The Efficiency Optimization of Permanent Magnet Synchronous Machine DTC for Electric Vehicles Applications Based on Loss Model

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Abstract. An efficiency optimization method of permanent magnet synchronous machine for electric vehicles applications is researched. Considering iron loss equivalent resistance and direct torque control scheme, the relationship of stator flux and power loss is derived based on loss model. And then the real-time optimal target flux can be obtained through the relationship of d-axis stator flux, target torque and electric speed at the minimum loss situation. A fitting curve of iron loss equivalent resistance versus speed is obtained by simulation. This makes the iron loss equivalent resistance closer to the actual value compared with the fixed value. Simulation results show that the motor efficiency has been improved compared with traditional direct torque control.

Introduction

Compared with conventional internal combustion engine vehicles, the electric vehicles are cleaner, more efficiency and lower noise. It is currently the most promising development direction of the automotive industry with better dynamic performance [1]. The permanent magnet synchronous motor (PMSM) with small size, light weight, compact structure, highly efficiency is suitable as electric vehicle drive motor. Variable Voltage and Variable Frequency (VVVF), Vector Control (VC), Direct Torque Control (DTC) are the three methods for permanent magnet synchronous motor control [2]. Direct Torque Control (DTC) has advantages of simple control structure, fast torque response and robustness. Although permanent magnet synchronous motors have higher efficiency compared with asynchronous motors, the loss of the motor is still exist.

Wang Jin [3] analyzed factors affecting motor’s losses and also concluded methods decreasing losses. Xu Jun-feng [4] and Xu Yan-ping [5] studied the relationship of current and loss of surface permanent magnet synchronous motor. Chen Xu [6] proposed LMC (loss minimum control) based on searching method. Kang Chang [7] presented a generalized relationship between d-q current for the LMC of PMSM. It showed that maximum torque per ampere and maximum torque per voltage can be derived as special case of LMC. The d-q current was treated as direct control value in this method. A. Dittrich [8] and Naomitsu Urasaki etc. [9] proposed a calculation method for iron loss resistance in the offline manner based on the linear feature between semi-input power and square of speed electromotive force.

The loss of motors includes iron loss, copper loss, stray loss and mechanical loss [10]. The mechanical loss can’t be controlled as it is not directly related to current, torque and flux values. Just iron loss and copper loss are described in this paper.

The loss model of PMSM

The d-q axis equivalent circuit of PMSM considering iron loss and copper loss is shown in Figure 1. For control purpose, the iron loss is modelled as a resistance, known as iron loss resistance which is in parallel in the circuit. The d-q axis current is divided into iron loss current and excitation current.

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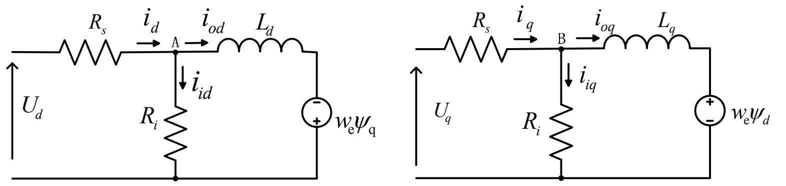


(a) The equivalent circuit of d-axis (b) the equivalent circuit of q-axis

Figure 1 the equivalent circuit

The d-q axis flux and the electromagnetic torque are calculated as the formula (1), (2), (3) shown.

$$\psi_d = L_d i_{od} + \psi_f \tag{1}$$

$$\psi_q = L_q i_{oq} \tag{2}$$

$$T_e = 1.5 n_p \left(\psi_f i_{oq} + \left(L_d - L_q\right) i_{od} i_{oq}\right) \tag{3}$$

where ψ_d is the d axis flux, ψ_q is q axis flux, L_d is the d axis inductance, L_q is the q axis inductance, ψ_f is the rotor flux, i_{od} is the d axis excitation current, i_{oq} is the q axis excitation current, n_p is the pole pairs, T_e is the electromagnetic torque.

According to the formula (1), (2), the excitation currents can be calculated as the formula (4), (5) shown.

$$i_{od} = \frac{\psi_d - \psi_f}{L_d} \tag{4}$$

$$i_{oq} = \frac{\psi_q}{L_q} \tag{5}$$

The i_d, i_q can be calculated as formula (6), (7) shown by applying the Kirchhoff's first law for node A, B in Figure 1.

$$i_d = i_{od} + i_{id} \tag{6}$$

$$i_q = i_{oq} + i_{iq} \tag{7}$$

Where i_d is the d axis current, i_q is the q axis current, i_{id} is the d axis iron loss current, i_{iq} is the q axis iron loss current.

The formula (8), (9) can be obtained by applying the Kirchhoff's second law to the right side loop in the Figure 1.

$$pL_d i_{od} - \omega_e L_q i_{oq} - R_i i_{id} = 0 \tag{8}$$

$$pL_q i_{oq} + \omega_e \left(L_d i_{od} + \psi_f\right) - R_i i_{iq} = 0 \tag{9}$$

Where p is the differential operator, ω_e is the electric speed, R_i is the iron loss resistance.

In the steady state, p = 0. The steady-state iron loss current expression is shown as formula (10), (11).

$$i_{id} = \frac{-\omega_e L_q i_{oq}}{R_i} \tag{10}$$

$$i_{iq} = \frac{\omega_e \left(L_d i_{od} - \psi_f\right)}{R_i} \tag{11}$$

The iron loss P_{iron} and copper loss P_{cu} are computed shown as formula (12), (13).

$$P_{iron} = 1.5 R_i \left(i_{id}^2 + i_{iq}^2\right) = \frac{1.5\omega_e^2 \left(L_q i_{oq}\right)^2}{R_i} + \frac{1.5\omega_e^2 \left(\psi_f + L_d i_{od}\right)^2}{R_i} \tag{12}$$

$$P_{cu} = 1.5 R_s \left(i_d^2 + i_q^2\right) = 1.5 R_s \left(\left(i_{od} - \frac{\omega_e L_q i_{oq}}{R_i}\right)^2 + \left(i_{oq} + \frac{\omega_e \left(L_d i_{od} + \psi_f\right)}{R_i}\right)^2\right) \tag{13}$$

The final power losses including both copper loss and iron losses can be represented as formula (14).

$$P_{loss} = P_{iron} + P_{cu} \tag{14}$$

According to the formula (4), (5), (12), (13), (14), formula (15) can be obtained.

$$P_{loss} = a\psi_d^2 + b\psi_q^2 + c\psi_d\psi_q + d\psi_d + e\psi_q + f \tag{15}$$

Where $a = \frac{R_s}{L_d^2} + \frac{\omega_e^2}{R_i} + \frac{R_s\omega_e^2}{R_i^2}, b = \frac{R_s}{L_q^2} + \frac{\omega_e^2}{R_i} + \frac{R_s\omega_e^2}{R_i^2}, \mathrm{c} = -\frac{2R_s\omega_e}{L_d R_i} + \frac{2R_s\omega_e}{L_q R_i}, d = -\frac{2R_s\psi_f}{L_d^2}, e = \frac{2R_s\psi_f\omega_e}{L_d R_i}, f = \frac{R_s\psi_f^2}{L_d^2}.$ Substituting formula (4), (5) into (3), the relationship of T_e and ψ_q is obtained as formula (16).

$$\psi_q = \frac{2T_e L_d L_q}{3n_p\left(L_d\psi_f + \left(\psi_d - \psi_f\right)\left(L_d - L_q\right)\right)} \tag{16}$$

The relationship of P_{loss} and Ψ_d including unknown quantity Ψ_d, T_e, ω_e can be obtained by substituting formula (16) into formula (15). In the steady state, T_e, ω_e are constant values. So, the power loss P_{loss} is only related to Ψ_d. The flux corresponding to the minimum loss of this torque value can be obtained by derivation the power losses P_{loss} with respect to Ψ_d as shown in formula 17.

$$\frac{\partial P_{loss}}{\partial \psi_d} = 0 \tag{17}$$

Formula (17) can be rewritten as formula (18).

$$a_4\psi_d^4 + a_3\psi_d^3 + a_2\psi_d^2 + a_1\psi_d + a_0 = 0 \tag{18}$$

Also the factor expressions are as: $a_4 = 2au^3, a_3 = 6au^2z + du^3,$ $a_2 = 6auz^2 + 3du^2z, a_1 = 2az^3 + ckuz + 3dz^2u - eku^2, a_0 = ckz^2 + dz^3 - 2bk^2u - uekz,$ $k = 2T_eL_dL_q, u = 3n_p(\mathrm{L}_d - \mathrm{L}_q), \mathrm{z} = 3n_pL_q\psi_f.$

According to the formula (18), the optimal d axis flux value can be obtained. The target q axis flux value can be obtained by substituting the target d axis flux value into equation (16). The stator target flux value corresponding to the minimum loss can be obtained shown as the equation (19).

$$\psi^* = \sqrt{\left(\psi_d^2 + \psi_q^2\right)} \tag{19}$$

The estimate of equivalent iron loss resistance

Loss resistance in minimum loss iron model is a changing value. There are different ways to estimate the resistance off-line. This paper estimates the iron loss resistance by finite element analysis. Motor finite element model is shown in Figure 2. Dimensions of the model are listed in Table 1.

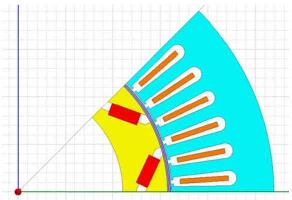


Figure 2 Motor finite element model

Table 1 Dimensions of the motor

name	value
DiaGap of Stator	161.9(mm)
DiaYoke of Stator	269.24(mm)
DiaGap of Rotor	160.4(mm)
DiaYoke of Rotor	110.64(mm)
Slots	48

The input power can be expressed as formula (20).

$$P_{in} = U_d i_d + U_q i_q = R_s\left(i_d^2 + i_q^2\right) + \frac{\omega_e^2\left(\psi_d^2 + \psi_q^2\right)}{R_i} + \omega_e\left(\psi_d i_{oq} - \psi_q i_{od}\right) \tag{20}$$

Where the first term is the copper loss, the second term is the iron loss, and the third term is the output power. The Electromotive Force (EMF) is proportional to the square of the iron loss and the ratio is the inverse of the iron loss equivalent resistance. The simulation parameters of the motor are listed in Table 2.

Table 2 The motor parameters used in the simulation

Stator resistance(Ω)	0.069
d axis inductance (H)	0.002
q axis inductance (H)	0.006
Rotor flux(Vs)	0.158
Pole pairs	4

By changing the d-axis current at the speed of 837.758rad/s, a set of iron loss is recorded shown in Table 3. Changing the d-axis current only affects the d-axis flux. The fitting curve shown in Figure 3 is acquired by using a linear fitting algorithm. The slope of the curve is the equivalent iron loss resistance at this speed.

Table 3 A set of iron loss at the electric speed of 837.758 rad/s

$\omega_e^2\psi_s^2$ (V2)	Piron (w)
22237.05	61.1584
27514.88	74.5987
33354.1	90.9784
39754.94	104.1844
46717.18	121.8611
54240.89	139.7776
62326.07	157.0671
70972.72	174.5733
80180.84	191.8711

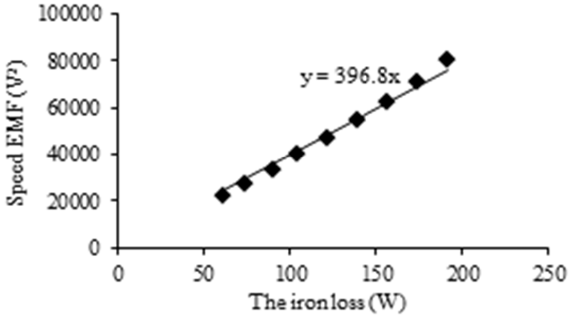


Figure 3 The fitting curve of iron power loss and EMF at 837.758 rad/s

In the same manner, the iron loss resistance at other speeds can be obtained shown in Table 4. It can be seen that the iron loss resistance increases with speed increasing.

Table 4 The iron loss resistance at different speed

Speed [rad/s]	Iron loss resistance[Ω]
418.879	235.1
628.3185	320.7
837.758	396.8
1047.198	456.4907
1256.637	512.5

The fitting curve is shown in Figure 4. The regression coefficient of the fitting curve is 0.991 which means that the formula well describes the trend of iron loss resistance. The iron loss resistance satisfies the formula (21).

$$R_i = 0.329\omega_e + 108 \tag{21}$$

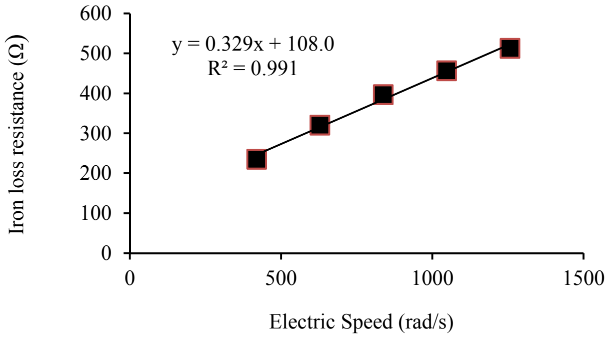
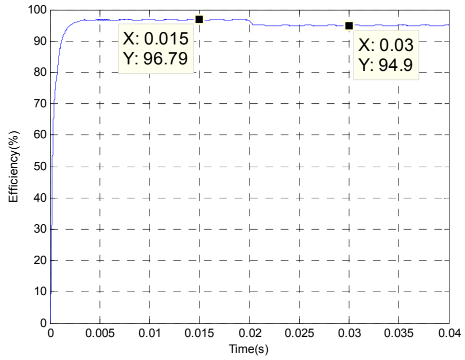


Figure 4 The curve of iron loss resistance and speed

Analysis of Simulation Results

The simulation is conducted at the electrical speed of 837.758 rad/s. According to the formula (21), the iron loss equivalent resistance is 383.6 Ω at this speed. The target torque steps from 30NM to 50NM at 0.02s. The loss minimization direct torque control and traditional direct torque control are simulated in the same situation respectively. The simulation results are shown in Figure 5, 6.



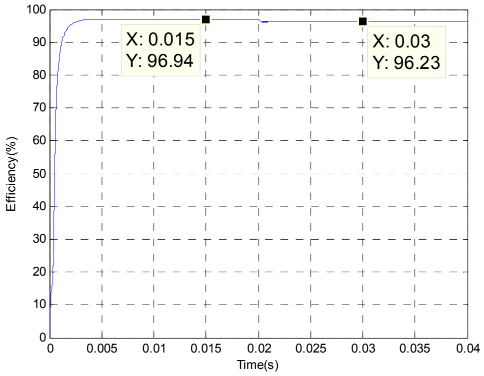


Figure 5 Efficiency of traditional direct torque control

Figure 6 Efficiency of loss minimum direct torque control

Using traditional DTC method, the motor efficiency is 96.79% when the target torque is 30NM and the efficiency is 94.9% when the target torque is 50NM. Using the method of loss minimization DTC, the motor efficiency is 96.94% when the target torque is 30NM and the efficiency is 96.23% when the target torque is 50NM. It can be seen that the motor efficiency improves 0.15% when the target torque is 30NM and the efficiency improves 1.33% when the target torque is 50NM compared with the traditional DTC.

Conclusions

This paper proposes a loss minimum control method through adjusting the flux reference dynamically based on loss model. The relationship between equivalent iron loss resistance and speed is acquired by finite element simulation under different conditions. The iron loss resistance increases linearly with speed increasing. Using the proposed LMC method, motor efficiency is improved compared with traditional direct torque control.

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