

An Accurate Modeling for Permanent Magnet Synchronous Wheel Motor Including Iron Loss

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ABSTRACT

For high torque permanent magnet wheel motor, this paper describes an experimental research method to optimize and identify the motor parameters based on the results of offline calculation. In order to improve the accuracy of motor parameters identification, the motor model considering the affect of iron loss was established, and the motor parameters were identified using genetic algorithm (GA). Based on this, parameters validation experiment was performed. The results show that: parameters obtained by this method can be used to describe the steady-state and transient-state response of permanent magnet synchronous motors accurately.

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INTRODUCTION

Because of its high efficiency, high torque density and other advantages, permanent magnet synchronous motor has been widely used as wheel motor. Permanent magnet synchronous motor controlled by FOC, can operate at fast torque response. Therefore the method has become one of the main methods to control permanent magnet synchronous motor. However, this control method more or less needs motor parameters involved, and the accuracy of parameters directly affects the performance of system. In addition, motor parameters are needed in the torque estimation, fault diagnosis and so on. Therefore, the accurate identification of motor parameters is the primary task to control the permanent magnet synchronous motor.

There is also energy saving and efficiency requirements about the 4WD electric vehicle in which the main energy transfer process is the motor drive system. If the efficiency of the motor drive system can be improved, the economical efficiency of the vehicle can be enhanced. In literature [1, 2], the optimal efficiency can be achieved based on the motor model by optimal torque distribution control. An accurate modeling of PMSM is very important.

In actual operation of permanent magnet synchronous motor, the iron loss actually exists and occupies a certain proportion in the total loss, which to some extent will affect the performance of the drive motor. As a result, establishment of motor model considering the affect of iron loss can increase the accuracy of parameters calculation. In literature [3], two kinds of motor model depending on whether the affect of iron

loss was considered were established and the inductance of d-axis and q-axis were calculated. The comparison of two motor model results shows that the inductance parameter model considering the affect of iron loss was more accurate.

For motor model considering the affect of iron loss, parameters identification methods mainly are mainly classified into two categories: offline and online identification [4, 5, 6]. In literature [4], the parameters of small power synchronous motor are determined through experiments. When identifying the inductance parameter, one of the q-axis and d-axis current was set to zero. In literature [5, 6], the online identification of motor permanents was simplified by assuming that the inductance of d-axis and q-axis is constant which is from the offline identification. Wheel motor with high torque has higher torque density than ordinary permanent magnet synchronous motor, and the coupling of d-axis magnetic field and q-axis magnetic field in the wheel motor is more serious [7, 8]. And the value of motor inductance changes along with the q-axis current. For high torque permanent magnet wheel motor, the value of motor parameters can be more accuracy by optimization based on the initial calculation results.

Offline identification of motor parameters using intelligent optimization algorithm, such as genetic algorithm, ant colony algorithm, and particle swarm et al., has become a research hotspot in recent years [9, 10]. In literature [9], the speed and accuracy of identification using genetic algorithm, ant colony algorithm and particle swarm were compared and analyzed by experimental methods. It was concluded that genetic algorithm can obtain the highest accuracy.



This paper first established the motor model considering the influence of iron loss in steady-state and transient-state conditions, and obtained the initial parameters in specific steady-state conditions. Then a genetic algorithm identification model was given to optimize the motor parameters. The variation range of first generation in genetic algorithm was determined according to the initial value of each parameter in specific operating conditions. The input of motor identification model was the target voltage, and appropriate fitness function was selected. The results of parameters validation experiment show that, parameters obtained by this method can be used to describe the steady-state and transient-state response of permanent magnet synchronous motors accurately. The accurate motor model can provide the theory foundation for the optimal torque distribution control which can improve the efficiency of the motor drive system about the 4WD electric vehicle.

MODEL DESCRIPTION

In literature [11], the voltage equation including the stator iron loss is based on the following assumptions: the harmonic components of current and flux linkage are neglected; the rotor iron loss and stray loss are neglected; the stator iron loss is expressed by the equivalent iron loss resistance.

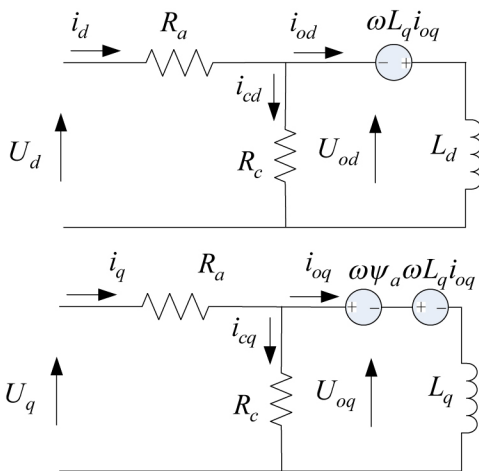


Figure1. The d-axis and q-axis equivalent physical model in the d-q coordinate which rotate synchronously with the electrical angular velocity ω .

Steady-State Model

In Fig. 1, voltages across the inductance in steady-state condition are zero. As a result, voltage equations of the PMSM in the steady-state are expressed as follows:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1 + \frac{R_a}{R_c}\right) \begin{bmatrix} U_{od} \\ U_{oq} \end{bmatrix} \quad (1)$$

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

Where i_{od} , i_{oq} , i_{cd} and i_{cq} are respectively expressed as follows:

$$i_{od} = i_d - i_{cd}, i_{oq} = i_q - i_{cq} \quad (3)$$

$$i_{cd} = -\frac{\omega L_q i_{oq}}{R_c}, i_{cq} = \frac{\omega(\psi_a + L_d i_{od})}{R_c} \quad (4)$$

Where i_d and i_q are respectively the armature current of d-axis and q-axis; i_{cd} and i_{cq} are respectively the iron loss current of d-axis and q-axis; i_{od} and i_{oq} are respectively the airgap current of d-axis and q-axis; U_d and U_q are respectively the voltage of d-axis and q-axis.

Accordingly, the current i_{od} and i_{oq} of the PMSM can be expressed as follows:

$$\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} = \frac{1}{1 + \frac{\omega^2 L_d L_q}{R_c^2}} \begin{bmatrix} 1 & \frac{\omega L_q}{R_c} \\ -\frac{\omega L_d}{R_c} & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q - \frac{\omega \psi_a}{R_c} \end{bmatrix} \quad (5)$$

For simplification, assuming that, $\frac{\omega^2 L_d L_q}{R_c^2} \ll 1$ and $\frac{R_a}{R_c} \ll 1$.

The steady-state equations are shown in Eq. (6).

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = \begin{bmatrix} R_s + \frac{\omega^2 L_d L_q}{R_c} & -\omega L_q \\ \omega L_d & R_s + \frac{\omega^2 L_d L_q}{R_c} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{\omega^2 L_q}{R_c} \\ \omega \end{bmatrix} \psi_a \quad (6)$$

Torque is estimated using Eq. (7).

$$T = 1.5p \left(\psi_a i_{oq} + (L_d - L_q) i_{od} i_{oq} \right) \quad (7)$$

Where p is the number of pole-pairs.



Transient-State Model

In Eq. (6), voltage equations are in the steady-state, but in certain cases the transient-state model is very important. As shown in Fig. 1, in transient-state condition the voltage equations of the PMSM are expressed as follows:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1 + \frac{R_a}{R_c}\right) \begin{bmatrix} U_{od} \\ U_{oq} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} U_{od} \\ U_{oq} \end{bmatrix} = \begin{bmatrix} PL_d & -\omega L_q \\ \omega L_d & PL_q \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} U_{od} \\ U_{oq} \end{bmatrix} = \begin{bmatrix} R_c & 0 \\ 0 & R_c \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} \quad (10)$$

The voltage equation in transient-state is obtained by using Eq. (8), Eq. (9) and Eq. (10) and Eq. (3). If Eq. (9), Eq. (10) and Eq. (3) are directly given into Eq. (8), the voltage equation will be quite complex including multidimensional differential. It is necessary to make appropriate simplification in the circuit. The voltage equation in transient-state is expressed as follows:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = \begin{bmatrix} R_s + \frac{\omega^2 L_d L_q}{R_c} + PL_d & -\omega L_q + P \frac{\omega L_d L_q}{R_c} \\ \omega L_d - P \frac{\omega L_d L_q}{R_c} & R_s + \frac{\omega^2 L_d L_q}{R_c} + PL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{\omega^2 L_q}{R_c} \\ \omega \end{bmatrix} \psi_a \quad (11)$$

MOTOR PARAMETERS CALCULATION

The parameters known of the surface mounted permanent magnet synchronous motor are listed in Table 1.

Table 1. Main Parameters of motor in the test

Rate Voltage	300VDC
Rate Current	45Arms
Rate Torque	100Nm
Rate Speed	480r/min
Poles	12
Moment of Inertia	0.201Kg

There are parameters to be measured as follows: the magnets flux linkage ψ_a ; the iron loss equivalent resistance R_c ; the copper loss equivalent resistance R_a ; the d- axis and q-axis equivalent inductance L_d L_q .

Caculation of Magnetic Flux Linkage

The permanent magnetic flux linkage is considered to be constant. If the stator currents in the model are zero, the voltage equation can be expressed as follows:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = \begin{bmatrix} \frac{\omega^2 L_q \psi_a}{R_c} \\ \omega \psi_a \end{bmatrix} \quad (11)$$

As a result the voltage is expressed as Eq. (12).

$$U = \sqrt{U_d^2 + U_q^2} = \omega \psi_a \sqrt{1 + \left(\frac{\omega L_q}{R_c}\right)^2} = \omega \psi_a k_{\psi_a} \quad (12)$$

Where k_{ψ_a} is expressed as Eq. (13).

$$k_{\psi_a} = \sqrt{1 + \left(\frac{\omega L_q}{R_c}\right)^2} \quad (13)$$

In the PMSM model without the motor iron loss, the Eq. (12) becomes Eq. (14).

$$U = \omega \psi_a \quad (14)$$

If ω is low enough, the value of k_{ψ_a} will become to 1 approximately. The permanent magnetic flux linkage is estimated using Eq. (15).

$$U = \omega \psi_a \Rightarrow \psi_a = \frac{U}{\omega} \quad (15)$$

This assumption need to be sure for the selected speed at last.

Caculation of Iron Loss Equivalent Resistance

According to the principle of electromagnetism, the iron loss equivalent resistance is expressed as follows:

$$R_c = R_{co} \frac{\frac{K_f}{K_h} + 1}{\frac{K_f}{K_h} + \frac{1}{\bar{\omega}}} \quad (16)$$

Where K_h and K_f are the coefficients of hysteresis and eddy losses, R_{co} is the value of R_c when motor operates at base speed and $\bar{\omega}$ is P.U. value.

In the steady-state model making $i_d = 0$, the torque can be estimated using Eq. (17).