Reluctance Torque Analysis and Reactance Calculation of IPM for HEVs Based on FEM

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***Abstract*-Rational utilization of reluctance torque can effectively improve torque performance and speed range in constant power region of interior permanent magnet(IPM) electric machines, thereby affecting dynamic performance of HEVs. This paper presents a reluctance torque analysis method on the basis of calculating the torque-power angle characteristic curve in advantage of FEM. Moreover, the direct(d) and quadrature(q) axis synchronous reactance is calculated. Furthermore, a measure of improving flux weakening performance by increasing salient-pole rate is proposed. The prototype experiment results verify this analysis method. The method presented in this paper provides reference for electromagnetic design of traction motors in HEVs.**

I. INTRODUCTION

In recent years, the issues of energy consumption and environment pollution have become increasingly evident. One of the important reasons of the atmospheric pollutions is the gas emission produced by the thermal powertrains of vehicles [1]. Thus governments around the world have begun to focus on the issues and paid efforts to develop technologies of hybrid electric vehicles.

Traction motor is the heart of electric drive system of HEVs [2]. Interior permanent magnet synchronous machine has been increasingly used as the traction motor in HEVs because of the advantages of simple configuration, high power density, high efficiency and good flux weakening performance in the condition of constant inverter capability [3,4]. The electromagnetic torque of IPM consists of two components. One is permanent magnet torque generated by the interaction of air-gap magnetic field and stator armature reaction magnetic field. The other is reluctance torque generated by the asymmetry of magnetic circuit of d-axis and q-axis. A reasonable increase of reluctance torque can improve torque and flux weakening performance, and then has a good effect on the overloading ability and power density of IPM. The value of reluctance torque is directly related to d-axis and q-axis synchronous reactance. Due to the saturation of magnetic circuit [4], finite element method is used to simulate IPM machines in this paper.

Firstly, the torque-power angle characteristic curve of selected synchronous motor is calculated in FEM. Based on the curve we can calculate the ratio of reluctance torque in the whole electromagnetic torque. Because the value of synchronous reactance is largely determined by the magnetic circuit structure of rotor, two kinds of typical rotor magnetic circuit structure are selected to illustrate this method and the calculation results are compared in order to provide reference in the motor design process. Secondly, d-axis and q-axis synchronous reactance is obtained on the basis of the analysis results. Furthermore, the calculation results are validated by the prototype experiment. In addition, in order to improve the flux weakening ability, a new method of increasing salient-pole rate based on reducing saturation degree of q-axis magnetic circuit is presented by changing the ratio of teeth and slot width. This method is verified to be feasible by the mentioned reactance calculation method. Therefore this analysis method is effective and can provide reference for motor design and optimization.

II. CALCULATION OF RELUCTANCE TORQUE AND SYNCHRONOUS REACTANCE

A Analysis of Reluctance Torque

In order to illustrate the analysis process of Reluctance torque, two kinds of typical rotor magnetic circuit structure of IPM for HEVs (Tangential-Type and V-Type) are selected to be analyzed and compared. The two motors selected as analytical models have the same technical parameters and dimension. The FEM analysis models of Tangential-Type and V-Type are shown in Fig. 1.

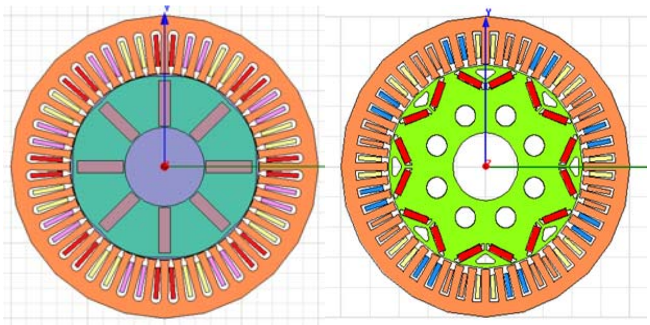

Fig. 1. FEA models of tangential-type and v-type.

The electromagnetic torque of IPMSM is defined as the following expression:

$$T_{em} = \frac{mpE_0U}{wX_d}\sin\theta + \frac{mpU^2}{2w}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\theta \quad (1)$$

As is shown in (1), fundamental component of electromagnetic torque is permanent magnet torque generated by the interaction of air-gap magnetic field and stator armature reaction magnetic field. The second harmonic component is reluctance torque generated by the asymmetry

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of magnetic circuit of d-axis and q-axis. Thus the following analysis process is implemented.

In order to analyze the respective ratio of permanent magnet and reluctance torque in the whole electromagnetic torque, the torque-power angle characteristic curve is firstly to be calculated. Respective torque values corresponding to different power angles are calculated as the following method.

1) Analyze the armature reaction of A-Phase winding at the time when the amplitude of fundamental synthetic rotating magnetic motive force wave is in superposition with A-Phase winding axis. And at that time the value of A-Phase current reaches the maximum.

2) Keep the A-Phase winding axis fixed and calculate the average electromagnetic torque respectively at different rotor position angle α as Fig. 2. Due to space limitations, only four of the models are listed.

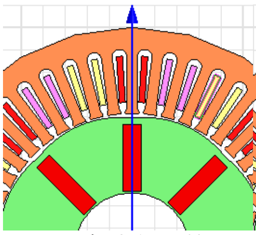

Fig. 2-1. α=0°

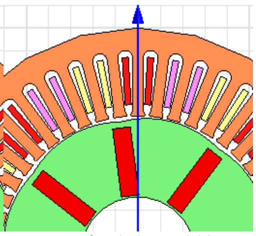

Fig. 2-2. α=30°

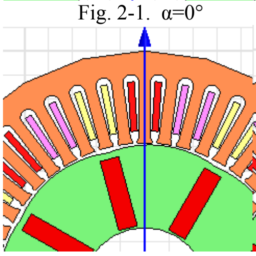

Fig. 2-3. α=60°

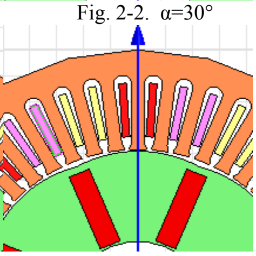

Fig. 2-4. α=90°

Fig. 2. FEA models of different rotor position angle.

3) Under the previous conditions, the rotor position angle α is equivalent to the angle between d-axis and A-Phase winding current but not the power angle needed in the curve drawing. The given current source waveform and phase voltage waveform by simulating are shown in Fig. 3. Thus the power factor angle (the angle between phase voltage and armature current) can be obtained. Therefore the power angle (the angle between phase voltage and no-load back EMF) is calculated. So far the torque-power angle curve can be drawn. The curves of Tangential-Type and V-Type structure are shown in Fig. 4 and Fig. 5.

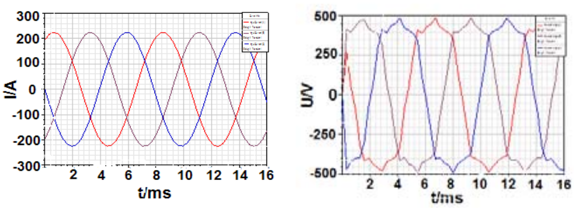

Fig. 3. Current source and phase voltage waveform.

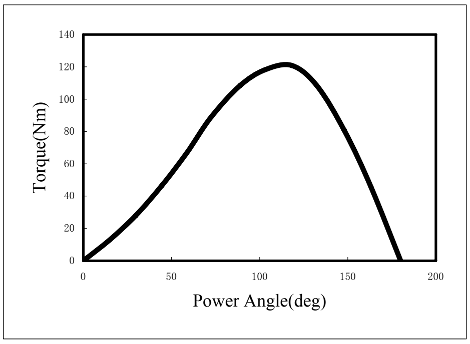

Fig. 4. Torque-angle characterisric curve of tangential-type.

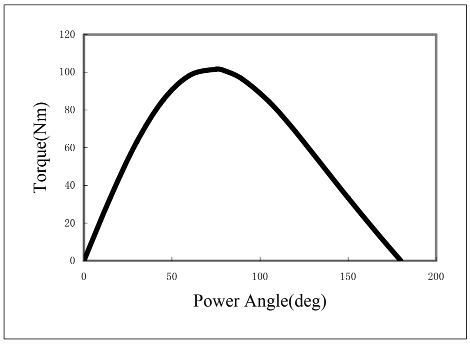

Fig. 5. Torque-angle characterisric curve of v-type.

4) The amplitude of fundamental and second harmonic wave component represents the proportion of permanent magnet and reluctance torque in the whole electromagnetic torque respectively. The fourier decomposition results of the curves are shown in Fig. 6.

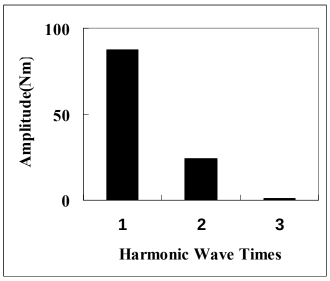

Fig. 6-1. Tangential-type.

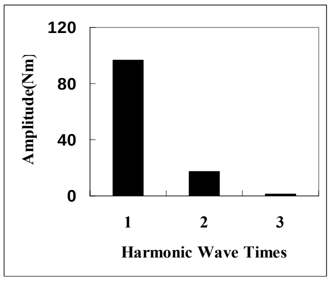

Fig. 6-2. V-type.

Fig. 6. Fourier decomposition results.

The decomposition results show the proportion of reluctance torque of two types. This analysis method can provide references in the magnetic circuit selection of motor design process.

B Calculation of Synchronous Reactance

On the basis of previous research, the d-axis and q-axis synchronous reactance can be calculated according to the following equation.

$$\begin{cases} T_{em1} = \dfrac{mpE_0U}{\omega X_d} \\ T_{em2} \dfrac{mpU^2}{2\omega}\left(\dfrac{1}{X_q} - \dfrac{1}{X_d}\right) \end{cases} \tag{2}$$

III. A Measure of Improving Flux Weakening Ability

According to relevant papers the increase of salient-pole rate (L_q/L_d) has a good effect on flux weakening ability. Taking advantage of the previous reactance calculation method, a new measure of increasing salient-pole rate based on decreasing saturation degree of q-axis flux path is presented. The q-axis armature reaction flux path of IPMSM is shown in Fig. 7.

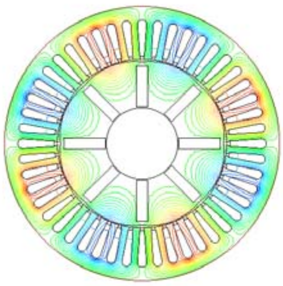

Fig. 7. Flux path of q-axis magnetic circuit

As is shown in the picture, the q-axis flux path is closed by stator teeth and yoke, rotor yoke and air gap. Thus under the premise of guaranteeing the winding performance, increasing the cross-sectional area of stator teeth and yoke properly can decrease the saturation degree at the load operating point. Furthermore, q-axis inductance increases so that the salient-pole rate is increased. The change of salient-pole rate(ρ) with the ratio of teeth and slot width(k) is shown in Fig. 8.

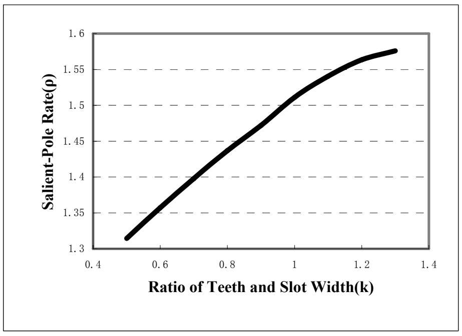

Fig. 8. Curve of salient-pole rate

IV. Experimental Validation

After the simulation and calculation, a test bed based on prototype and AVL dynamometer is set up to verify the research results as is shown in Fig. 9.

Fig. 9. Test bed of prototype

A experiment is designed to measure d-axis and q-axis reactance of the prototype. An inverter with flux-weakening strategy is selected to match the motor. Firstly, turn on the enable-switch of inverter and drive the prototype with AVL dynamometer at a speed which is higher than rated speed. The three-phase voltages and currents are monitored by power analyzer. At this time the motor is running in a no-load state, so the q-axis current is zero. According to the phasor diagram of steady state shown in Fig. 10-1, the relationships of various phasors can be obtained, which is shown in Fig. 10-2. The value of d-axis reactance can be calculated by the following equation,

$$U^2-\left(I_1R_1\right)^2=\left(E_0-I_dX_d\right)^2 \tag{3}$$

Then impose a certain load to the motor by inverter. Because the speed is the same as no-load steady state, the increase of current is caused by q-axis current. The value of it can be calculated. Furthermore, the angle between phase current and no-load back EMF is obtained. By the phasor relationship diagram shown in Fig. 10-3, (4) can be derived.

$$\dot{U}-\dot{I}\,R-\dot{E}_0=\dot{I}_d\,X_d+\dot{I}_a\,X_a \tag{4}$$

The phasor on left side of (4) can be calculated by experiment results. The projections in the direction of back EMF and d-axis are respectively products of d-axis current and synchronous reactance ,q-axis current and synchronous reactance. Therefore, the value of reactance can be obtained.

The comparison of calculated and tested results is shown in Table Ⅰ.

TABLE I

Comparison Of Calculated And Tested Results

	Calculated Results	Tested Results
X_d/Ω	0.322	0.334
X_q/Ω	0.537	0.546

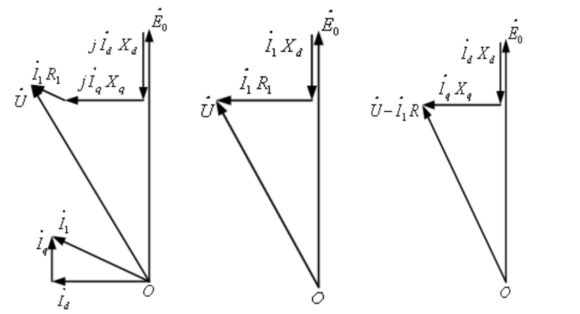

Fig. 10-1.Steady state Fig. 10-2. d-axis Fig. 10-3. d-q axis

Fig. 10. Phasor diagrams in the calculation process

V. Conclusion

This paper presents a reluctance torque analysis method of IPMSM, which is on the basis of torque-power angle characteristic curve, using FEA method due to the impact of magnetic circuit saturation. With this method the proportion of reluctance torque in the whole electromagnetic torque can be analyzed. Furthermore, a calculation method of d-axis and q-axis synchronous reactance is presented. The analysis and calculation method is verified by experiments. This analysis and calculation method can provide references in the magnetic circuit selection of motor design process and give a great help to further research about flux weakening ability of IPMSM for HEVs.

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