnetic flux density should be obtained. Time-stepping FEA can be used to analyze the magnetic field and obtain the distribution of flux density in time and space. The governing equation for 2-D FE model analysis is given as

$$\frac{1}{\mu}\left[\frac{\partial}{\partial x}\left(\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial A_z}{\partial y}\right)\right]-\sigma\frac{dA_z}{dt}+J_0=0 \quad (10)$$

where Az is the z component of magnetic vector potential, μ is the permeability, σ is the conductivity of the materials, and J0 is the excited current density of the stator winding. Due to the unknown J0, the voltage equation of phase winding (11) is necessary.

$$V_{abc}=I_{abc}R+L_e\frac{dI_{abc}}{dt}+\frac{d\lambda_{abc}}{dt} \quad (11)$$

where Le is the end-coil inductance which is especially used in 2-D FEA, λabc is the flux linkage which can be calculated by (10). In this paper, the time step is fixed. And according to a sinusoidal curve, the input voltage is defined at each time step.

4.4 Harmonic Analysis

After obtain the flux density of each element, the frequency and amplitude of each harmonic component should be analyzed. In this paper, the Discrete Fourier Transform (DFT) is used. It can be expressed as

$$B_{pk}(k)=\sum_{n=0}^{N-1}B_p(n)e^{j(2\pi nk)/N}$$

(12)

where k is the harmonic order, N is the number of the discrete data, Bpk(k) is the amplitude of magnetic flux density of the kth harmonic, and Bp(n) is the magnitude of the point n (n=0,1,2,…,N-1)

When the frequencies and amplitudes of magnetic flux density at each element are obtained, depending on them, the iron losses at each element are calculated from an iron loss data sheet that is tested by the Epstein test apparatus. Then, sum the results of all harmonics and all elements, the total iron loss can be obtained. The flowchart of this calculation process is described in Fig. 4.

4.5 Equivalent Resistance Calculation

At the end, the iron loss equivalent resistance is calculated by (13)

$$R_c=\frac{v_0^2}{P_c} \quad (13)$$

where v0 is the terminal voltage at base speed and no-load condition. And the iron loss resistance is 36.5 Ohm in this calculation.

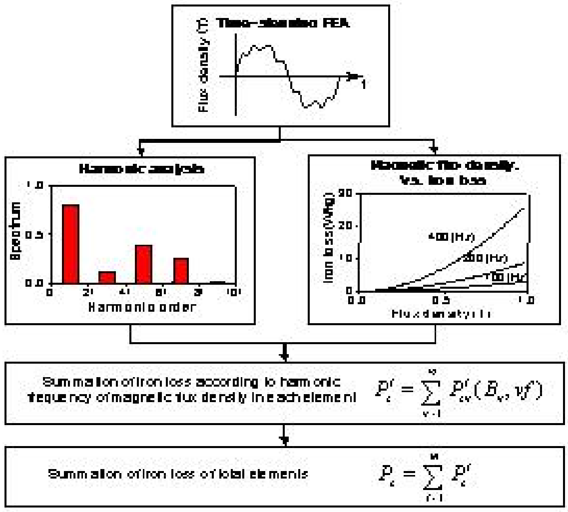


Fig. 4 Flowchart of iron loss calculation process

5. CHARACTERISTIC ANALYSIS

The IPMSM using in traction system usually is operated in Maximum Torque per Ampere (MTPA) control method and flux weakening control method. Although there is the corresponding equation for each control method [3], the characteristic analysis is much difficult to be done with it due to the nonlinear inductances. This paper proposes a computer aided method which uses the iteration computation and loop condition to calculate the motor characteristics. Before base speed, the lop condition is the maximum torque and current due to MTPA control. And after base speed, the maximum power is the loop condition. Once loop condition is satisfied, the calculated data is stored. The detail process is shown in Fig. 5. By means of this method, the maximum torque/speed curve and efficiency map can be obtained.

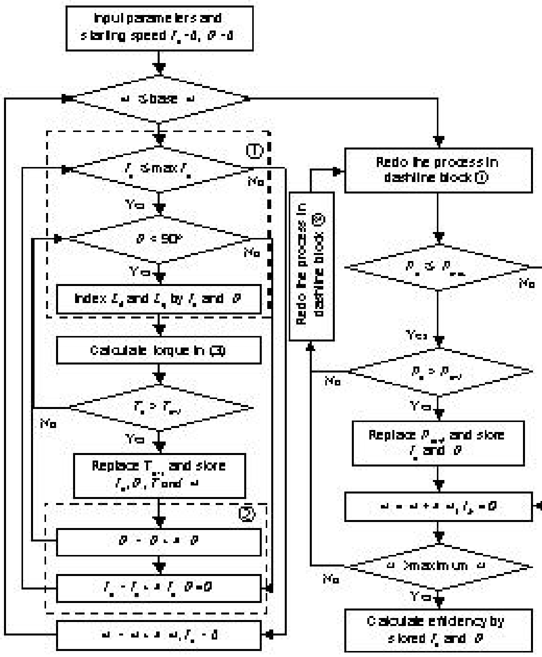


Fig. 5 Flowchart of the process of characteristics calculation

6. CALCULATED RESULTS AND DISCUSSION

Fig. 6 shows the calculated d- and q-axis inductances profiles. It is obvious that the Ld has not much change in total current distribution, while the Lq behaves significant nonlinearity and saturation with the variation of id and iq.

Fig. 7 shows the characteristics of this IPMSM. The efficiency map calculated by the proposed method is shown in Fig. 8 (a). Fig. 8 (b) shows the measured efficiency. It can be seen that the efficiency values and distributions of these two maps are quite similar.

Based on the dimension of this IPMSM, the mass and inertia also are calculated in geometry. Finally, the total parameters are saved in a *.m file and loaded into

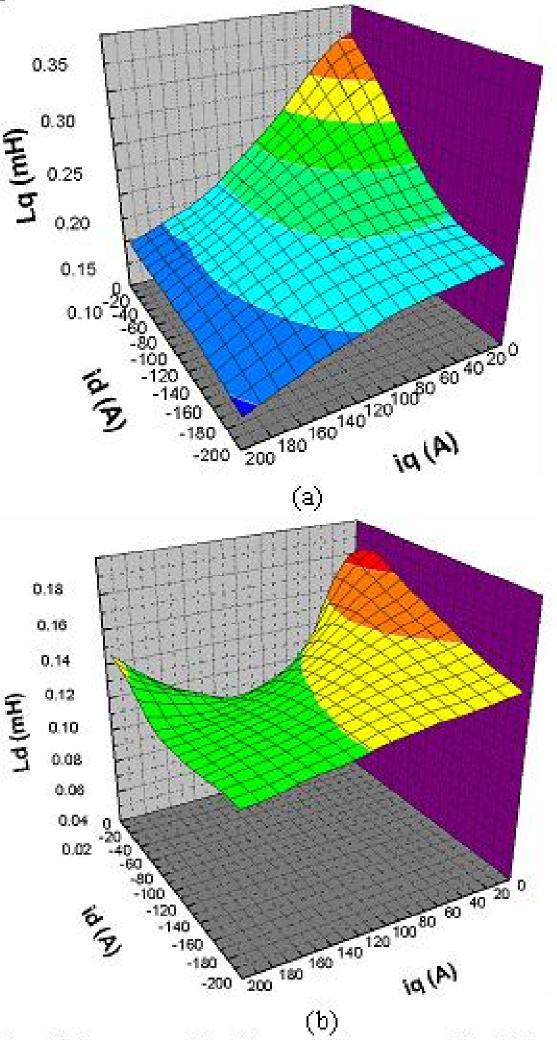


Fig. 6 Inductance profiles: (a) q-axis inductance profile; (b) d-axis inductance profile

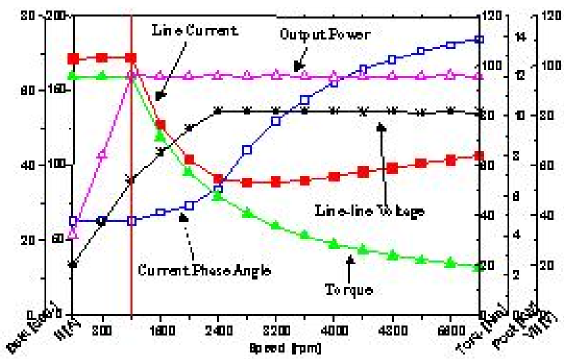


Fig. 7 Characteristics of the IPMSM

ADVISOR. These self-specified parameters are simulated in a default parallel type HEV. After simulate the model in an urban road condition, the operation points in the efficiency map are obtained and showing in Fig. 9. Note the efficiency map in generating mode is simply converted from the same data of motoring mode. It is observed that the most operation points distribute in low speed and high torque region. It implies this motor is often used to be starting torque assistant.

7. CONCLUSIONS

This paper presents a series of methods for calculating the parameters of the motor module which is employed in general hybrid/electric vehicle simulator. In the proposed methods of this paper, the motor parameters such as d- and q-axis inductances, iron loss resistance are calculated in numerical method first. And then, according to the equivalent circuit, the characteristics of this motor are investigated. By means of the comparison with experiment results, the valid of these methods are proved. Finally, the parameters are converted to a *.m file and implemented in ADVISOR, and a successful test is obtained.

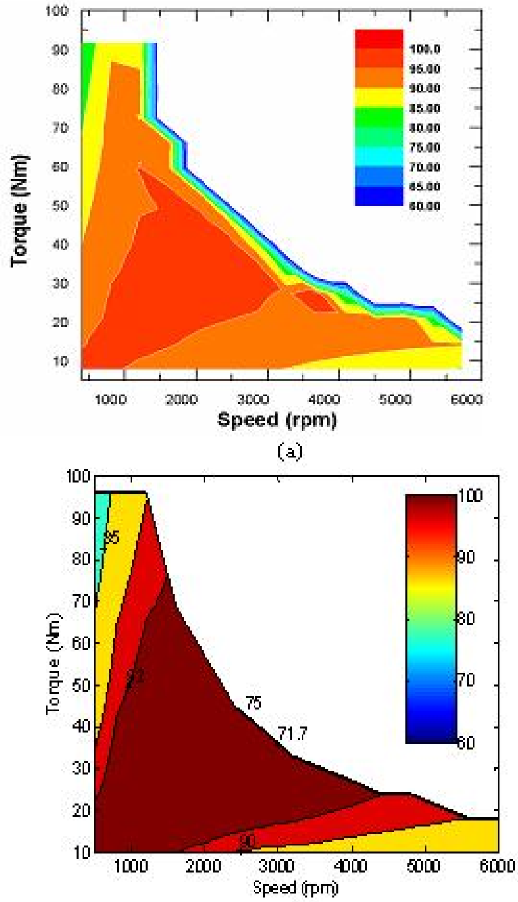


Fig. 8 Efficiency map of the IPMSM: (a) analysis data; (b) experiment data

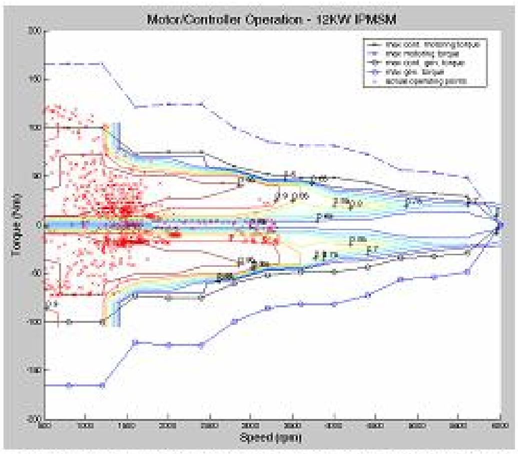


Fig. 9 Operation points in efficiency map of motor module employed in ADVISOR

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