Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 2267 – 2272

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Maximum Efficiency Control of Permanent-Magnet Synchronous Machines for Electric Vehicles

Qingbo Guo[a], ChengMing Zhang[a]*, Liyi Li[a], Jiangpeng Zhang[a], Mingyi Wang[a]

[a]*Department of Electrical Engineering Harbin Institute of Technology, No. 2 of Yikuang Street, Harbin, 150001. China*

Abstract

Electric vehicles (EVs) are considered as a new generation of transport to solve the energy crisis. The efficiency of permanent-magnet synchronous machine (PMSM) is an important performance for the energy loss of EVs. Considering the harmonic current caused by the PWM output voltage of inverter, this paper proposes a novel global loss model of PMSM, which can calculate both fundamental loss and harmonic loss. This model precisely estimates the harmonic loss of PMSM by double Fourier integral analysis. Based on the proposed loss model, a maximum efficiency control strategy is presented which can achieve the minimum energy loss in the whole operation range of EVs. The optimum flux-weakening current can be quickly found by the maximum efficiency control, and optimization of energy loss in PMSM direct drive system is verified by theoretical analysis and experimental results.

Keywords: Efficiency; maximum efficiency control; fundemental loss; double Fourier integral analysis; harmonic loss; PMSM.

1. Introduction

By necessity of energy diversification, more and more international attention is given to the development of an alternative vehicle to the gasoline-powered car, and the electric vehicles (EVs) have been regarded as the best solution. The important advantages of EVs are the negative aspects of internal combustion engines such as pollution, noise, and smell. The permanent-magnet synchronous machine (PMSM) with potential high efficiency, high power factor, and high power density is one of the best choices for the EV system.

For enjoying the high efficiency performance, the electromagnetic structure of PMSM has received more attention. However, the motor control strategy can also affect the efficiency of the PMSMs droved

---

* Corresponding author. Tel.: +0-086-0451-86403771; fax: +0-086-0451-86403771.
E-mail address: cmzhang@hit.edu.cn.

doi:10.1016/j.egypro.2017.03.650

by power inverters. Hence the loss optimization control algorithm is crucial to achieve the best efficiency of EV propulsion system. Many common vector control strategies have been known for PMSM operation in rated speed, such as i_d=0 control [1], unit power factor (UPF) control [2], maximum torque per ampere (MTPA) control [3], minimum speed per voltage control (MSPV) and etc. Although the UPF control can make the active power equated with the apparent power, the efficiency of PMSM may not achieve the maximum value. The i_d=0 control, MTPA and MSPV can not acquire maximum efficiency as they only pay attention on the optimization of the fundamental loss and elide the harmonic loss.

This paper proposes a global loss model for PMSM in EV which can calculate both the fundamental loss and the harmonic loss. The fundamental loss model is built by the fundamental current in d-axis and q-axis. This research analyses the harmonic component of the PWM output voltage in space vector pulse width modulation (SVPWM) by double Fourier integral analysis, and creates the harmonic loss model for PMSM in the EV. Based on the global loss model, a maximum efficiency control strategy is proposed in this paper, which can acquire the maximum efficiency performance of PMSM in the whole range of operation conditions by optimization both on the fundamental loss and harmonic loss. The loss reduction effect is tested by theoretical analysis and experimental researches.

2. Maximum Efficiency Control Strategy

2.1. Fundamental Loss Model of PMSM

The fundamental loss of PMSM in the EV can be divided into two parts, fundamental copper loss and iron loss. The fundamental copper loss can be calculated by d-axis current and q-axis current as

$$P_{Cu\_f} = 1.5R_s\left(i_d^2 + i_q^2\right) \tag{1}$$

where R_s is the stator's winding resistance, i_d is fundamental current in d-axis and i_q is current in q-axis.

Based on the Bertotti iron loss formula [4], the fundamental iron loss caused by d-axis and q-axis flux linkages in the tooth and the yoke can be obtained as

$$\begin{aligned} P_{Fe\_f} &= dP_{Fetd,q}V_t + dP_{Fejd,q}V_j = 1.5k_{hd}\left[\psi_d^2 + \psi_q^2\right] + 1.5k_{ep}\left[\psi_d^{1.5} + \psi_q^{1.5}\right] \\ &= 1.5k_{hd}\left[\left(L_d i_d + \psi_f\right)^2 + \left(L_q i_q\right)^2\right] + 1.5k_{ep}\left[\left(L_d i_d + \psi_f\right)^{1.5} + \left(L_q i_q\right)^{1.5}\right] \end{aligned} \tag{2}$$

where k_{hd} is the coefficient of equivalent iron hysteresis and eddy losses, and k_{ep} is the coefficient of equivalent iron excess loss, i.e.

$$k_{hd} = \left(k_h f_0 + \frac{\pi^2 \sigma k_d^2}{6} f_0^2\right)\left(\frac{V_t}{S_{tc}^2} + \frac{V_j}{S_{jc}^2}\right), k_{ep} = k_e B_m^{1.5} f_0^{1.5}\left(\frac{V_t}{S_{tc}^{1.5}} + \frac{V_j}{S_{jc}^{1.5}}\right) \tag{3}$$

where $V_{t,j}$ are the total volumes of stator tooth and yoke, S_{tc} and S_{jc} are the equivalent areas of stator tooth and stator yoke for flux density calculation, respectively, ψ_f is the permanent-magnet flux linkage. k_h and k_e are the coefficients of hysteresis loss and excess loss, respectively. σ is the conductivity of the material, and k_d is the thickness of the lamination. These four parameters can be referred to the data sheet from steel manufacturer. f is the fundamental current frequency.

2.2. Harmonic Loss Model of PMSM