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Performance Comparison of Si IGBT and SiC MOSFET Power Module driving IPMSM or IM under WLTC

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Summary

The cumulative inverter losses and power consumption of silicon insulated gate bipolar transistors (Si IGBTs) and silicon carbide metal-oxide-semiconductor field-effect transistors (SiC MOSFETs) were evaluated on an electric motor test bench under a worldwide harmonized light vehicles test cycle. SiC MOSFET showed higher performance than Si IGBT regardless of the motor type and test vehicles. In the case of driving an interior permanent magnet synchronous motor, the latest 4th generation SiC MOSFET in ROHM has the lowest inverter loss and energy consumption compared with the other generations. The ratio of the inverter loss to the entire energy for driving the test cycle is 3%-level. There is room for improvement of the inverter loss of 0.115 kWh and the energy consumption of 0.5 kWh/100 km.

Keywords: inverter, powertrain, efficiency, energy consumption, EV (electric vehicle)

1 Introduction

Vehicle electrification is one of the worldwide trends to reduce air pollution, energy consumption, and environmental load. Automotive electrification can reduce fossil fuel dependence and the exhaust emission of passenger cars and road freight vehicles. Electric vehicles (EVs) have a higher efficiency motor than a combustion engine. xEV, referring to all kinds of EVs, has electric power components other than a motor to drive itself; a traction inverter, a dc–dc converter, and a battery charger. The power converters also require high-efficiency power conversion performance to keep low energy consumption. Silicon insulated gate bipolar transistors (Si IGBTs) are mainly used for xEV's traction inverters because of their high withstand voltage, low loss in the high current range, and their continuing performance evolution. Meanwhile, silicon carbide metal-oxide-semiconductor field-effect transistors (SiC MOSFETs) steadily catch up to Si IGBTs in performance and are increasingly adopted in commercial traction inverters. SiC MOSFET has excellent characteristics: low transient loss, low conduction loss, high-speed operation, and high-temperature operation. These features are effective in energy saving and reduction in size and weight.

The common evaluation of Si IGBT and SiC MOSFET focuses on loss analysis and efficiency improvement rate in a specific circuit or the whole of a power conversion system [1–5]. However, the more important point should be how much these transistors influence the overall performance of xEV. We are interested in the ratio of the dissipation energy of an inverter to the energy required for driving and how the ratio and the dissipation vary with kind of power modules.

In this paper, we used Si IGBTs and three kinds of SiC MOSFETs to drive an interior permanent magnet synchronous motor (IPMSM) and an induction motor (IM), respectively, under a drive cycle of worldwide harmonized light vehicles test cycle (WLTC). We evaluated power devices' performance through accumulated inverter loss and electric energy consumption.

2 Experiment Overview

2.1 System Configuration Outline

Fig. 1 shows the experimental system configuration for evaluating power modules. The device under test (DUT) of power modules drives a load given by a motor dynamo through a traction motor. The motor dynamo adjusts the load according to the speed. The inverter comprising the DUTs is driven according to drive patterns indicated by the controller. The controller has a pre-installed reference speed table of speed command values. Input and output power of the inverter and output of the traction motor is measured by a power meter with current sensors. Additionally, there are two-line cooling systems that cool the test motor and inverter of Si IGBT or SiC MOSFET. Table I presents the equipment details. The module packaging of the SiC-4G prototype is the same as SiC-2G and SiC-3G.

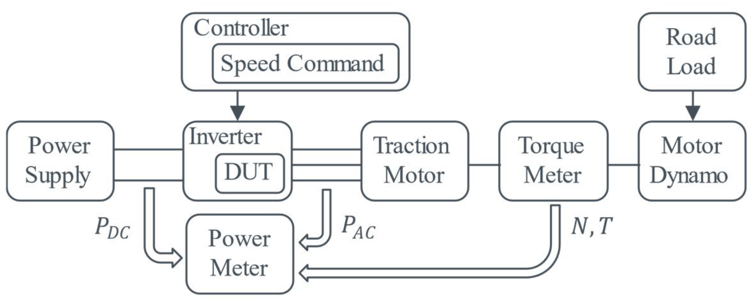

Figure 1: System configuration diagram

Table 1: Equipment detail

	Maker	Model	Specifications
Power Supply	SINFONIA TECHNOLOGY	-	850 V/ 500 A/ 100 kW
DUT	INFINEON	IGBT FF450R12ME4	1,200 V/ 450 A
	ROHM	SiC-2G BSM400D12P2G SiC-3G BSM400D12P3G SiC-4G prototype	1,200 V/ 400 A
Torque Meter	HBM	T40B	20,000 rpm/ 500 Nm
Traction Motor	MOTION SYSTEM TECH	IPMSM	850 V/ 500 A/ 100kW
		IM	12,000 rpm/ 300 Nm/ 100 kW
Motor Dynamo	SINFONIA TECHNOLOGY	-	12,000 rpm/ 300 Nm/ 100 kW
Controller	MYWAY PLUS	PE-EXPERT4	-
Power Meter	HIOKI	PW6001	w/ CT6876

2.2 Experimental Conditions

Fig. 2 shows the reference speed table pre-installed on the controller. It is one dynamic segment of WLTC Class 3b Shortened Type 1 test that excludes the extra high-speed phase in Japan. The original Shortened Type 1 test has two dynamic segments and two continuous speed segments [6]. However, there is no battery aiding in this paper since this evaluation system employs a power supply without reproduction of a battery profile. We do not need to consider an input voltage drop of the inverter and can evaluate just power modules' performance.

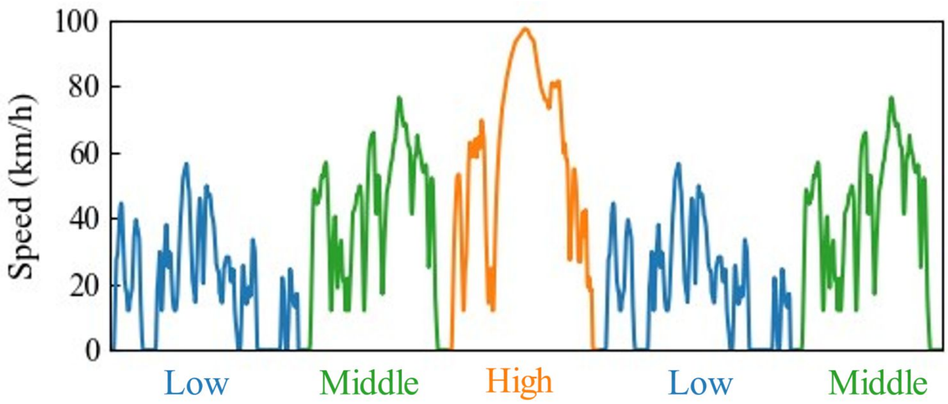

Figure 2: Evaluation cycle of one dynamic segment in WLTC Class 3b in Japan

The motor dynamo determines the load as follows:

$$T_{R/L} = J \cdot \dot{\omega} + (0.5 C_d A \rho v^2 + \mu m g) \cdot r / G \quad (1)$$

where $T_{R/L}$ is the road load torque; J is the vehicle inertia automatically calculated with set vehicle parameters in the motor dynamo system; other parameters are presented in Table 2 [7].

We choose two vehicles for comparative evaluation. One is the 2017 Nissan Leaf G, which is one of the major EVs in Japan. Another is the 2022 BMW i4 eDrive 40 whose required current is the maximum in other vehicles that we set available parameters.

Table 2: Parameters of test vehicles

Parameter	Symbol	Unit	2017 Nissan Leaf G	2022 BMW i4 eDrive 40
Tire Radius	r	m	0.323	0.356
Gear Ratio	G	-	8.193	8.774
Aerodynamic Drag Coefficient	C_d	-	0.28	0.24
Frontal Area	A	m^2	2.48	2.41
Vehicle Mass	m	kg	1646	2251
Air Density	ρ	kg/m^3	1.189	
Rolling Resistance Coefficient	μ	-	0.011	
Gravity Constant	g	m/s^2	9.8	

In this paper, we set the inverter input voltage as 800 V for high voltage use evaluation. However, the battery voltage of the original vehicles is around 400 V. The gate resistance values of each DUT are decided that the peak voltage of the switching sarge is around 1,100 V when the test current is around 800 A in the double pulse test. The gate voltage of ROHM modules is each recommended voltage for the inverter, and one of the Infineon modules is limited by the used gate driver circuit (BSMGD2G17D24-EVK001).

Table 3: Parameters of driven DUT

Parameter	Unit	IGBT	SiC-2G	SiC-3G	SiC-4G
Inverter Input Voltage	V	800			
Inverter Input Capacitor	μF	960 (320μF × 3: 947C321K122CDMS) 150 (25μF × 6: B32778G1256K000)			
Snubber Capacitor	nF	4,050 (1,350nF × 3: EVSM1D72J2-142H16)			
Discharge Resistance	MΩ	0.73 (2.2MΩ × 3-parallel)			
Gate Resistance (ON/OFF)	Ω	0.0 / 6.8	1.2 / 2.2	1.2 / 2.2	2.7 / 6.8
Gate Voltage (ON/OFF)	V	15 / –4	18 / –4	18 / –2	18 / –2
Switching Frequency	kHz	10			
Dead Time	us	2			

2.3 Evaluation Index

The original energy consumption requires complex calculation procedures [6]. However, in this paper, we employed a simplified calculation as follows:

$$EC = E_{DC}/D \tag{3}$$

where EC is the energy consumption; E_{DC} is the total integrated inverter input energy; D is the total driving distance. Then,

$$E_{DC} = \sum P_{DC} \cdot \Delta\tau_1 \tag{4}$$

where P_{DC} is the inverter input power; $\Delta\tau_1$ is 50 milliseconds (refresh rate is 20 Hz) and is decided by the accumulation function of the power meter, PW6001. Then,

$$D = 2\pi r \cdot N_{total}/(4096 \cdot G) \tag{5}$$

where N_{total} is the total number of the a/b pulses converted from a resolver of the traction motor.

The integrated inverter loss energy E_{loss_inv} is calculated as follows:

$$E_{loss\_inv} = \sum(P_{DC} - P_{AC}) \cdot \Delta\tau_1 \tag{6}$$

where P_{AC} is inverter output power.

The integrated motor loss energy E_{loss_mtr} is calculated as follows:

$$E_{loss\_mtr} = \sum P_{AC} \cdot \Delta\tau_1 - \sum P_{MC} \cdot \Delta\tau_2 \tag{7}$$

where P_{MC} is the motor output; $\Delta\tau_2$ is about 200 milliseconds (refresh rate is 5 Hz) and is decided by the data accumulation speed between a PC and other measurement equipment. Then,

$$P_{MC} = 2\pi \cdot T \cdot N/60 \tag{8}$$

where T is the torque, and N is the number of rotations. Both parameters are measured using a torque meter.

3 Experimental Results

Fig. 3 shows the energy consumption for each experiment, divided into three categories: traction energy, motor losses, and inverter losses. The traction energy of each case should have the same value; however, there is variation within 3%-error in the actual values. This variation comes from the slow refresh data acquisition rate of the mechanical part. The order of lowest energy consumption is SiC-4G < SiC-2G < SiC-3G < IGBT for IPMSM, and SiC-2G < SiC-4G < IGBT for IM. These orders did not change depending on the type of car used. All SiC modules perform better than IGBT.

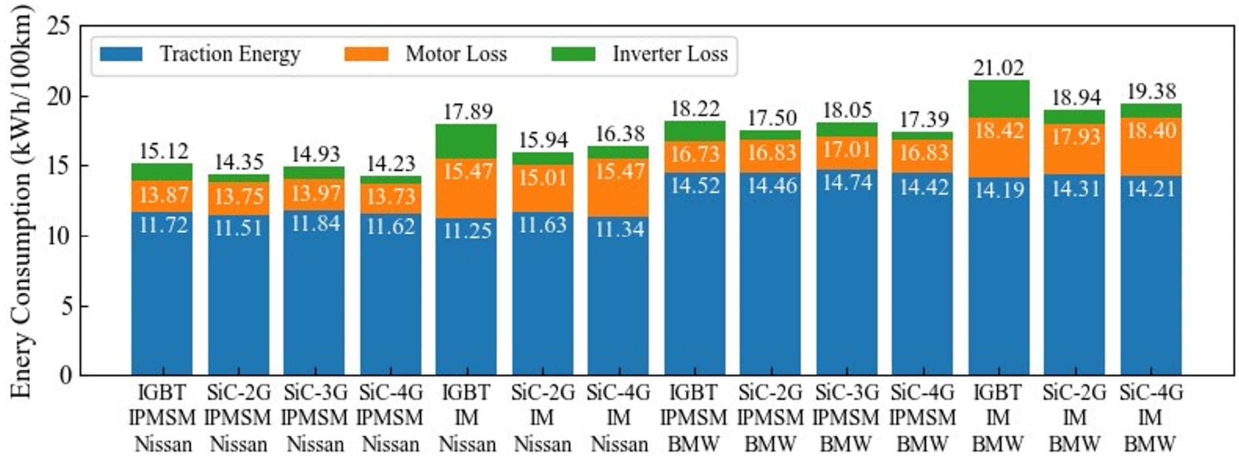

Figure 3: Energy consumption of each experimental case

Fig. 4 shows only inverter loss measured using the power meter, whose accuracy is better than mechanical output. For IPMSM, the inverter loss and energy consumption of SiC-4G are better than SiC-2G. Meanwhile, the inverter loss of SiC-4G is almost the same or slightly better than SiC-2G for IM; however, the energy consumption is worse.

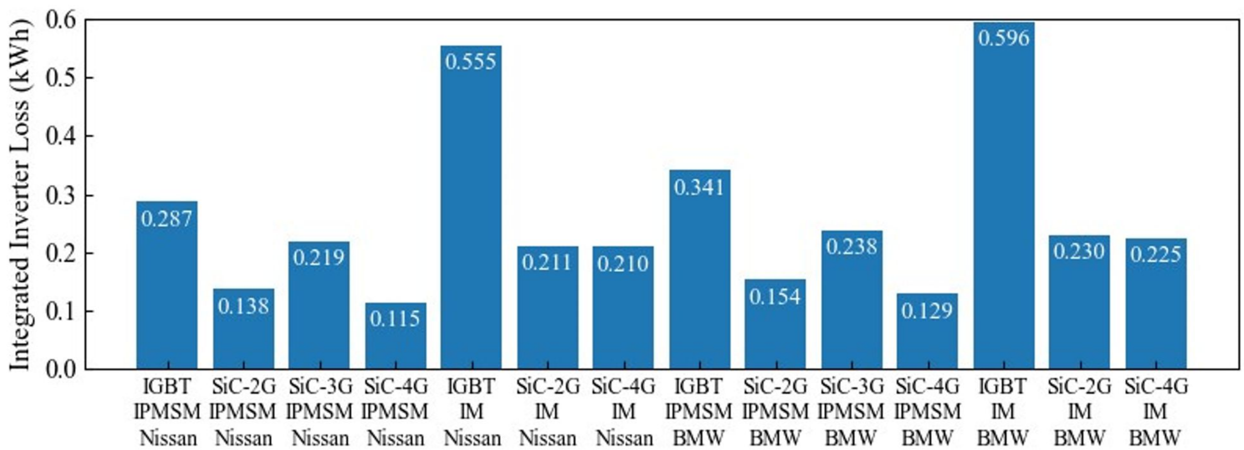

Figure 4: Inverter loss comparison between experimental cases

Fig. 5 shows energy consumption as a function of powertrain loss for the entire evaluation cycle and each phase in the experimental cases. The straight line is drawn by a simple average of all data. The slope of these lines signifies how much impact powertrain loss brings on energy consumption. The line slope is relatively steep in the phase low, meaning that the powertrain loss highly affects energy consumption. Meanwhile, the line slope is relatively loose in the phase high, meaning that the powertrain loss slightly affects energy consumption. The intercept of the lines represents experimentally obtained ideal energy consumption without motor and inverter loss. The intercept is about 11.56 kWh/100 km for Nissan Leaf G, and the one is about 14.41 kWh/100 km BMW i4 eDrive 40 in Fig. 5 (a). Therefore, the energy increase in traction purely due to the difference in vehicle type is about 25%. All the plots are almost on line, and each the same marker between the vehicles is within 10% of powertrain loss. The difference in the experimental cases in IPMSM slightly affects the motor loss because the plots are roughly overlapping. The gap between the filled and open markers shows inverter loss. If replacing IGBT with SiC-4G, the outlined circle can be improved to the outlined diamond. For IM, the motor loss of SiC-2G is exceptionally smaller than IGBT and SiC-4G, but the gap has the same tendency as the IPMSM.

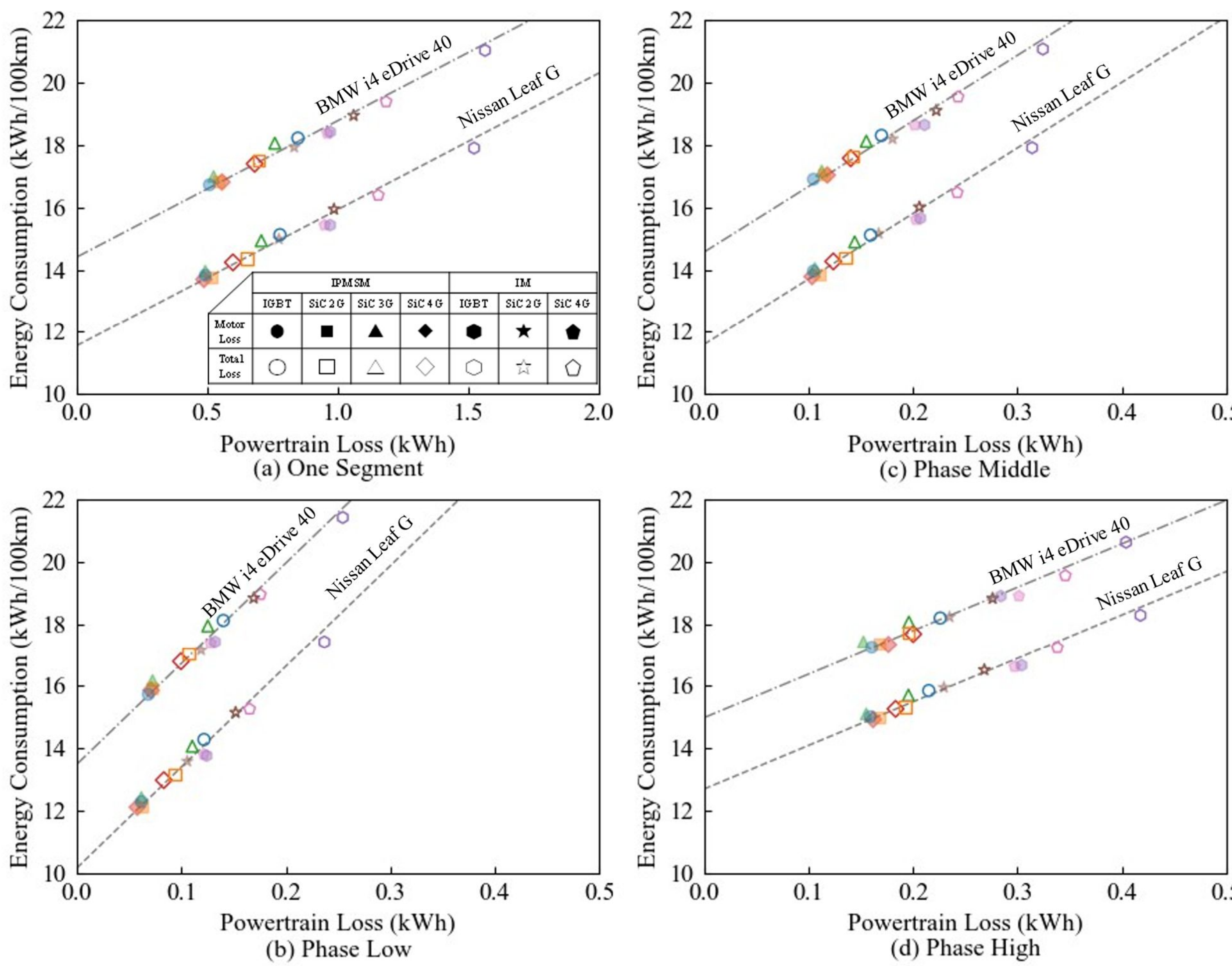

Figure 5: Energy consumption vs. powertrain loss of each phase

Fig. 6 shows the energy ratio of traction energy, motor loss, and inverter loss. SiC-4G can reduce inverter loss ratio around 5% in IPMSM and 7%–8% in IM.

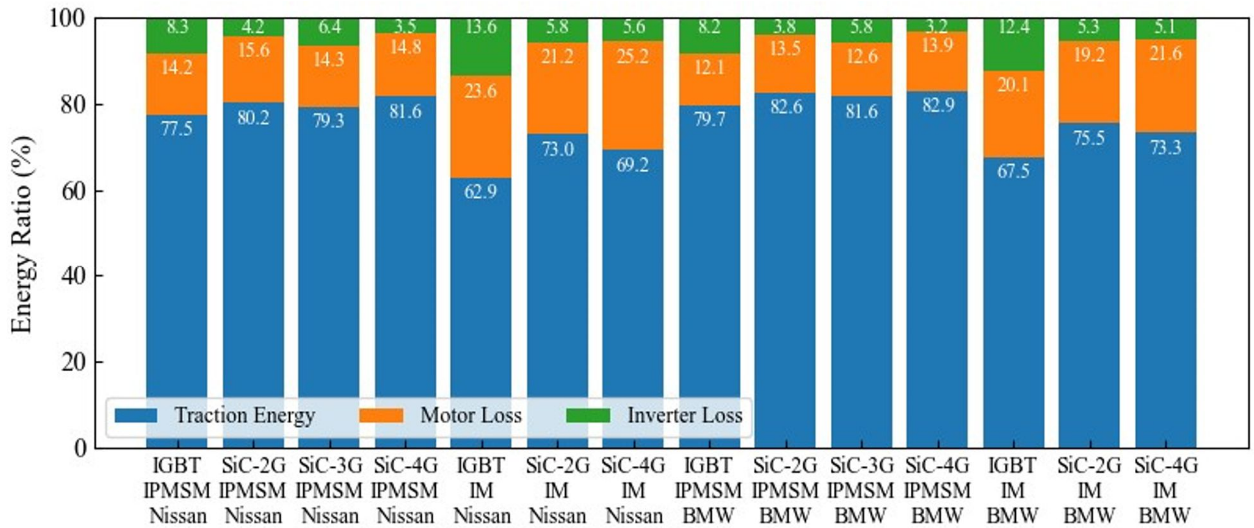

Figure 6: Energy consumption ratio of each experimental case

4 Conclusions

In this paper, Si IGBT and SiC MOSFET performance are evaluated with the electrical motor test bench by driving IPMSM or IM along WLTC under road load of Nissan Leaf G or BMW i4 eDrive 40. It is an effective selection for saving battery capacity to replace IGBT with SiC MOSFETs since the inverter loss and electric energy consumption can be improved. However, it is not easy to select SiC MOSFET. At least, the latest 4th generation SiC MOSFET in ROHM can be an effective choice in driving IPMSM. The ratio of the loss to the entire energy can be reduced to a 3%-level. However, there is no remarkable difference between the inverter losses of the 2nd and 4th SiC MOSFETs in driving IM, and the electric energy consumption of the 4th is worse than that of the 2nd.

In the case of driving IPMSM with SiC-4G, there is room for improvement of the inverter loss of 0.115 kWh for the entire evaluation cycle and the energy consumption of 0.5 kWh/100 km.

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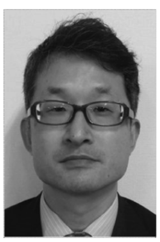

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