Design, Test and System Evaluation of Silicon Carbide Power Modules and Motor Control Units

Leadrive Technology (Shanghai) Co., Ltd. (hereafter referred to as "Leadrive Technology") is a high-tech company focusing on R&D, manufacturing and sales of new electric vehicles powertrain and power semiconductor modules. At the end of 2019, Leadrive Technology and ROHM Semiconductor established a joint laboratory and signed a strategic cooperation agreement. Main purpose of this cooperation is the development of power semiconductor modules and the motor control unit (MCU) based on ROHM silicon carbide chips. This paper will introduce the design, testing and system evaluation of SiC power modules, which were all performed by Leadrive.

Introduction

In recent years, the silicon carbide power semiconductor has become a hot topic in energy conversion applications. Thanks to its material properties, it has higher maximum junction temperature, lower loss and smaller thermal resistance than silicon-based semiconductor devices. This is the main reason why many people believe that SiC inverter system will have higher power density, smaller volume, higher allowable operating temperature and lower energy loss.

Leadrive Technology develops power modules based on silicon carbide chips, and applies them to motor control unit of new energy vehicles (hereafter referred to as "MCU"), therefore replacing existing silicon-based IGBT power modules (peak power is about 150 kW).

Before even starting the development phase, it needs to be pre-evaluated which characteristics of silicon carbide can bring the greatest value to the main drive application. For example, for motor controller applications, the introduction of silicon carbide technology has no significant effect on the reduction of the volume. The volume of MCU mainly depends on the packaging technology of its subcomponents and the power module only accounts for a small percentage. Additionally, some people claim that the advantage of higher working junction temperature of silicon carbide can be used to reduce the amount of chips that need to be installed, which can reduce the cost. This feature may be suitable for applications with high ambient temperatures, such as underground drilling. However, in the case of new energy vehicles, this advantage is questionable. Because of the loss of silicon carbide will increase at high temperature (better than Si), which reduces the efficiency of MCU under high temperature.

In the view of Leadrive, the main system advantages of applying silicon carbide technology to the main drive MCU lie in the improvement of efficiency and increase of peak output power. The former can magnify the range or reduce the number of batteries installed, while the latter can bring greater acceleration to the vehicle. The first module developed by Leadrive is a 750V SiC module for passenger vehicles of class A and above. The second is a 1200V SiC module, which can be applied to 800V passenger or commercial vehicles. All SiC modules developed by Leadrive use the latest fourth generation 750V and 1200V chips of ROHM. Taking the 1200V chip as an example, its comprehensive performance has been significantly improved compared with its previous generation, as shown on table 1.

Table 1: Performance overview of the fourth generation SiC chip of ROHM Semiconductor

Parameters	Unit	S4601 （4th Gen.）	S4103 （3rd Gen.）
Breakdown voltage V_{DSS}	V	1200	1200
Continuous drain current I_D	A	136 @ 175°C	95 @ 175°C
Drain source on state resistance $R_{DS,on}$	mOhm	12 @ 25°C	22 @ 25°C

This paper illustrates the R&D process of this project. First, the system performance evaluation (top-down flow) is introduced to determine the number of chips being used in parallel. Afterwards, the power module design is introduced, including packaging form, electromagnetics, thermal, structure and manufacturability. Moreover, a module performance test benchmarking a well-known IGBT power module is conducted. According to the calibration results of the module, the system performance is evaluated, including the maximum output power and high efficiency zone, and its impact on endurance mileage. Based on the above stated results, this paper summarizes the design methodology of SiC modules in EV drive applications.

System analysis

According to the specifications of the fourth generation SiC chips provided by ROHM the relevant parameters are imported into ScanTool, a system simulation tool developed by Leadrive. ScanTool is a time-domain and frequency-domain hybrid simulation tool, which is mainly used in the preliminary design phase of power electronic systems. It can be used to calculate the power, efficiency, output waveform distortion, voltage ripple and current stress of DC-link capacitor under different hardware and software configurations. The calculation principle of ScanTool is shown in Figure 1. The excitation waveform is converted into the frequency-domain spectrum, and the plant is described in frequency-domain matrix format. The response of the system can be obtained from the product of the former two, and the results can be converted to time domain, so that the response waveform can be obtained. In this way, the output waveform has high steady-state accuracy - without the waiting time from initial state to reach final steady-state, which cannot be avoid by time domain simulation tools. Simulation time can be reduced from tens of minutes to 1-2 seconds per simulation point. Therefore, ScanTool is especially suitable for the early design of power electronic systems since it still allows a high degree of freedom needed to simulate hundreds of hardware and software design combinations.

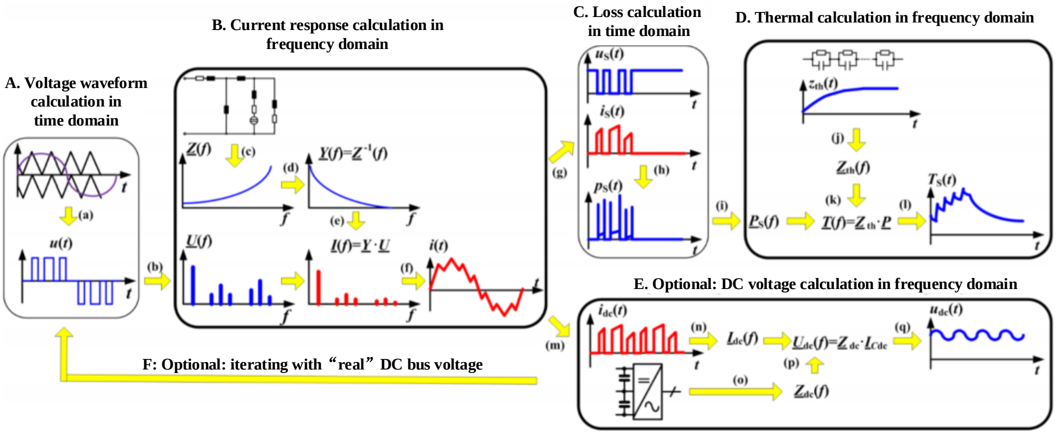


Fig. 1: Principle of loss calculation

Generally speaking, when people design a power module based on IGBT chips, the type and the number of parallel connections is mostly defined by the assessed junction temperature of the chip (or the peak output power at the maximum junction temperature). For silicon carbide chips, due to their small chip size, parallel alignment of multiple chips was deemed suitable. On the other hand, silicon carbide is a unipolar device. This means that arranging a higher number of SiC chips in parallel will lower the total conduction loss, thus improving the efficiency of the MCU. In this context, when selecting the amount of parallel chips, not only the maximum junction temperature needs to be considered, but also system efficiency needs to be considered. Especially the improvement of the endurance mileage under the cycling road conditions such as NEDC, WLTC, CLTC, etc., needs to be taken into account as well as conducting a comprehensive analysis combined with a financial return model.

A simplified financial model is developed, which includes the cost difference caused by using silicon carbide power modules (compared with IGBT power modules), reduced battery installation and subsequent charging costs. The first two are the initial investment expenditure (CAPEX), the latter is the operating expenditure (OPEX). The break-even point can be estimated to be between 1-4 years depending on the vehicle type and usage frequency. Due to the high number of assumptive variables of this system level financial model, this model will not be described in details.

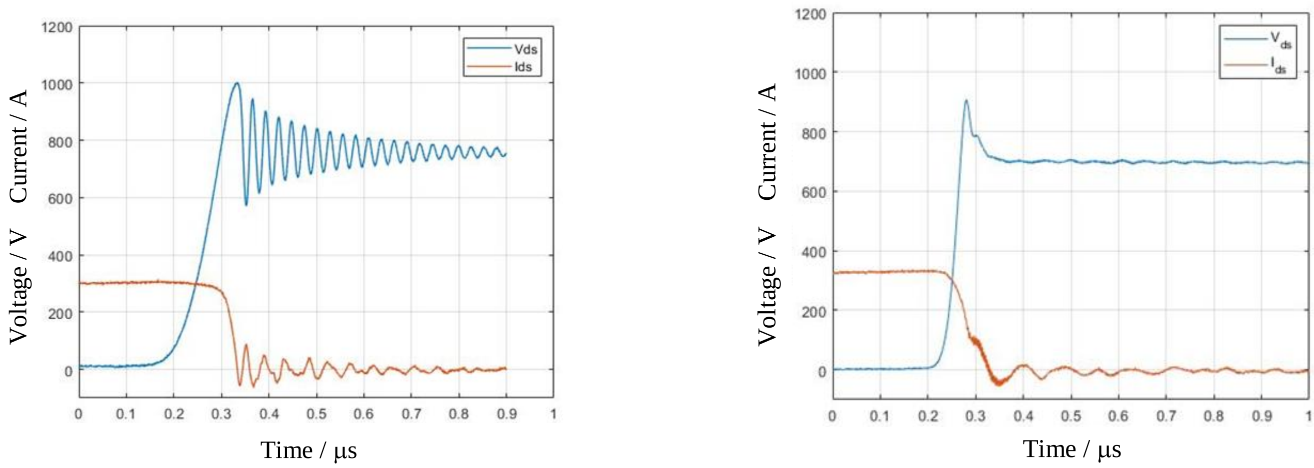
After conducting a series of system analysis, it was verified that when installing too many silicon carbide chips in parallel, only the maximum vehicle acceleration can be increased, yet the endurance mileage will not be further improved. If too few silicon carbide chips are used, the efficiency / economic advantage will be lost - especially taking the positive temperature coefficient of silicon carbide into account.

Based on these observations, the author optimized the selected number of chips according to the financial model. Not only does it avoid the unnecessary cost increase by installing too many chips, but also evade the economic disadvantage caused by installing too few chips in parallel. Additionally, Leadrive SiC power modules also introduce the concept of standardized design, that is, if customers have specific requirements for vehicle acceleration (i.e. for some high-end vehicles), more chips can be installed in parallel in the module. This design will improve the maximum instantaneous output power and provide vehicle users with a greater push back experience.

Module Design

Generally, the power module design stage includes electromagnetic, thermal, structure and manufacturability. It should be noted that the switching speed of silicon carbide MOSFET is much higher than that of silicon-based IGBT. Consequently, some indexes that are not as strict in IGBT power modules design phase will become very important in relation to silicon carbide power modules. These indicators include the switching time synchronization between parallel chips, the balance of transient current and voltage stress, and the interference of power loop to the gate. Among them, the first two indicators are reflected in the external characteristics of the power module, which determine the ultimate voltage and current output capacity. The interference of power loop to the gate is the result of the electromagnetic energy being linked to the control bond through space when the device is turned on or off. A consequence may be, that the transient voltage stress of the gate is too large, resulting in accelerated obsolescence of the gate, which may cause the spurious triggering, ultimately damaging module and system.

In addition, according to the experience of SiC power module design, the oscillation in the silicon carbide power module became obvious. It is a LC resonance composed of leakage inductance of the power module and junction capacitance of the silicon carbide chips, and its frequency is usually in tens of megahertz. This oscillation will affect the EMC performance of the MCU system as well as reducing the efficiency advantage of the silicon carbide power module. Under extreme conditions, the resonance will be further deteriorated, the voltage and current amplitude will exceed the safe operating area (SOA) of the device. In order to solve this problem, Leadrive developed a series of tools and optimized the power module ontology design, finally eliminating this issue. Figure 2 is a comparison of the two output waveforms. As explained, under the same working conditions there is no obvious oscillation phenomenon in the optimized module design.



(a) before improvement (b) after improvement

Fig. 2: Turn off voltage and current waveforms before improvement (left figure) and after improvement (right figure)

Finally, after many iterations, the transient stress imbalance between multi-chips in the module is reduced to less than 10%. According to the competitive product benchmarking evaluation conducted by the team, it is concluded that this performance alone has reached the top level in the industry. At the same time, the interference of the power loop to the gate has been greatly reduced. Ultimately, the high frequency oscillation problem during switching time is also solved.

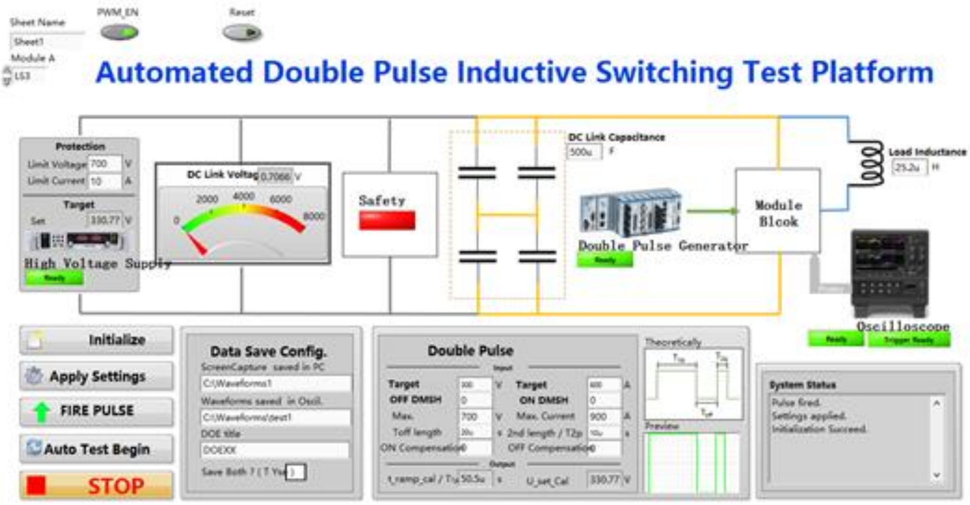
Performance Test for Silicon Carbide Module

The test of the power module includes the electric test and the reliability test. The electric test can be divided into static test for conduction loss and dynamic test for switching loss evaluation. The common implementation method of the latter is called "double-pulse test". During the testing phase different levels of voltage, current, device temperature, and even gate driving resistance need to be applied to the device. A complete design of experiment table often contains thousands of work points. Considering the amount of necessary post-processing work, the dynamic testing of power devices is without a doubt a time-consuming and laborious task. Consequently, in many cases users had to reduce the density of test points, which means cutting down the length of the DOE table to shorten the test time.

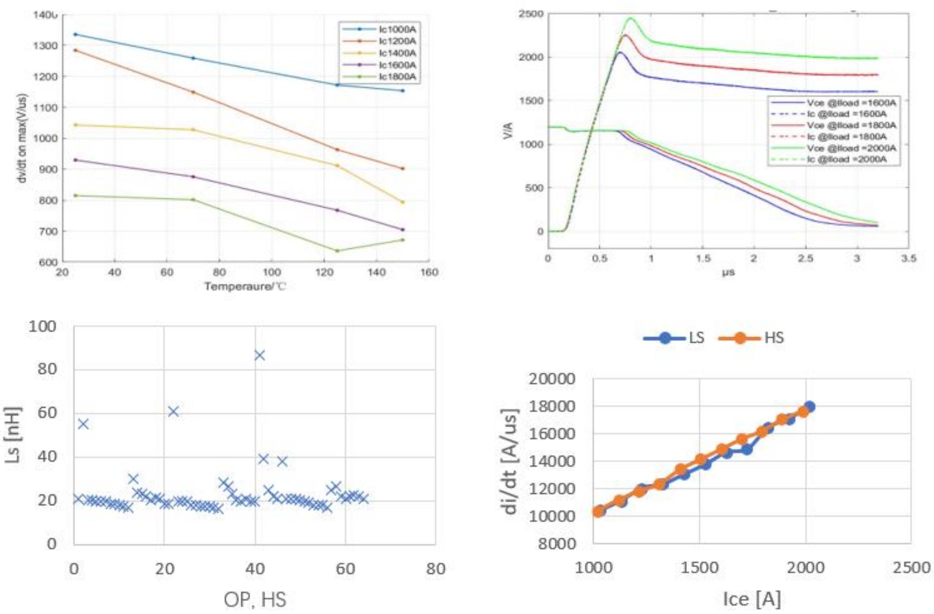
Given these obstacles, Leadrive Technology has developed a set of high-precision and high-speed dynamic testing platforms for power modules. The automatic testing of thousands of working points can basically be completed with "one key". Automatic data post-processing and semi-automatic report writing functions have also been developed. All users need to do is configure the pre-test hardware, generate a scientific DOE form and add subjective evaluation to the final test report. Comparing the general manual / semi-manual test system with this automatic calibration platform, it shows that a module calibration task with more than 3000 test points can be compressed from two months to two days - including data post-processing and report generation. Figure 3 illustrates the core functions of the test platform.

In this project, a well-known IGBT power module is used for dynamic performance comparison. The test results show that the SiC power module developed by Leadrive surpasses the reference

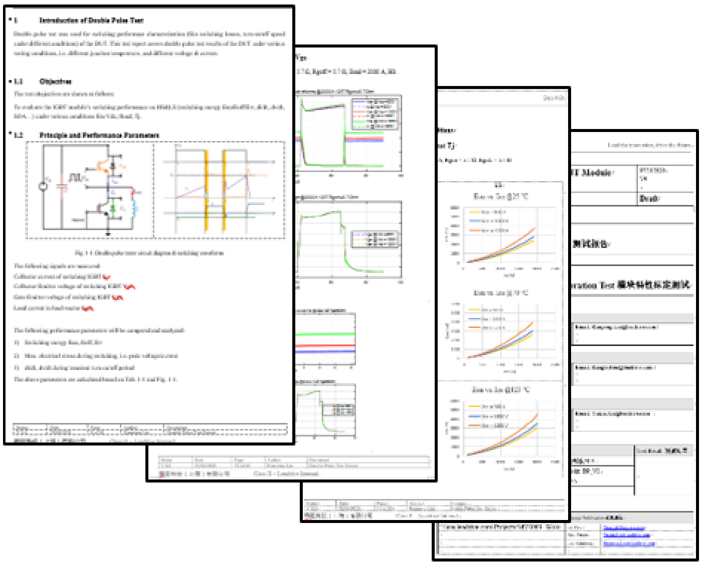
IGBT power module in dynamic performance in many indicators, including turn on or turn off losses as well as reverse recovery loss of body diodes. At the same time, there is no obvious oscillation of the SiC power module at extreme temperatures.



(a) Automatic test interface



(b) Automatic data post-processing



(c) Semi-automatic report generation

Fig. 3: Core functions of dual pulse test platform

Efficiency Test of Silicon Carbide Electronic Control

The silicon carbide power module based on ROHM fourth generation 750V SiC and its matching gate driver (based on ROHM's isolated gate driver: BM6104FV) are installed in the inverter, while a permanent magnet motor is matched to calibrate the efficiency diagram. The results are used to benchmark the MCU based on the IGBT power module. This test system is shown in Figure 4.

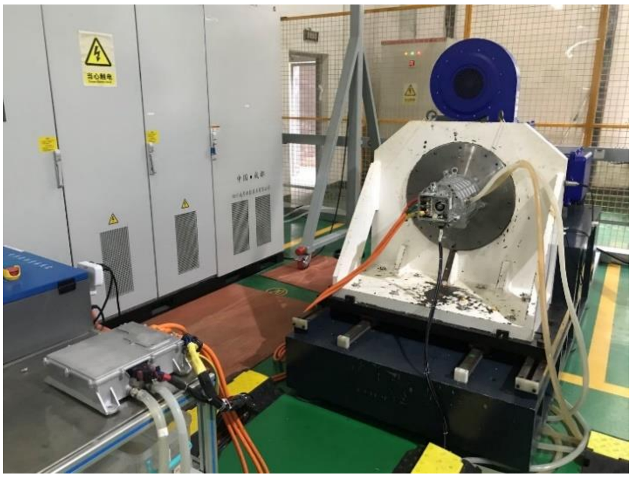
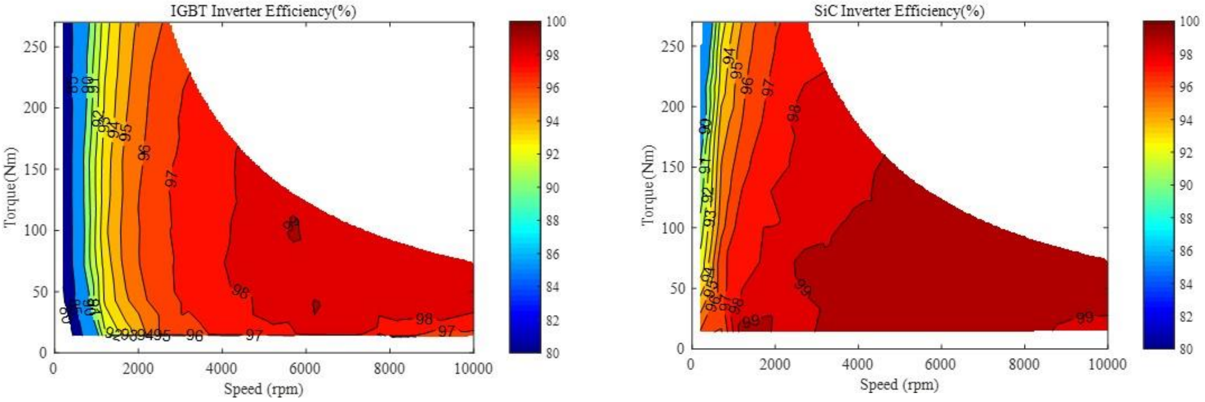


Fig. 4: Efficiency test of SiC motor controller



(a) Efficiency contour of IGBT inverter

(b) Efficiency contour of SiC inverter (ROHM 4th Gen. chips)

Fig.5: Comparison of testing efficiency between IGBT and SiC (750V)

The comparison of the measured efficiency diagram and the key parameters of IGBT MCU and SiC MCU are respectively shown in fig. 5 and table 2. It can be seen that silicon carbide power module significantly increases the maximum efficiency as well as high efficiency range. Especially in the case of low torque with light load, the efficiency advantage of SiC is striking. This is primarily due to the low conduction loss of unipolar power devices under light load and low switching loss of SiC.

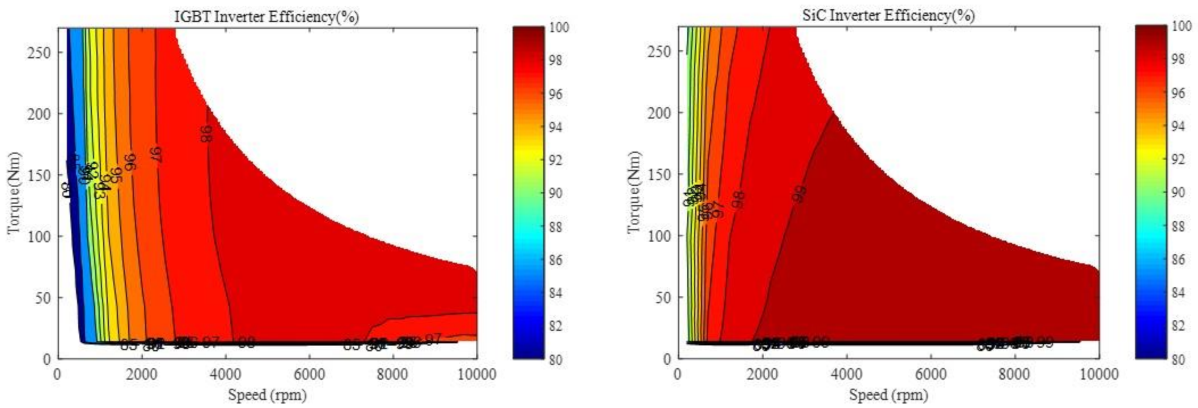
Table 2: Comparison of testing efficiency between IGBT and SiC

Parameters	IGBT	SiC
Highest efficiency	99.1 %	99.9 %
Lowest efficiency	74.8 %	86.4 %
Zone Proportion with efficiency > 95%	73.7 %	90.7 %
Zone Proportion with efficiency > 90%	90.1 %	98.7 %

Note: The actual efficiency of electronic control is measured by power analyzer. There may be some errors in the extremely high efficiency range due to the limitation of equipment accuracy.
Yokogawa WT3004E power analysis equipment is used to measure the efficiency.

Simulation and Verification of SiC MCU Efficiency

Moreover, the test results of the double-pulse test are imported into ScanTool to simulate the efficiency diagram. It should be pointed out that SiC devices have obvious positive temperature coefficient characteristics (i.e. the loss increases with the raise of temperature). Given this circumstance, the temperature iteration function is set in ScanTool. In this function, the loss of the device is calculated according to the results of the junction temperature applied in the previous simulation. Afterwards, the junction temperature is recalculated according to the loss until the temperature deviation between the two calculation results is less than 1 degree. When too few chips are in parallel in one power module, the loss of chips will increase due to the raise of junction temperature. On the contrary, when the number of chips in parallel is large enough, the loss of the single chip will be decreased, so the junction temperature will be lower. At this low junction temperature, the loss of silicon carbide chips will be further reduced. It has become evident that the temperature loss iteration function is the key to ensure the modeling accuracy.



(a) Efficiency of IGBT inverter

(b) Efficiency of SiC inverter (ROHM 4th Gen. chips)

Fig. 6: Efficiency comparison of IGBT and SiC inverter based on simulation (750V)

The simulation results are shown in Fig. 6 and table 3. Compared with the measured results in Fig. 5 and table 2, we can see that the analysis tool is in accordance with the measured results. The residual difference between the two is mainly reflected in the low-speed range, in which the output power of the MCU is very low. Thus, the residual loss in the MCU is obvious, such as the loss of busbar and DC-link capacitance. Likewise, the pulse width modulation scheme and the accuracy of the test equipment are additional potential factors, yet these small differences do not affect the next system level range analysis.

Table 3: Comparison of simulation efficiency between IGBT and SiC

Parameters	IGBT	SiC
Highest efficiency	98.8 %	99.7 %
Lowest efficiency	64.0 %	89.6 %
Zone Proportion with efficiency > 95%	76.7 %	90.8 %
Zone Proportion with efficiency > 90%	89.8 %	98.4 %

Maximum output capacity Analysis of Silicon Carbide MCU

The more parallel chips are aligned in the silicon carbide power module, the greater output capacity of the MCU. In this analysis, we assume that SiC and IGBT are allowed to work at the same maximum junction temperature, i.e. 150 ℃. The simulation results of ScanTool illustrate that the maximum output power increases by 12.4% if 6 chips are connected in parallel, and by 31% if there are 8 chips used in parallel.

In the experiment inductance was used as load to test the maximum output capacity given the limitation of the powertrain test bench. Compared with the real motor load, this compromise is acceptable for evaluating SiC power modules, since the bidirectional conduction characteristic of SiC chips make the loss insensitive to the power factor of the load.

Figure 9 shows that the silicon carbide MCU output has reached 600 Arms, as well as reaching the maximum capacity of the test equipment. It needs to be pointed out that in the MCU application, the switching frequency remains at 10kHz, while the percentage of switching loss of SiC module remains low (about 20%). Therefore, by upgrading the control frequency of the software and the power capability of the gate driver, the switching frequency of the MCU can be significantly raised without obvious power derating. At high switching frequency, the fundamental frequency of the load can also be greatly increased, meaning MCU can be used in high-speed applications such as high-speed air compressors or aerospace.

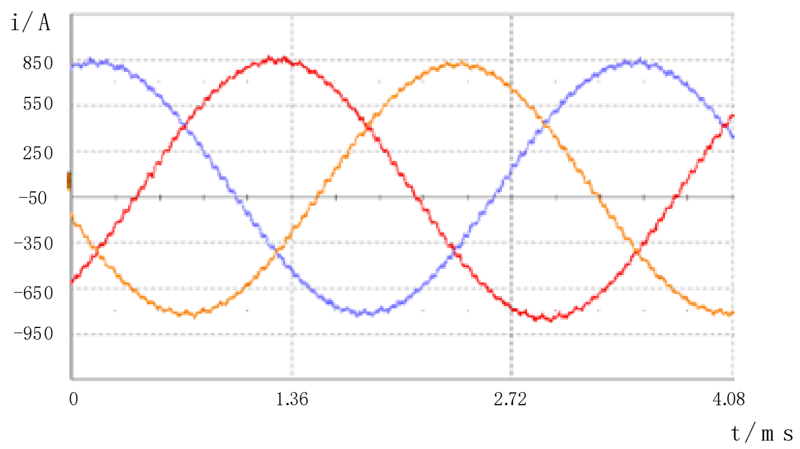


Fig. 9: Actual operation waveform of SiC MCU

System Evaluation of the Advantages Brought by The Silicon Carbide

System evaluation in this case mainly primarily refers to the vehicle level endurance mileage analysis. At this point, Leadrive Technology has developed a set of vehicle calculation tools based on the specified road spectrum. After the user selects a vehicle type and specifies the road condition template, the tool will output the torque and speed instructions corresponding to the powertrain (motor + MCU), and the endurance mileage can be obtained according to the efficiency diagram.

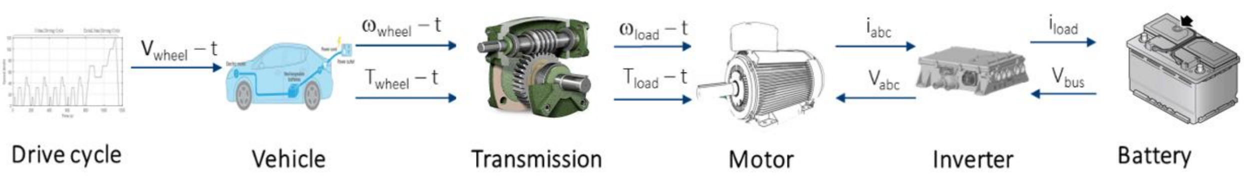


Fig. 10: Concept diagram of endurance mileage evaluation for electrical vehicle
(*Note: Some sub-component pictures are from the network)

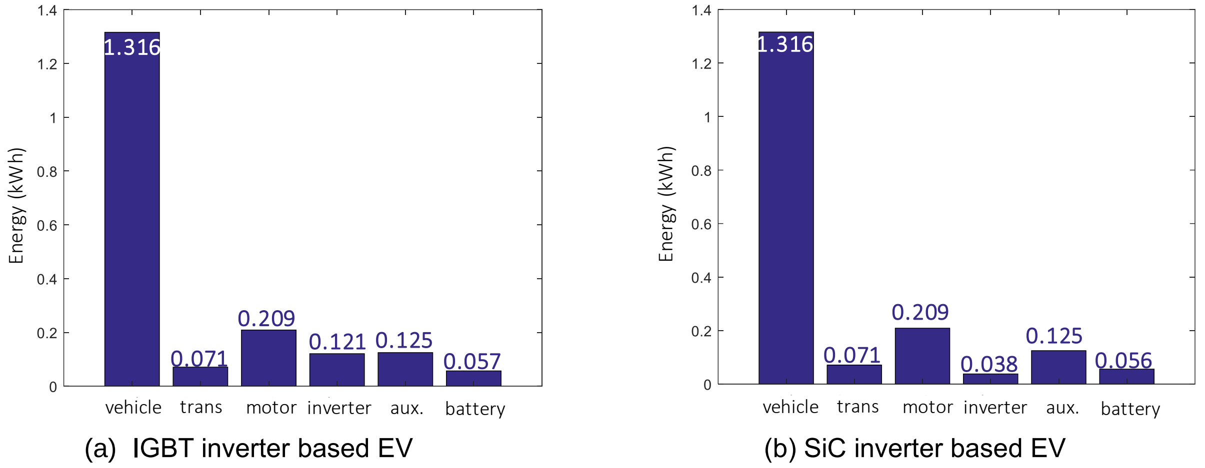


Fig. 11: Comparison of energy consumption under CLTC-P condition

In our examination, we select a car with low wind resistance and match the IGBT / SiC MCU with the measured efficiency of its corresponding drive motor as shown in Figure 5. By the same token, we conduct a simulation analysis under CLTC-P (China light duty vehicle test cycle passenger car) road spectrum. The energy consumption comparison of the whole vehicle system is shown in figure 11. Contrasted with the original IGBT MCU, the energy consumption of the vehicle equipped with the silicon carbide electronic control system is reduced by 4.4%, which means the endurance mileage can be increased by 4.4% with the same battery capacity! This exciting result proves the significant advantages of silicon carbide technology when applied to new energy vehicles.

Project summary

This paper introduces the development, testing and system evaluation of the power module based on ROHM fourth generation SiC chips and motor control system. The results show that the SiC power module works stably with a striking loss reduction compared to the IGBT power module. In relation to IGBT MCU, the corresponding SiC MCU has clear advantages in terms of maximum power output and endurance mileage. This project also provides evidence that the application of SiC technology in the main drive of new energy vehicles is the general trend.

(a) assembly line

(b) test line

Fig. 12: Leadrive automatic production line

The silicon carbide power module developed in this paper is compatible with a mainstream IGBT power module in the power terminal. Additionally, the gate position has been optimized to improve the internal electrical performance of the module. The silicon carbide MCU developed in this paper is fully compatible with an IGBT MCU. While having obvious performance advantages, it can also be used in the existing MCU automation production line of Leadrive Technology to realize batch production.

Leadrive Technology has developed a set of automatic production lines (see Figure 12). Its projected capacity is 150 000 units per year, and the automation rate of the assembly line is about 85%, while the automation rate of the test line is 100%. The factory has passed the IATF16949 quality system certification of TUEV (German Technical Supervision Association).

Conclusively, the author's discussion on silicon carbide MCU is as follows:

1. The main advantage of SiC used in MCU is efficiency. The economic advantage of higher efficiency lies in the decrease of battery installation and charging cost.
2. Concerning the design of SiC power modules, the number of parallel chips needs to be over designed appropriately to achieve the best economic benefits; too many chips in parallel will reduce the economy benefits, yet can help the vehicle to achieve greater acceleration.
3. The challenges of SiC power module design lies in the electromagnetic component, so accurate modeling and tool chains need to be developed.
4. When SiC power module technology is used in vehicles with small wind resistance, the endurance mileage can be increased by more than 4%.

Generally speaking, SiC technology is suitable for high-end vehicles with long endurance mileage and low wind resistance, likewise offering higher economic value for users with higher vehicle use frequency.

More information: https://www.rohm.com/products/sic-power-devices

ROHM Co.,Ltd.
2323 Owen Street,
Santa Clara, CA 95054 U.S.A
TEL : +1-408-720-1900
www.rohm.com

Catalog No. 63WP040E Rev.001