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Design and Implementation of a Loss Optimization Control for Electric Vehicle In-Wheel Permanent-Magnet Synchronous Motor Direct Drive System

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Abstract

As a main driving force of electric vehicles (EVs), the loss of in-wheel permanent-magnet synchronous motor (PMSM) direct drive system can seriously affect the energy consumption of EVs. This paper proposes a loss optimization control strategy for EV in-wheel PMSM direct drive system which can optimize both the loss of PMSM and loss of inverter. The proposed method adjusts the copper loss and iron loss by optimal flux-weakening current, and as a result the PMSM achieve the lower loss in the whole operation range. According to the speed, the PWM frequency is optimized by the proposed control strategy, which can acquire high efficiency of inverter and not affect the stability of the PMSM system in the each operation condition. The optimum flux-weakening current and PWM frequency can be quickly found, and optimal effects of energy loss are verified by theoretical analysis and experimental results.

Keywords: Efficiency; loss control; direct drive; double Fourier integral analysis; PMSM system.

1. Introduction

With the worldwide shortage of energy, the improvement of energy efficiency and development of new energy have become a social problem. With the advantage of high energy efficiency and low emissions, the electric vehicles (EVs) are considered alternative to the traditional internal combustion engine vehicles. Compared with traditional permanent-magnet synchronous motor (PMSM) system with automated mechanical transmission (AMT) [1], the in-wheel PMSM direct drive system has the advantages of high dynamic performance and low transmission loss which is more suitable for EVs, as

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shown in Fig.1. There are several vector control strategies for PMSM in rated speed, such as i_d=0 control [2], unit power factor control [3], maximum torque per ampere (MTPA) control [4] and etc. However, all these current vector control strategies only focus either the copper loss or iron loss of PMSM and ignore the inverter loss of PMSM direct drive system.

This paper proposes a novel loss optimization control strategy for PMSM direct drive system which can achieve a higher efficiency compared with traditional vector control in the whole operation range. Based on the loss model of PMSM, the loss optimization control can synthetically optimize the copper loss an iron loss together. The PWM frequency is carefully adjusted to the direct drive system by the proposed control method which can decrease the loss of inverter and make the harmonic current small enough. The loss optimization control strategy can reduce the energy consumption and not affect the stability of the PMSM direct drive system for EVs. The proposed loss optimization control strategy is analyzed in both theory and experiment.

2. Loss Optimization Control Strategy

2.1. Loss Optimization of PMSM

The equivalent circuits of PMSM in the d-q coordinate which rotate synchronously with an electrical angular velocity ω_e are shown in Fig.2. The copper loss and iron loss can be calculated by the armature resistance R_s and the iron loss resistance R_c respectively.

From Fig.2, the voltage equations of PMSM in the steady state are expressed as

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & -n_p\omega_r L_{mq} \\ n_p\omega_r L_{md} & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ n_p\omega_r\psi_f \end{bmatrix} \tag{1}$$

where U_d and U_q are the terminal voltage in d-axis and q-axis. $L_{1d,q}$ and $L_{md,q}$ are the armature leakage-inductance and self-inductance, respectively. i_d and i_q are the armature current, i_{cd} and i_{cq} are the exciting current in d-axis and q-axis respectively. n_p is the number of pole-pairs.

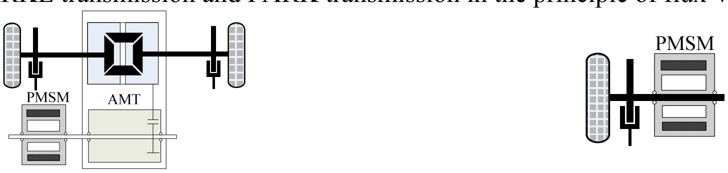
And the current equation of PMSM in the steady state can be also described as

$$\begin{cases} i_{od} = i_d - i_{cd}, i_{oq} = i_q - i_{cq} \\ i_{cd} = u_{od}/R_c = -n_p\omega_r L_q i_{oq}/R_c, i_{cq} = u_{oq}/R_c = n_p\omega_r\left(\psi_f + L_d i_{od}\right)/R_c \end{cases} \tag{2}$$

From equation (1) and equation (2), the copper loss of PMSM in the steady state can be calculated as

$$P_{Cu} = 1.5R_s(i_d^2 + i_q^2) = 1.5R_s\left\{\left(i_{od} - n_p\omega_r L_q i_{oq}/R_c\right)^2 + \left[i_{oq} + n_p\omega_r\left(\psi_f + L_d i_{od}\right)/R_c\right]^2\right\} \tag{3}$$

where transformation coefficient 1.5 is caused by that the current in d-axis and q-axis is calculated by the CLARKE transmission and PARK transmission in the principle of flux-value-constant.



(a) (b)

Fig.1. PMSM drive system in EVs; PMSM with AMT; (b) PMSM direct drive system