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Design and implementation of a loss optimization control for electric vehicle in-wheel permanent-magnet synchronous motor direct drive system ☆

Qingbo Guo [a], Chengming Zhang [a,*], Liyi Li [a], David Gerada [b], Jiangpeng Zhang [a], Mingyi Wang [a]

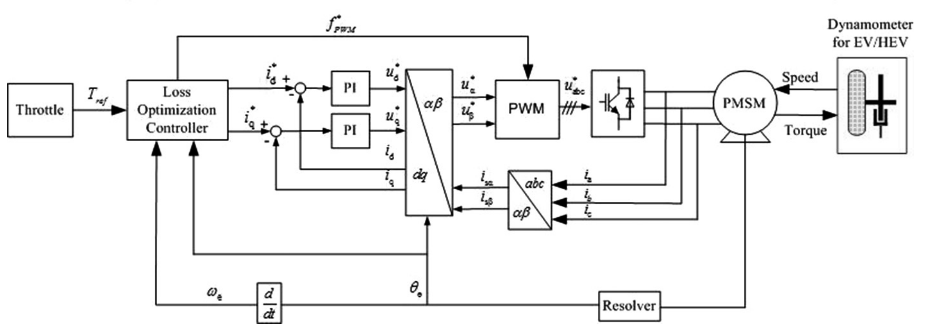
[a] Department of Electrical Engineering, Harbin Institute of Technology, No. 2 of Yikuang Street, Harbin 150001, China
[b] School of Electrical and Electronic Engineering, The University of Nottingham, Nottingham NG7 2RD, United Kingdom

HIGHLIGHTS

- The nonlinear characteristics of the power device are modeled.
- The harmonics of PWM inverter output voltage are analytically solved.
- The proposed control strategy can optimize the motor losses and inverter losses.
- The system efficiency is increased by 4.6% in a SPMSM system with SiC-MOSFETs.
- The proposed control strategy has been validated by the experimental tests.

GRAPHICAL ABSTRACT

Efficiency optimization on both motor loss and inverter loss in the PMSM direct dirve system



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ABSTRACT

As a main driving force of electric vehicles (EVs), the losses 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 in-wheel PMSM direct drive system of EVs which optimizes the losses of both the PMSM and the inverter. The proposed method adjusts the copper losses and iron losses by identifying the optimal flux-weakening current, which results in the PMSM achieving the lower losses in the whole operational range. Moreover there are strongly nonlinear characteristics for the power devices, this paper creates a nonlinear loss model for three-phase half-bridge inverters to obtain accurate inverter losses under space vector pulse width modulation (SVPWM). Based on the inverter loss model and double Fourier integral analysis theory, the PWM frequency is optimized by the control strategy in order to maximize the inverter efficiency without affecting the operational stability of the drive. The proposed loss optimization control strategy can quickly find the optimum flux-weakening current and PWM frequency, and as a result, significantly broaden the high efficiency area of the PMSM direct drive system. The effects of the aforementioned strategy are verified by both theoretical analysis and experimental results.

1. Introduction

With the worldwide shortage of energy and increasingly stringent emission requirements, the improvement of energy efficiency

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* Corresponding author.
E-mail address: zhangchengming1024@163.com (C. Zhang).

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and development of new clean energy have become of increasing importance to society. With the advantage of high energy efficiency and low emissions, electric vehicles (EVs) [1,2] and hybrid electric vehicle (HEVs) [3,4] are considered an attractive proposition to the traditional internal combustion engine vehicles. HEVs are more commonly used for long distance or heavy load transportation, while EVs have a stronger application case for transportation within cities. As EVs are a battery-powered, limited energy system, the consumption characteristics of the energy management system are of fundamental importance and an order of magnitude higher in terms of priority compared to HEVs. As regards the system layout, compared to traditional motor drive system with automated mechanical transmission (AMT) [5], the in-wheel motor direct drive system has the advantages of high dynamic performance and low transmission loss which is more suitable for EVs, as shown in Fig. 1.

To improve the endurance mileage of EVs in one charge, it is important to minimize the energy consumption. As the main power output mechanism of EVs, any efficiency gains on the traction drive directly translate to a markedly improved endurance mileage [6]. There are several types of electric motor used within the power system of EVs, such as the direct-current (DC) motor, induction motor (IM), permanent magnet synchronous motor (PMSM) and switched reluctance motor (SRM). The PMSM due to high efficiency, high power factor, and high power density is often the machine of choice. The operational efficiency of the PMSM drive depends on the motor's electromagnetic design and the applied control strategy [7–9]. The electromagnetic design optimization consists of tailoring the constituent geometries, materials and losses with the aim of improving the efficiency at rated operation [10–13]. On the other hand, control strategies take consideration on efficiency within the overall operational range of the drive [14–16]. There are many vector control strategies for PMSM power system of EVs, such as the $i_d = 0$ control, unity power factor (UPF) control, maximum torque per ampere (MTPA) control, maximum speed per voltage (MSPV) control and loss model control (LMC). The $i_d = 0$ control maintains the electromagnetic torque and q-axis current in proportional relationship within the linear machine operation mode by keeping the d-axis current to zero [17,18]. The $i_d = 0$ control is widely used in surface-mounted PMSMs (SPMSMs) due to the lack of saliency. However, $i_d = 0$ control cannot maximize the electromagnetic torque in interior PMSMs (IPMSMs), and therefore, MTPA control is presented to make the most use of the inherent saliency and thus available reluctance torque [19,20]. The MTPA control strategy achieves the minimum copper loss since the least armature current is used to obtain the desired torque output. However, it only optimizes for reducing the copper losses and will thus not maximize the efficiency of the PMSM which is constituted of various other loss terms [21–23]. Similarly, the MSPV control which minimizes the winding terminal voltage

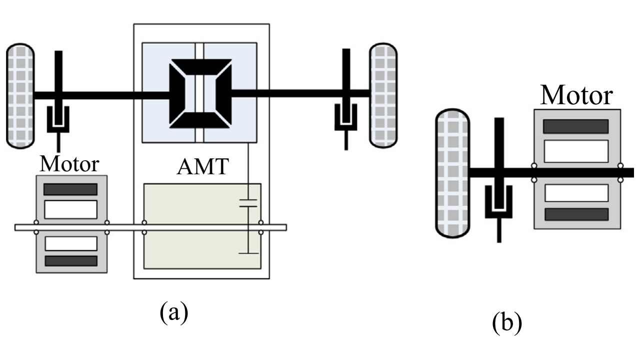

Fig. 1. PMSM drive system in EVs; (a) PMSM with AMT; (b) PMSM direct drive system.

and decreases the iron losses also misses on achieving the maximum machine efficiency. The UPF control decreases the reactive power to zero and thus reduces the energy loss between power transmissions [24,25], however in doing so, it does not focus on the loss of PMSM and can be thus comparatively inefficient on the machine side [26–30]. The motor losses of a PMSM can be divided into four parts: mechanical losses, copper losses, iron losses and stray losses. The copper losses and iron losses are so-called controllable losses which can be influenced directly by the control strategies. The MTPA control and MSPV control only focus on part of the controllable loses while the LMC takes into consideration both the copper losses and iron losses, and can thus optimize for maximizing the efficiency over the whole operational range of the PMSM [31,32].

The literature on LMC focuses attention on the motor loss reduction, however, the inverter losses also play an important part in the overall energy consumption characteristics of EVs. Current research on reduction inverter loss focuses on the modulation mode of the three-phase inverter [33–35], and ignores the coupling relations between the power converters loss and motor loss which affect the stability of PMSM system. Other research simply applies SiC power devices to improve the inverter efficiency. Although SiC power devices with low switching losses decrease the inverter loss and increase the inverter efficiency of the PMSM system, the resulting low efficiency when the vehicle slows down can be an issue in EV applications [36–38]. From the foregoing discussion clearly in optimizing the EV PMSM drive system, it is required to take into account the constituent controllable losses of both the machine and the inverter, while carefully considering the stability and dynamic performance requirements.

This paper systematically analyzes the losses of a PMSM drive system in EVs and proposes a novel loss optimization control strategy for PMSM direct drive system which achieves a higher efficiency compared to traditional vector control over the whole vehicle operational range. Based on the loss model of the PMSM, the loss optimization control can optimize the copper losses and iron losses together. In order to characterize the inverter losses accurately, this paper creates a nonlinear loss model of a three-phase half-bridge inverter in the space vector pulse width modulation (SVPWM). This research analyses the harmonic component of pulse width modulation (PWM) output voltage in SVPWM by double Fourier integral analysis, and creates the harmonic model of the PMSM in EVs. Based on the system loss model, the PWM frequency is carefully adjusted to the direct drive system by the proposed control method, which decreases the loss of inverter while ensuring small current harmonic content. The loss optimization control strategy can reduce the energy consumption without affecting the stability of the PMSM direct drive system for EVs and is validated both theoretically and experimentally.

The remainder of this paper is organized as follows. In Section 2, the model for describing the PMSM direct drive system which considers both the PMSM losses and inverter losses is analysed. In Section 3, based on the model of PMSM direct drive system, the loss optimization control strategy is developed. In Section 4, the experimental setup is illustrated and the proposed control strategy is validated by experimental results. Conclusions are then drawn in the final section.

2. Model of PMSM direct drive system

The typical topology of PMSM drive system is shown in Fig. 2. In order to increase the efficiency of PMSM drive system, a quantitative power loss analysis is necessary for EVs. Therefore, this paper presents a novel loss model of PMSM which considers both the motor and inverter losses. Moreover it creates a nonlinear loss