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# A new strategy of efficiency enhancement for traction systems in electric vehicles

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## HIGHLIGHTS

- A novel efficiency enhancement strategy for traction system was proposed.
- The proposed method supplies a fast search of the optimal variable (direct-axis current $i_d$).
- The maximum increment of the efficiency for the overall inverter-motor system was 2.7%.
- The saving of battery consumption is more than 9% due to the proposed strategy.
- The proposed method has been validated by the experimental test.

## ARTICLE INFO

*Keywords:*
Electric vehicles (EVs)
Overall efficiency
Inverter-motor
Loss model
Golden section search

## ABSTRACT

The inverter-motor drive system is the main traction force in electric vehicles (EVs). The overall efficiency of inverter-motor will directly determine the energy consumption of EVs. In this paper, aiming at improving the overall efficiency of inverter-motor, a novel methodology is proposed. Firstly, the iron loss, copper loss and stray loss of motor, as well as the devices' conduction loss and switching loss in inverter are modeled. Afterwards, based on previous loss model strategy and gold section search strategy, a novel hybrid efficiency-optimization control strategy is proposed. The proposed method combines each benefit in loss-model and gold section search, and can realize high efficiency operation of the inverter-motor system in large power range. Additionally, the proposed method manifests faster search speed and better accuracy compared to conventional methods. Experiment results validated the effectiveness of the proposed hybrid control strategy. Meanwhile, the impact of the efficiency improvement on the driving cycle is further investigated through Advanced Vehicle Simulator (ADVISOR) simulations.

## 1. Introduction

Due to the depletion of fossil fuels and the severe environmental pollution, electric vehicles (EVs) are considered one of the alternatives to traditional internal combustion engine vehicles [1–3]. Compared with other motors, permanent magnet synchronous motors (PMSM) have advantages of smaller size, higher efficiency, higher output torque, etc. Hence, PMSM combined with inverter is preferred as traction system usually in the EVs [4]. With batteries as power sources, its energy is limited. Therefore, the efficiency of traction system is of vital importance [5–9]. As mentioned in [10], the fuel economy can be improved by 5% if the conventional traction systems were replaced with the higher efficiency one. Similar improvements are discussed in another study [11]: the fuel economies of HEV and PHEV are improved by 14.7% and 18.1% respectively.

Motors are also widely adopted in the other industrial applications, such as ventilation, machine tool, air conditioning systems, etc. Around $3–5 billion could be saved by adopting more efficient motor systems in the US [12]. Recently motor efficiencies have been improved greatly by novel materials, optimal designs and loss minimization controls, etc.

Previously, different methods are proposed to improve the efficiency of motors [13–20]. In the motor design stage, optimal design and novel materials have been adopted to high efficiency electric machines [13]. After the motor is designed, manufactured and implemented in the drive system, the system's efficiency can be further enhanced through loss minimization algorithms (LMAs) [14–20]. The LMAs are

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**Nomenclature**

| | |
|---|---|
| $v_d(v_q)$ | $d(q)$-axis voltage |
| $i_d(i_q)$ | $d(q)$-axis current |
| $\psi_d(\psi_q)$ | $d(q)$-axis flux linkage |
| $\omega$ | electrical angular velocity |
| $\psi_m$ | permanent magnet flux linkage |
| $L_d(L_q)$ | $d(q)$-axis inductance |
| $P$ | the number of pole pairs of the motor |
| $R$ | the phase resistance |
| $\mu$ | lagrange coefficient |
| $I_n$ | the root-mean-square (RMS) of phase current |
| $c_{fe}$ | the coefficient of iron loss |
| $c_{str}$ | the coefficient of stray loss |
| $V_r$ | the reference voltage |
| $I_r$ | the reference current |
| $E_{on,I}$ | turn-on energy losses of the IGBT |
| $E_{off,I}$ | turn-off energy losses of the IGBT |
| $E_{off,D}$ | turn-off energy losses of the diode |
| $P_{1s}$ | the expression of the switching loss |
| $a$ | modulation index |
| $\varphi$ | power factor angle |
| $v$ | fixed on-state voltage drops for IGBT and diode |
| $r$ | fixed on-state resistances for IGBT and diode |
| $T_e$ | the electromagnetic torque |
| $T_0$ | the load torque of the motor |

used to search the operating point, namely direct-axis current $i_d$ and quadrature-axis current $i_q$, when the total losses of PMSM are minimum while producing a specified torque at a given speed.

The LMAs can be summarized into two main categories: the "loss-model control (LMC)" techniques and the "search control" algorithms. The "loss-model control" technique is based on the loss model of PMSM, and the losses are calculated during operation. Uddin et al. [14] developed a loss model-based LMA to search the optimal operation point. Morimoto et al. [15] also proposed a loss-model control methodology. An approximation equation and a look-up table were used to save the computation time. Mannan et al. [16] proposed a loss-model control LMA through constructing a Lagrange function. The optimal value of $i_d$ was achieved by differentiating the Lagrange function with respect to $i_d$. As can be seen, an accuracy loss model is important in "loss-model control". However, an accurate identification of the parameters in the model remains a challenge as these parameters are dependent on the amplitude of the current, temperature, etc.

The "search control" algorithm, on the contrary, is independent on loss models. This method changes the value of the control variable $i_d$ step by step. The input power of the motor for each step is measured, and the minimum loss of the motor is searched by comparing the measurement result with the previous one at a given speed and output torque. Vaez et al. [17] proposed an online search control strategy to achieve the minimum input power. Kirschen et al. [18] also proposed an online efficiency optimization based on search-control algorithms. It was manifested that the losses of the motor can be changed by adjusting the flux reference step by step. Colby et al. [19] proposed another search-control algorithm in which voltage was selected as the control variable. Kim et al. [20] developed an online search-control algorithm based on Fibonacci search method. The square value of rotor flux was defined as the control variable. Though the "search control" algorithm has the advantage of independence of motor loss model, it will induce torque ripples and decrease the response time.

As a summary of the state of the art LMAs, most works only focus on the losses of the motor, few has taken the inverter's losses into consideration. Additional, some other's works solely consider the efficiency of the inverter. One method is adopting the wide-band gap power devices, such as silicon carbide (SiC), gallium nitride (GaN), gallium arsenide (GaAs), etc. [5,21–24]. The other one is proposing some new pulse width modulations (PWM) [25–31]. The continuous space vector PWM (SVPWM) and discontinuous PWM (DPWM) are two major modulations for a three-phase voltage source inverter (VSI) [25–27]. Most of VSIs adopt the constant switching frequency (CSF), which is easy to be implemented. In order to improve the efficiency and electromagnetic capability (EMC) of VSIs, different strategies of variable switching frequency PWM (VSFPWM) have been proposed [28–30].

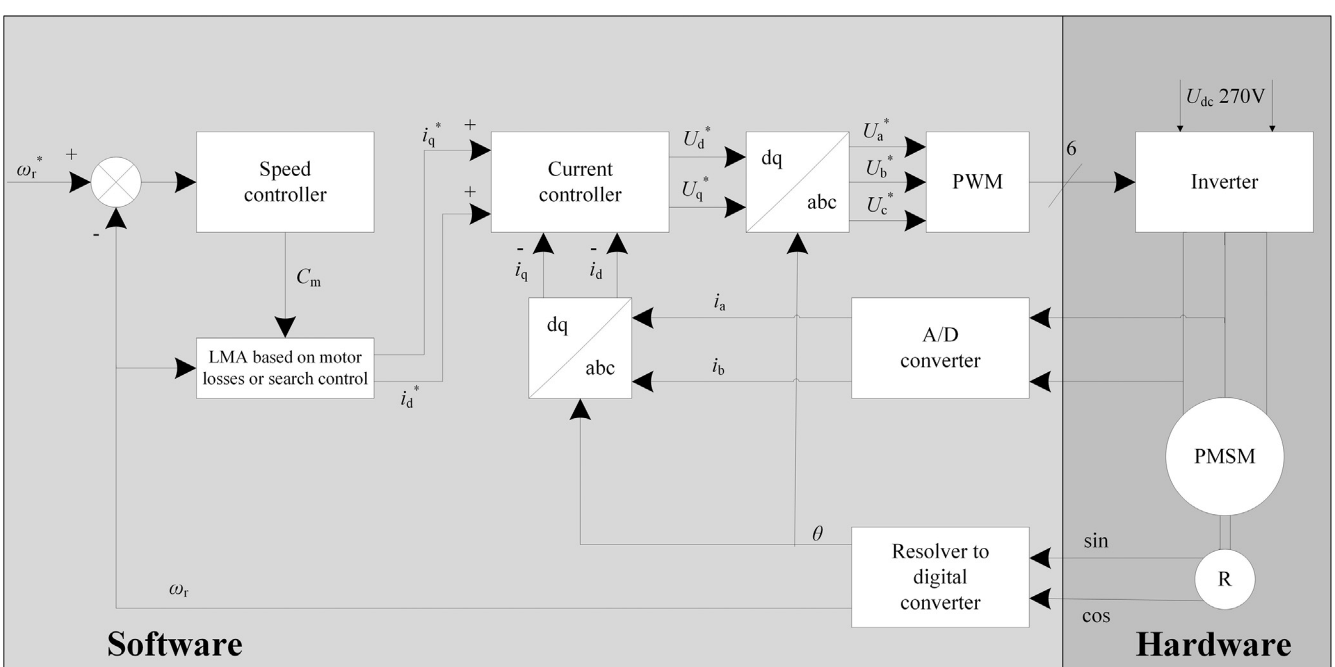


**Fig. 1.** Simplified schematic of the IPMSM drive with the conventional efficiency improvement method.