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# Comprehensive comparison between silicon carbide MOSFETs and silicon IGBTs based traction systems for electric vehicles ☆

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## HIGHLIGHTS

- A novel model for describing the loss considering thermal of SiC-MOSFETs was proposed.
- The power density of the inverter has been greatly increased by adopting SiC.
- The inverter efficiency has been increased to more than 99% from around 96%.
- The efficiency of SiC based inverter-motor traction system has been increased.
- The proposed novel method has been validated by the experimental test.

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## ABSTRACT

In this paper, the performance of both silicon carbide (SiC) MOSFETs and silicon (Si) IGBTs based electric vehicle (EV) traction systems are investigated and compared comprehensively, particularly from the efficiency point of view. Both conduction loss and switching loss of SiC-MOSFETs are analyzed and modeled taking temperature effect into account. Such approach yields a more accurate prediction of SiC losses. The temperature distribution of SiC-Inverter is described by ANSYS finite element analysis (FEA), and compared with Si counterparts. According to the lower losses and higher thermal conductivity, SiC exhibits much lower temperature than Si under the same power rating and cooling condition. Subsequently, this paper goes further by conducting an investigation of the effect of SiC-Inverter on the motor efficiency. Experimental results show that the SiC-based inverter-motor traction system has observably higher efficiency of overall system compared to the Si-based traction system, and first explore that the motor has extremely high efficiency under low speed and light load when it is driven by a SiC-MOSFETs based inverter due to the higher switching speed of SiC MOSFETs. Meanwhile, the experimental results also confirm the losses models of SiC MOSFETs.



## 1. Introduction

Owing to high fuel economy requirements and the limited availability of petroleum, more and more companies of transportation vehicles are developing new technologies of electric vehicles (EV). Electric vehicle (EV) traction systems are undergoing significant changes with the application of wide band-gap semiconductor devices, such as silicon carbide (SiC) or gallium nitride (GaN) MOSFETs, according to their increased high switching speed, low on-resistance, high junction operation temperature, and low thermal resistance [1–4]. Previous research has indicated the superior characteristics of SiC MOSFETs compared to Si counterparts. Based on the semiconductor physics properties, including band gap energy, the critical electric field, saturation velocity and thermal conductivity, high switching speed, low power loss, high temperature stability were investigated respectively.

Prototype inverter systems equipped with SiC-MOSFETs demonstrated a marked loss reduction compared with that of a conventional inverter system with Si power devices [5]. The efficiency improvement of SiC-MOSFETs based inverter system is prominent and research focus is generally done on SiC MOSFET's power loss issues only [6–10]. Refs. [9,10] developed the loss model of SiC, and both conduction loss and switching loss of SiC

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are less than that of Si. The efficiency of inverter based on SiC is 99.1% while Si-inverter efficiency is 97.1%. In addition, the fuel economy of EV is improved because of the less losses of SiC [11,12]. Ref. [11] showed that fuel economy in the standard Japanese JC08 test cycle improved by approximately 5% when the Si IGBTs and diodes in the converters of traction system were replaced with SiC MOSFETs. In Ref. [12], the application of the SiC inverters in the plug-in EV (PHEV) and conventional hybrid EV (HEV) improve the fuel economy by 18.1% and 14.7%, respectively.

The above work focuses on the losses of SiC and the impact of SiC on the fuel economy. However, the motor losses are often not counted with the inverter losses although the modeling of motor losses already known [13–15]. The components of traction system in EV and corresponding losses are shown in Fig. 1. The power source of traction system for the EV is a limited battery or fuel cell [16]. The losses of the motor is comparable with that of the inverter. Furthermore, the reduced system losses not only can be translated to lower operating cost and extend drive distance, but also can reduce the thermal stress on the motor and inverter devices in return will improve the reliability of overall system [17]. This paper goes further by conducting an investigation of efficiency of overall inverter-motor system instead of only inverter or motor. Therefore, both the fundamental and harmonic losses of the electrical machine in conjunction with the inverter losses are investigated simultaneously in this paper.

In addition, the traction system performing with high efficiency during full power range is preferred in EV [18], especially for the direct drive wheel hub motor. The traction motors usually operate under low speed when the EV driven in city [19]. This constitutes the majority of usage in situations where the EV is operated. The efficiency of conventional traction system based on Si-IGBTs is relatively higher around rated power. Therefore, an exploration of advantages of SiC MOSFETs based traction system under low power is more interesting and is explored in this paper.

This paper systematically evaluates the performance of EV traction system based on SiC-MOSFETs and makes a comprehensive comparison between SiC-MOSFETs and Si-IGBTs based traction systems, particularly from efficiency point of view. Both conduction loss and switching loss of SiC-MOSFET are analyzed and modeled taking the temperature effect into account. Using the loss information, the heat sink of SiC-MOSFETs based inverter is optimally designed, and is compared with the heat sink of Si-IGBTs based inverter. Subsequently, both SiC-MOSFETs and Si-IGBTs based experimental benches are built. The overall efficiency of the SiC-based traction system is compared to the Si-based traction system systematically based on experimental results. And the experimental results are also used to validate the losses models of SiC MOSFETs.

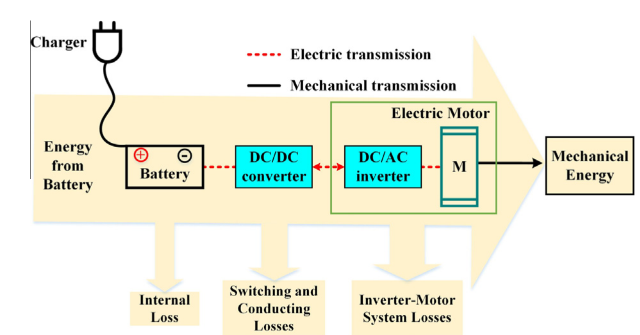


**Fig. 1.** The structure of traction system in EV and corresponding losses distribution.

The remainder of this paper is organized as follows. In Section 2, the model for describing the power losses of the inverter has been proposed, and the thermal effect has been considered. In Section 3, the heat sink of SiC-MOSFETs based inverter is optimally designed, and its performance has been evaluated with the counterparts of Si-IGBTs based inverter. In Section 4, the experimental setup and the validation are illustrated. Conclusions are drawn in the final section.

## 2. Inverter power losses

In order to present the advantages of SiC-MOSFETs traction system, a quantitative power loss analysis of inverter is obtained based on the primary electrical characteristics parameters [20,21]. The comparison will be done between the SiC MOSFETs and Si IGBTs. Specifically, the performance of Cree 1200 V 300 A SiC MOSFETs (CAS300M12BM2) will be investigated and compared with Infineon 600 V 300 A Si IGBTs (FF300R06KE3). The basic electrical characteristics parameters are outlined in Table 1.

This paper develops the models of conduction loss and switching loss of a SiC MOSFET taking the temperature effect into account, which yields a more accurate prediction of losses. The switching loss of reverse diode is not included as it is much smaller in comparison to the switching loss of a MOSFET. In addition, the calculations of Si-IGBT losses will use models of Si-IGBT losses developed in [22–24].

The simplified schematic of the SiC MOSFET is shown in Fig. 2. Gate threshold voltage ($V_{GS(th)}$) of the SiC MOSFET is much smaller than Si IGBT shown in Table 1. SiC MOSFET is characterized by faster switching speed and lower on-state-resistance compared with Si IGBT in the same current and voltage rating. Consequently, both switching loss and conduction loss of SiC-MOSFETs based system are much smaller than Si-IGBTs based system.

### 2.1. Conduction loss

The conduction loss of SiC MOSFET depends on the on-state-resistance ($R_{DS(on)}$) of the MOSFET. Hence, the conduction loss expression is following.

$$P_{con} = I_{rms}^2 \times R_{DS(on)} \tag{1}$$

where $I_{rms}$ is average value of the current through the MOSFET. $R_{DS(on)}$ is positive proportional to the temperature.

According to characteristics of SiC MOSFETs tested under different temperatures, the quadratic fitting curve of $R_{DS(on)}$ is developed shown in Fig. 3 taken into consideration temperature. Hence, the expression of $R_{DS(on)}$ is developed as,

**Table 1**
The primary electrical characteristics parameters of SiC-MOSFETs and Si-IGBTs modules.

| Electrical characteristics parameters | SiC-MOSFETs | Si-IGBTs |
|---|---|---|
| Voltage rating $V_{DS(on)}$ | 1200 V | 600 V |
| Continuous drain current $I_D$ | 300 A | 300 A |
| On-state-resistance $R_{DS(on)}$ | 5 mΩ | / |
| Collector-emitter saturation voltage | / | 1.45 V |
| Reverse transfer capacitance $C_{rss}$ | 0.07 nF | 0.57 nF |
| Input capacitance $C_{iss}$ | 11.7 nF | 19 nF |
| Gate-source capacitance $C_{gs}$ | 11.63 nF | / |
| Gate-emitter capacitance $C_{ge}$ | / | 18.4 nF |
| Output capacitance $C_{oss}$ | 2.55 nF | / |
| Internal gate resistance $R_G$ | 3.0 Ω | 1.0 Ω |
| Gate threshold voltage $V_{GS(th)}$ | 2.3 V | 5.8 V |
| Transconductance $g_{fs}$ | 94.8 S | / |
| Turn-on time $t_{on}$ | 144 ns | 160 ns |
| Turn-off time $t_{off}$ | 211 ns | 540 ns |

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