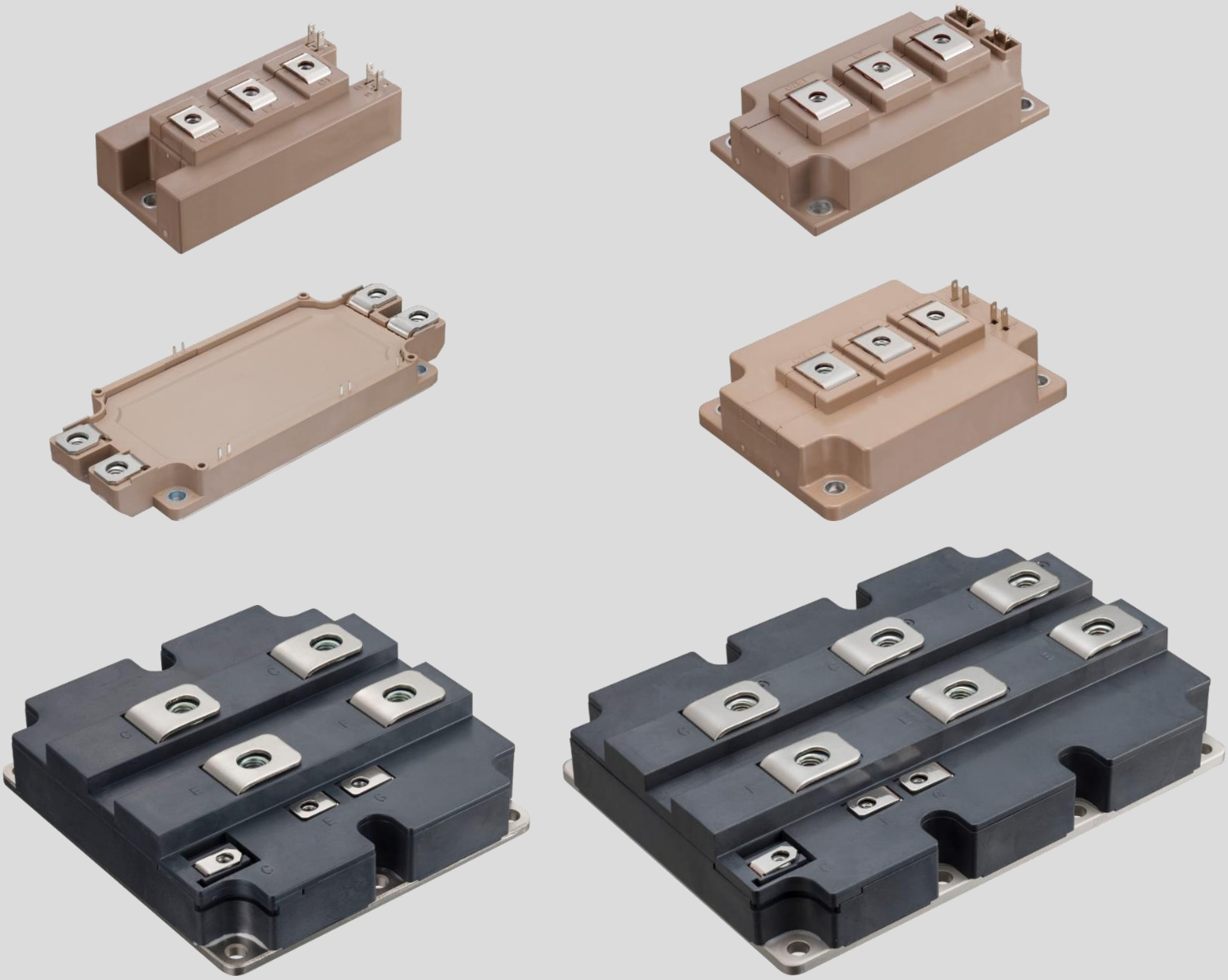
Fuji Electric
Innovating Energy Technology



Fuji SiC Hybrid Module
V series

Application Manual

Nov. 2021

Fuji Electric Co.,Ltd.

MT5F35778a

Warning:

This manual contains the product specifications, characteristics, data, materials, and structures as of Nov. 2021.
The contents are subject to change without notice for specification changes or other reasons. When using a product listed in this manual, be sure to obtain the latest specifications.

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⚠ Cautions

(1) During transportation and storage

Keep locating the shipping carton boxes to suitable side up. Otherwise, unexpected stress might affect to the boxes. For example, bend the terminal pins, deform the inner resin case, and so on.

When you throw or drop the product, it gives the product damage.
If the product is wet with water, that it may be broken or malfunctions, please subjected to sufficient measures to rain or condensation.

Temperature and humidity of an environment during transportation are described in the specification sheet. There conditions shall be kept under the specification.

(2)Assembly environment

Since this power module device is very weak against electro static discharge, the ESD countermeasure in the assembly environment shall be suitable within the specification described in specification sheet. Especially, when the conducting pad is removed from control pins, the product is most likely to get electrical damage.

(3)Operating environment

If the product had been used in the environment with acid, organic matter, and corrosive gas (hydrogen sulfide, sulfurous acid gas), the product's performance and appearance can not be ensured easily.

CONTENTS

Chapter 1 Basic Concept and Features

The improved characteristic of SiC devices relating to high temperature operation and high breakdown voltage capability compared to Si devices make them a very promising technology for achieving high efficiency and downsizing of equipment. Fuji Electric has commercialized SiC hybrid modules with rated voltages of 1200V~3300V as power devices for inverters that contributes to energy saving.

The SiC hybrid module uses Si IGBT chip for the main switching device and SiC SBD (Schottky Barrier Diode) chip for the FWD. This allows further characteristic improvements compared to conventional Si modules. This chapter explains the features of SiC hybrid modules in detail.

1. Basic Concept of SiC Hybrid Module

In order to prevent global warming, the reduction of greenhouse gases including CO_2 is required more than ever. One of the means of reduction is the energy saving of power electronics equipment. Important items to achieve this are the improvement of efficiency and the miniaturization of inverters through technological innovations such as circuit control and power device optimization.

The strong demand for power devices with low losses was solved until now with the well-known IGBT (Insulated Gate Bipolar Transistor) module, using Si (silicon) IGBT chip and FWD (Free Wheeling Diode) chip. However, the performance of Si devices is reaching the theoretical limits based on the physical characteristics. Therefore, SiC (silicon carbide) power devices which can operate under higher temperature than Si devices and providing a high breakdown voltage are promising to achieve high efficiency operation and downsizing of equipment.

On this background, the SiC hybrid modules (Si-IGBT + SiC-SBD) were developed with the basic concept of "High efficiency and miniaturization of equipment".

The basic requirements for IGBT modules are the improvement of performance and reliability as well as the reduction of environmental impact. The characteristics for performance, environmental impact and reliability are correlative and therefore it’s important to improve those characteristics in a good balance to achieve the defined target.

2. Features of SiC Hybrid Module

2.1 Product composition

Table 1 shows an overview of the SiC hybrid module series. 2in1 modules with 1200V SiC-SBD for 400VAC systems, 2in1 modules with 1700V SiC-SBD for 690VAC systems, and 1in1 modules with 3300V SiC-SBD for traction applications.

By using these SiC hybrid modules, the power dissipation can be reduced by about 25% compared to conventional Si-IGBT modules*.（* In case of 1700V/400A module、f_C=10kHz）

Table1 Series of SiC hybrid module

Application	Structure	Configuration
400VAC system	1200V SiC-SBD+ Si-IGBT	2in1
690VAC system	1700V SiC-SBD+ Si-IGBT	2in1
Traction	3300V SiC-SBD+ Si-IGBT	1in1

2.2 Characteristic improvement

2.2.1 Forward characteristic of FWD

The forward voltage characteristics of FWD for a SiC hybrid module and a Si module are shown in Fig.1-1. Fig.1-2 shows an example of temperature dependence. When the junction temperature is 125°C and the rated current is 400A, the forward voltage V_F of the SiC hybrid module is equivalent to the V_F of the Si module. The strong positive temperature coefficient of the SiC hybrid module makes current imbalance less likely to occur, even when using with multiple parallel connection.

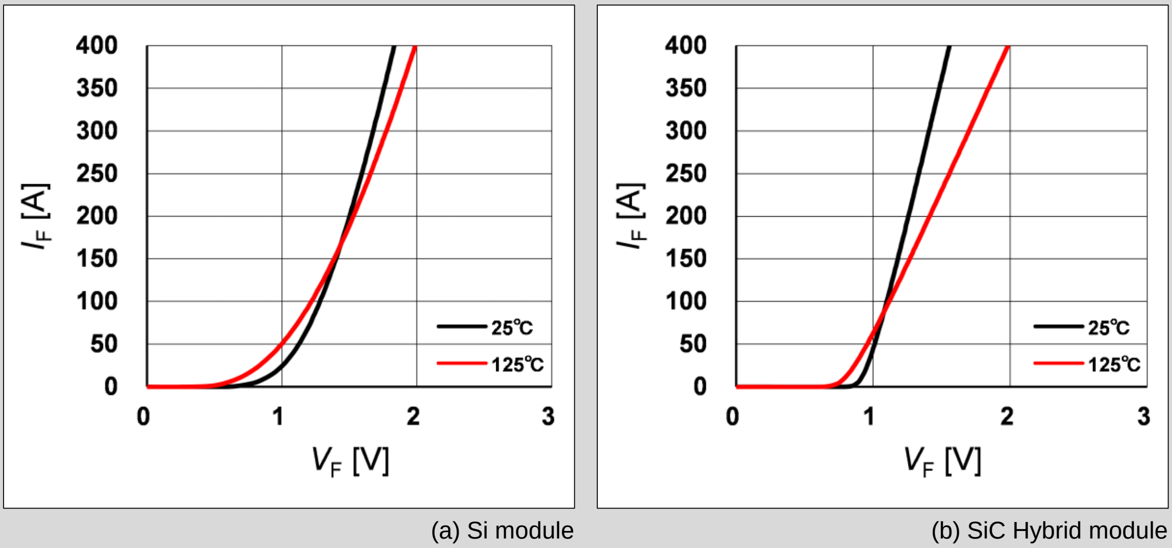


Fig.1-1 Forward characteristic of FWD (1700V/400A)

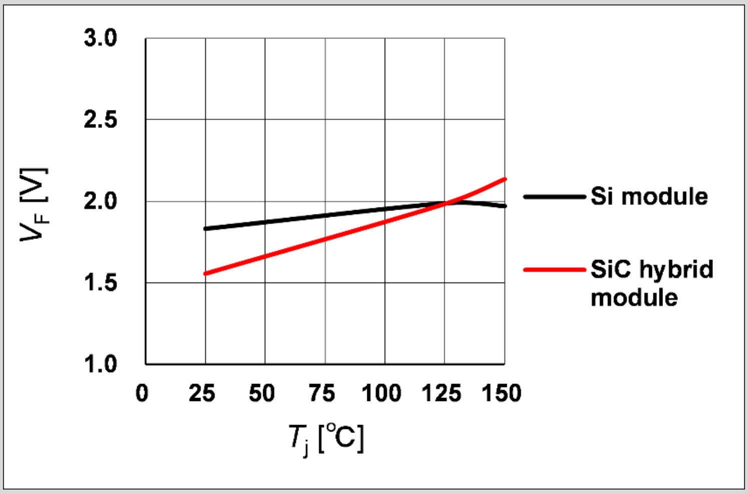


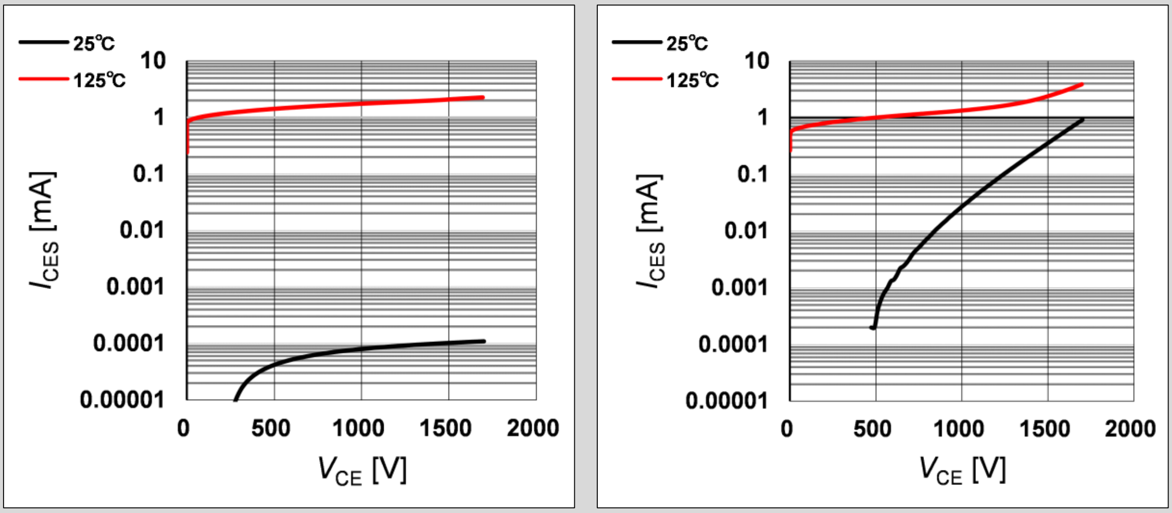
Fig.1-2 Temperature dependency of FWD (1700V/400A)

Note) SiC-SBD has a strong positive temperature characteristic in which V_F rises as the temperature rises, and is also characterized by high V_F at high currents. When applying to a circuit with an inrush current, carefully consider the generated loss and temperature rise.

2.2.2 Leakage current characteristic

Leakage current characteristics for a SiC hybrid module and a Si module are shown in Fig.1-3. Leakage current I_{CES} at rated voltage of SiC hybrid module at 25°C is several thousand times larger than the I_{CES} of Si module, but it drops to about two times the value of Si module at 125°C. The temperature dependence of leakage current of SiC-SBD is smaller compared to a Si-FWD. Therefore, SiC hybrid modules can operate at high temperatures similar to Si modules. One major reason for this behavior is the band gap of SiC which is about three times wider than the one of Si. The temperature dependence of leakage current of SiC-SBD is smaller compared to a Si-FWD. Therefore, SiC hybrid modules can operate at high temperatures similar to a Si module. This is because the band gap of SiC is about three times wider than that of Si, and SiC-SBD operates at a higher electric field than Si-FWD. Therefore, the leakage current of SiC-SBD is dominated by the tunnel current of the SiC-SBD and is less susceptible to temperature.

The Si-PN diodes used in Si modules and the SiC-SBDs used in SiC hybrid modules have different leakage current mechanisms, and therefore, there are significant differences in temperature and voltage dependence. It is recommended to fully consider the loss generated by the leakage current and the temperature rise, especially in the case of application where high temperature and high voltage are continuously applied.



(a) Si module (V series) (b) SiC Hybrid module (V series)

Fig.1-3 Temperature dependence of leakage current (1700V/400A)

2.2.3 Switching characteristic

(1)Reverse recovery characteristic

There is no accumulated charge during the on period, and very fast reverse recovery operation can be expected.

(2)Turn-on loss characteristic

Turn-on loss characteristic of SiC hybrid module and Si module are shown in Fig.1-4. The capacitive charging current of the SiC-SBD affects the IGBT turn-on current in the opposite arm side, leading to a reduction in turn-on loss. The turn-on loss of the 1700V/400A hybrid module is about 40% lower than that of Si device.

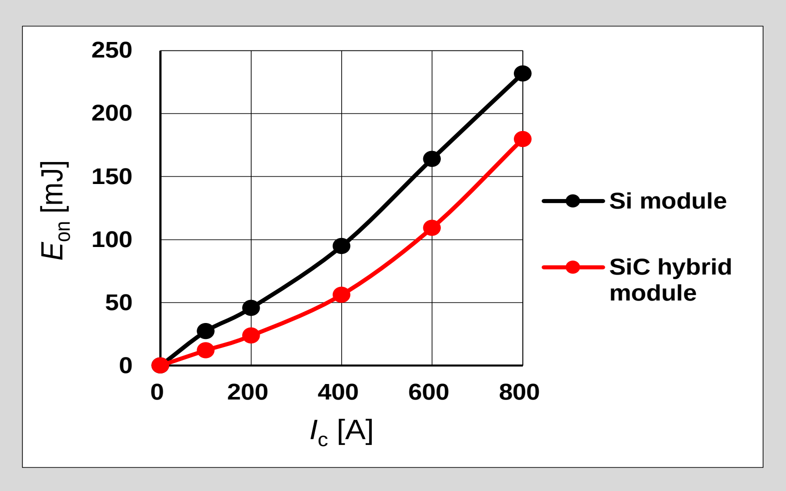


Fig.1-4 Turn-on loss characteristic (1700V/400A)

(3) Turn-off loss characteristic

Turn-off loss characteristic for SiC hybrid module and Si module are shown in Fig.1-5. The peak value of surge voltage during turn-off of SiC Hybrid module is expressed by equation (1). If the device characteristics of the IGBT and the inductance of the main circuit are equal, the difference of transient on voltage of the diode becomes the difference in surge voltage. SiC-SBD has a lower transient on voltage in comparison to Si-PN diode because of the lower drift layer resistance. Therefore, the surge voltage at turn-off is suppressed, leading to a reduction in turn-off loss.

$$V_{\mathrm{SP}} = V_{\mathrm{CC}} + L_{\mathrm{S}} \frac{dI_c}{dt} + V_{\mathrm{FR}} \quad \cdots\cdots (1)$$

V_{SP} : Surge peak voltage, V_{CC} : Applied voltage, L_S : Main circuit inductance
I_C : Collector current, V_{FR} : Transient on voltage

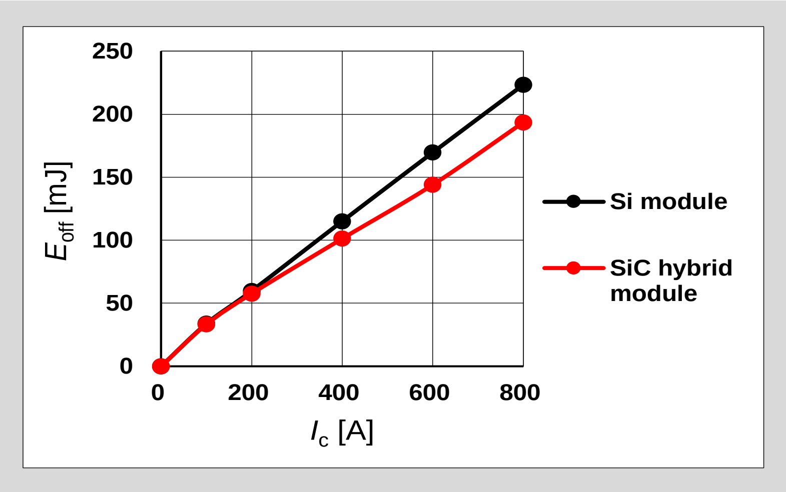


Fig.1-5 Turn-off loss characteristic (1700V/400A)

3. Switching Time Definition of SiC Hybrid Module

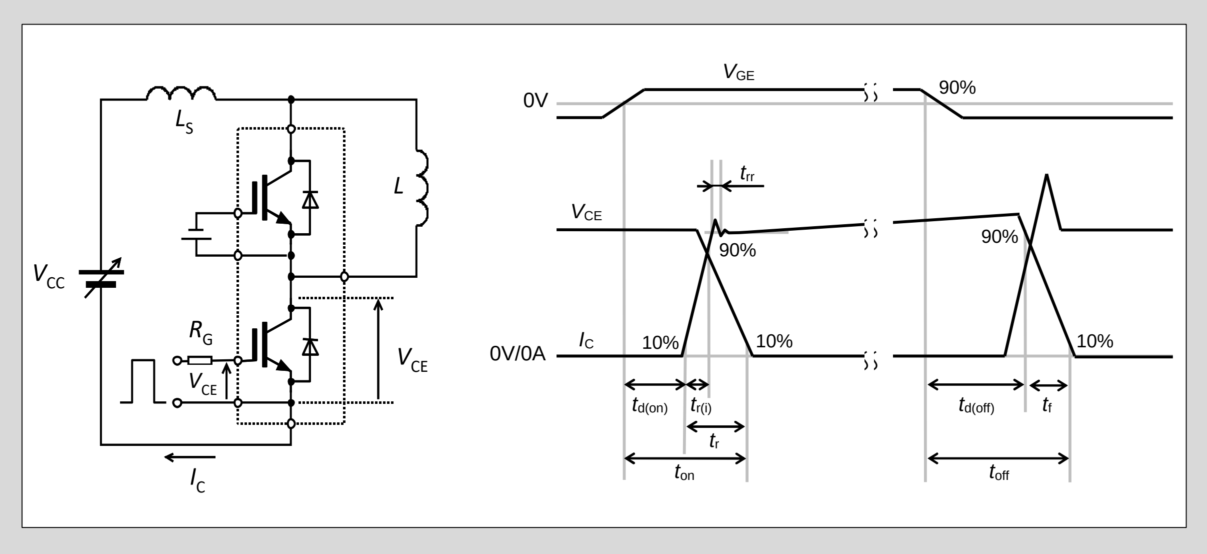


Fig.1-6 Switching definition of SiC hybrid module

Chapter 2 Precautions for Use

1. Maximum Junction Temperature

The maximum junction temperature $T_{vj(max)}$ is 150°C for all modules of Fuji's 5th generation (U,U4 series). For the 6th generation (V series), it is increased by 25°C to 175°C.

Taking into account of design margin the U and U4 series can be used at a continuous operating temperature $T_{vj(op)}$ of around 125°C. For the V series, continuous operation temperature of $T_{vj(op)}$=150°C is guaranteed. This value is based on the verification tests conducted according to the JEITA standards.

This increase in $T_{vj(op)}$ contributes to downsizing of applicable module and heat sink, improvement of output current and carrier frequency and expansion of the applicable range of inverter.

On the other hand, if the product is used above the maximum continuous operation temperature of 150°C, the power cycle capability may degrade and will lead to a reduced product lifetime.

2. Short Circuit (Overcurrent) Protection

In the event of a short circuit, first the IGBT's collector current I_C will increase. Once it has reached a certain level, the collector-emitter voltage V_{CE} will increase suddenly. Depending on the device's characteristics, during the short circuit, the I_C can be kept at or below a certain level. However the IGBT will continue to be subjected to a heavy load of high voltage and high current. Therefore, this condition must be removed as soon as possible.

Fig. 2-1 shows the correlation between the short circuit capability (guaranteed short circuit withstand time) and the applied voltage at the time of short circuit occurrence for the 1700V SiC hybrid module.

Set the short circuit detection time by referring to this graph as well as the operating conditions of the application.

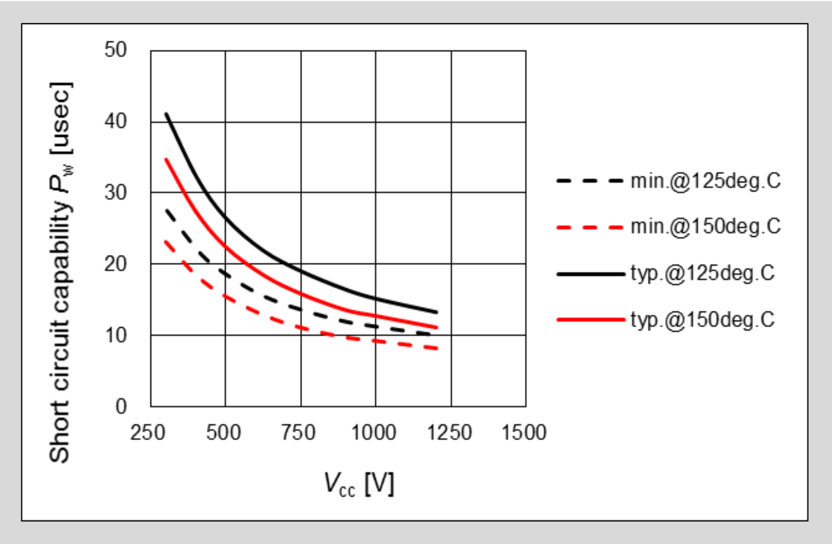


Fig.2-1 Relation between Short Circuit Capability and Applied Voltage when Short Circuit Occurs in 1700V SiC hybrid module

3. Overvoltage Protection and Safe Operating Area

3.1 Overvoltage protection

Due to the fast switching speed of IGBT, high d*i*/d*t* is generated during the IGBT turn-off and the IGBT turn-on / FWD reverse recovery. This high d*i*/d*t* causes a high surge voltage due to the external wiring stray inductance. If the surge voltage exceeds the module's maximum rated voltage (V_{CES}), it can lead to the destruction of the module. There are several methods to suppress this overvoltage such as adding a snubber circuit, adjusting the gate resistance R_G, or reducing the inductance of the main circuit.

To show the correlation between the surge voltage and the related parameters, an example of surge voltage characteristics for the SiC hybrid module 2MSI400VAE-170-53 is shown.

Fig.2-2 shows an example of the dependency between the stray inductance and the surge voltage at turn-off. As shown in the graph, the surge voltage increases as the stray inductance increases. It can be seen that the effect on the turn-off surge voltage is particularly large.

Fig.2-3 shows an example of the dependency between the collector voltage and the surge voltage at IGBT turn off. The surge voltage becomes higher when the collector voltage increases.

Fig.2-4 shows an example of the dependency between the collector current and the surge voltage at IGBT turn off. The surge voltage at IGBT turn off will be higher when the collector current is larger.

As described above, the value of the surge voltage generated in IGBT modules varies greatly depending on the main circuit stray inductance. Besides this, external circuit conditions such as snubber circuits, capacitor values and gate drive conditions also have an influence on the surge voltage.

When using IGBT modules, please make sure that the surge voltage is within the Reverse Bias Safety Operating Area (RBSOA) under all operating conditions. If the surge voltage exceeds the RBSOA, please take countermeasures such as changing the gate resistance, reducing the stray inductance or adding a snubber circuit.

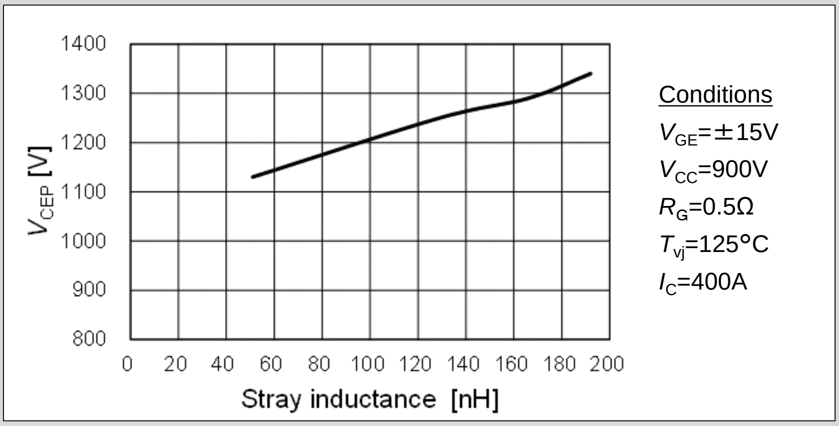


Fig.2-2 Example of Stray Inductance Dependence of Surge Voltage at IGBT Turn-Off

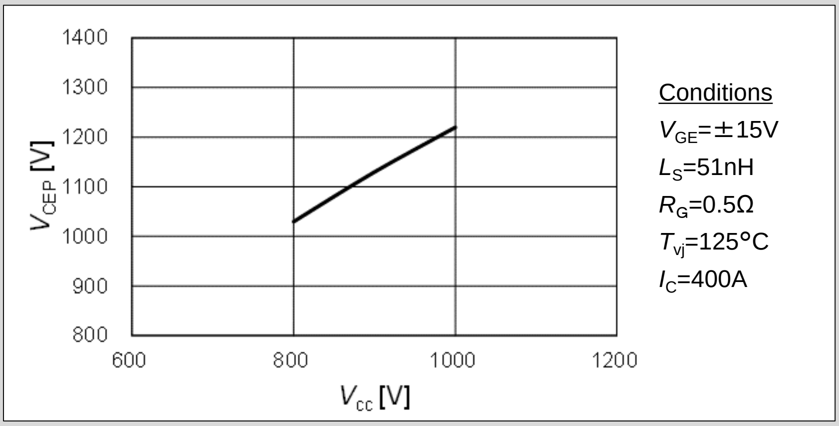


Fig.2-3 Example of Collector Voltage Dependence of Surge Voltage at IGBT Turn-Off

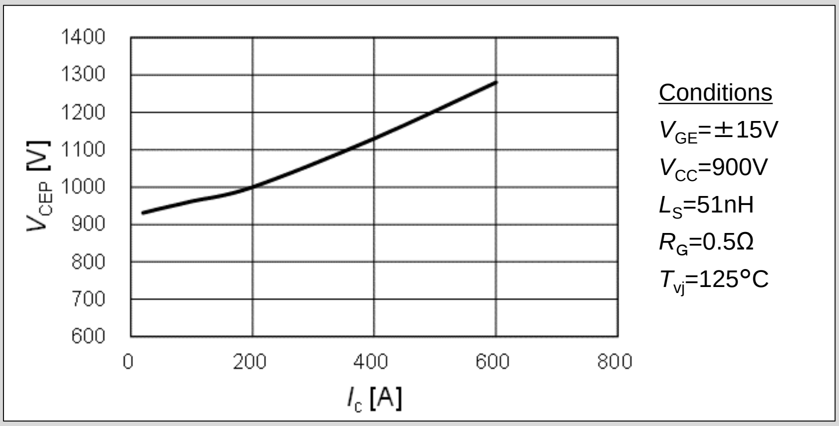


Fig.2-4 Example of Current Dependence of Surge Voltage at IGBT Turn-Off

3.2 Gate resistance influence on surge voltage during turn-off

In order to properly design the overvoltage protection, Fig.2-5 shows the relation between the gate resistance R_G value and the turn-off surge voltage V_{CEP} for SiC hybrid module.

Generally, in order to suppress the surge voltage increasing the R_G value has been a suitable countermeasure. However, since the carrier injection efficiency has been improved starting with the 5th generation (U series), the relation between R_G value and the surge voltage has also changed. Therefore, increasing R_G value may now cause the surge voltage V_{CEP} to increase, unlike the older generation products.

Therefore, please select the R_G value carefully during the design phase to match the requirements and parameters of the actual equipment where the IGBT module is used.

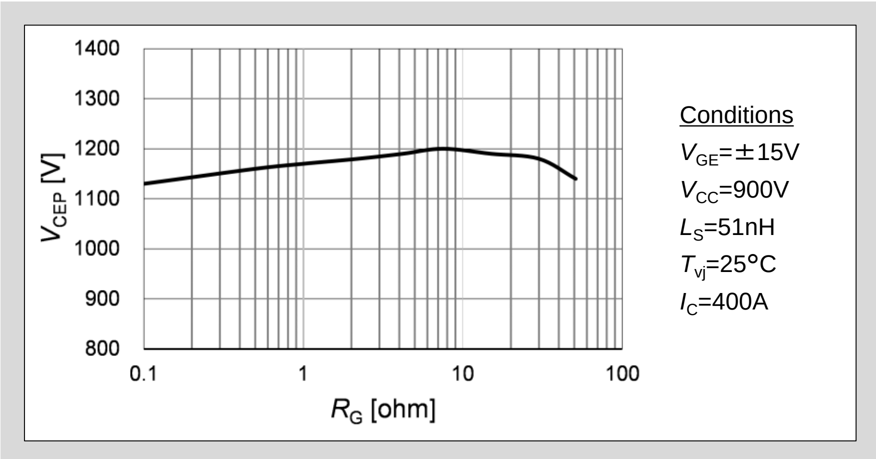


Fig.2-5 Example of Gate Resistance Dependence of Surge Voltage at IGBT Turn-off

Reference

1) Y. Onozawa et al., “Investigation of carrier streaming effect for the low spike fast IGBT turn-off”, Proc. ISPSD, pp173-176, 2006.

3.3 Overvoltage protection during short circuit current cut off

When a short circuit occurs, the collector current I_C increases sharply. In this case a larger I_C has to be cut off compared to a normal turn-off operation. Thus, an additional SCSOA (Short Circuit Safety Operating Area) for non-repetitive pulse is defined for the short circuit condition.

Fig.2-6 shows the SCSOA and RBSOA for SiC hybrid module (1700V). For turn-off operation at short circuit cut off, keep the operation trajectory of V_{CE}-I_C within the SCSOA. Note that SCSOA is defined as non-repetitive whereas RBSOA is defined as repetitive.

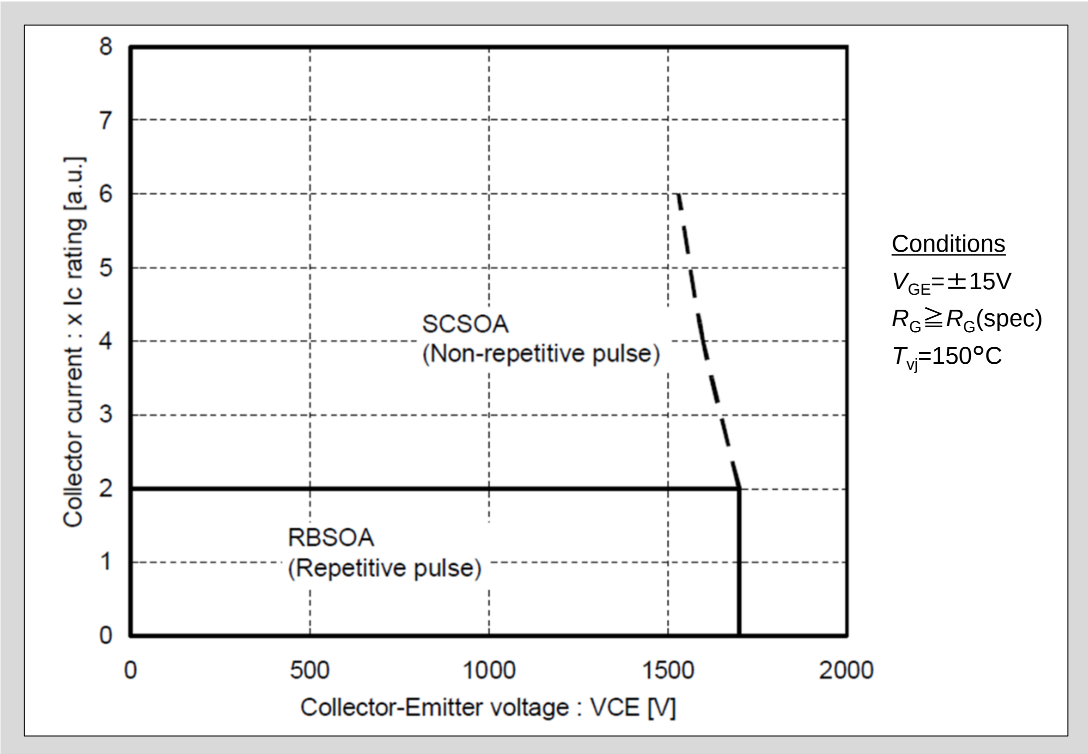


Fig.2-6 RBSOA and SCSOA (1700V)

4. R_G Selection

Standard gate resistance R_G is indicated in the specification sheet.

Regarding the turn-on R_G, the standard resistance value described in the specification sheet is recommended, but it is necessary to confirm that the radiation noise stays within the allowable range.

Regarding the turn-off R_G, as shown in Fig.2-7, increasing the R_G may cause the surge voltage to increase, so it's necessary to confirm that the surge voltage in the actual equipment is within the allowable range.

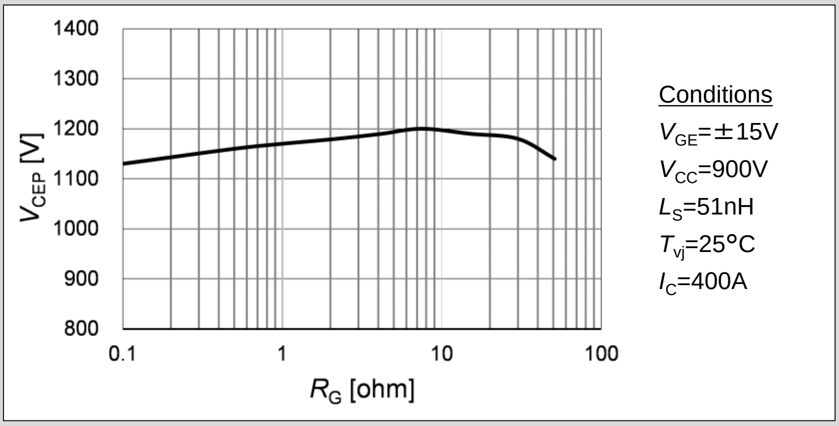


Fig.2-7 Example of Gate Resistance Dependence of Surge Voltage at IGBT Turn-off

Reference

1) Y. Onozawa et al., "Investigation of carrier streaming effect for the low spike fast IGBT turn-off", Proc. ISPSD, pp173-176, 2006.

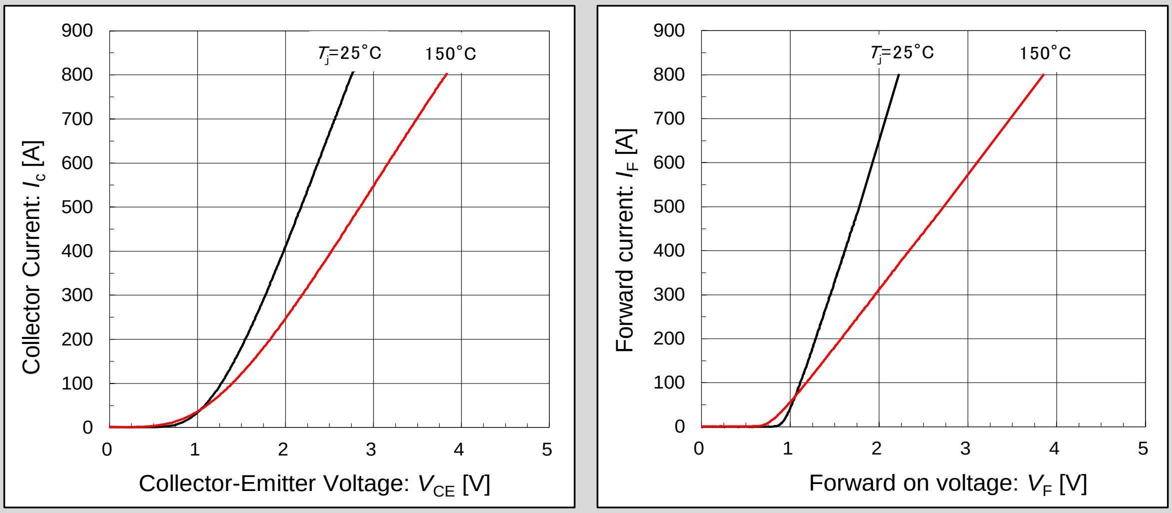
5. Parallel Connection

When using IGBT modules, they may be connected in parallel to handle larger output current. This section describes the precautions for parallel connection of the SiC hybrid modules.

5.1 Junction temperature dependence of output characteristics and current imbalance

The junction temperature dependence of the output characteristics has a big influence to the current imbalance. Typical output characteristics of a 1700V/400A rated module are shown in Fig.2-8. The temperature dependence of the V-IGBT and SiC-SBD used in the hybrid module is positive. Therefore, the collector current decreases while the junction temperature increases. This will automatically improve the current imbalance.

Therefore, all chips mounted in the hybrid modules have characteristics that are suitable for parallel operation.



(a) Output characteristics of IGBT (b) Output characteristics of SiC-SBD

Fig.2-8 Junction temperature dependence of output characteristics（1700V/400A）

5.2 $V_{CE(sat)}/V_F$ variation and current imbalance ratio

The ratio of current sharing, which occurs at parallel connection of SiC hybrid modules, is called current imbalance ratio. This is determined by the variation in $V_{CE(sat)}/V_F$ and the junction temperature dependence of these characteristics.

Fig.2-9 shows the relation between typical variation of $V_{CE(sat)}/V_F$ and current imbalance ratio. This figure shows the current imbalance ratio for two parallel connected modules of V series IGBT and SiC - SBD. As shown in the figure, it can be seen that the current imbalance ratio increases as the variation of $V_{CE(sat)}/V_F$ increases. Therefore, when connecting in parallel, it is important to combine products with small $V_{CE(sat)}/V_F$ difference ($\Delta V_{CE(sat)}/\Delta V_F$).

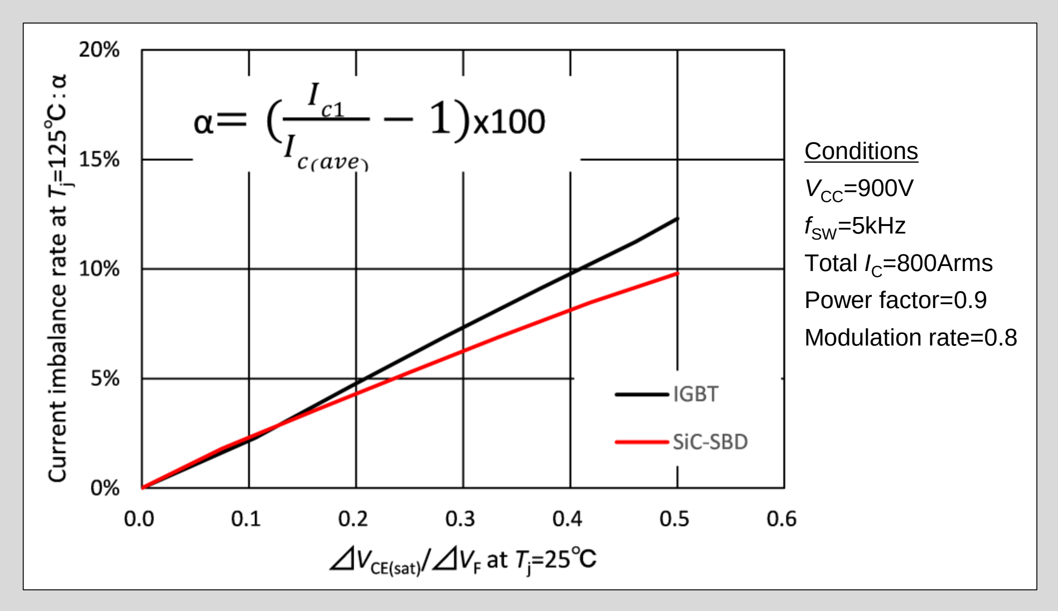
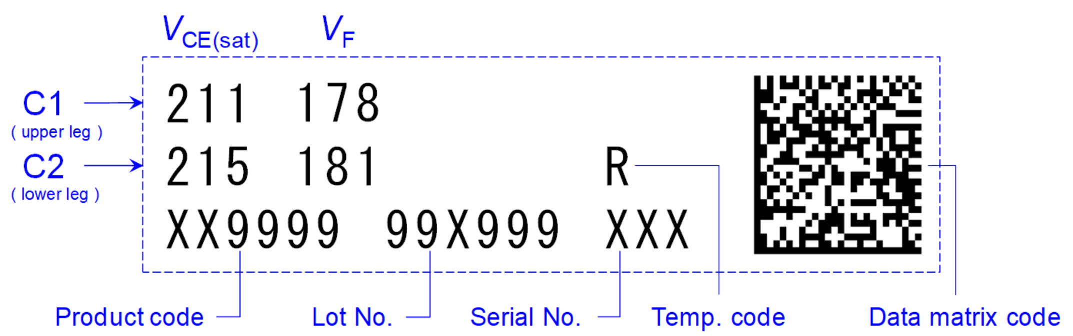


Fig.2-9 Variation and current imbalance ratio of $V_{CE(sat)}/V_F$(1700V/400A)

■ **Supplement: regarding label notation of module characteristic data**

The module's $V_{CE(sat)}$ and V_F values are mentioned on the label. Good current balance can be obtained by combining the same or close V_F rank and $V_{CE(sat)}$ rank. Fig.2-10 shows an example of label notation.

Notation contents :
- $V_{CE(sat)}$, V_F values (ex. '211' = 2.105 ~ 2.114 V)
- Temperature code : R
- Product code
- Lot No.
- Serial No.
- Data matrix code



Characteristics indication

Product code	comma	Lot No.	comma	Serial No.	comma	$V_{CE(sat)}$(C1) upper leg	comma	V_F(C1) upper leg	comma	$V_{CE(sat)}$(C2) lower leg	comma	V_F(C2) lower leg	comma	Temp. code*
	,		,		,		,		,		,		,	
6digits		5 or 6digits		3digits		3digits		3digits		3digits		3digits		1digit

*Room temp.=R
*High temp.=H

Data matrix code contents

Fig.2-10 Notation example of characteristic data

5.3 Current imbalance during switching

5.3.1 Main circuit wiring inductance variation

Inhomogeneous main circuit wiring inductance cause an imbalanced current sharing of parallel connected modules.

Fig.2-11 shows the equivalent circuit at parallel connection in consideration with the main circuit wiring inductance. If I_{C1} and I_{C2} flow through IGBT1 and IGBT2 respectively, the current sharing is approximately decided by the ratio of main circuit wiring inductance, $L_{C1}+L_{E1}$ and $L_{C2}+L_{E2}$. So, the main circuit wiring need to be designed as equally as possible in order to reduce current imbalance during switching. However, even if ideal wiring inductance of $(L_{C1}+L_{E1}) = (L_{C2}+L_{E2})$ is realized, a difference between L_{E1} and L_{E2} can cause current imbalance which is described below.

Inhomogeneous inductance of L_{E1} and L_{E2} will cause different induced voltage to generate even if with the same d*i*/d*t*. This difference in induced voltage affect the gate emitter voltages and will cause current imbalance. This imbalance will increase the total collector current imbalance.

Therefore, it is extremely important to ensure the symmetry of the wiring structure for the collector and emitter side separately: $L_{C1} = L_{C2}$, $L_{E1} = L_{E2}$.

Another point is to keep the inductance of the main circuit as low as possible because of the direct correlation between inductance and surge voltage during turn-off. Place the paralleled modules as close together as possible and design the wiring as uniform as possible.

If the IGBT module has an auxiliary emitter, it is recommended to drive the gate with this emitter terminal in order to reduce the influence of the main circuit inductance.

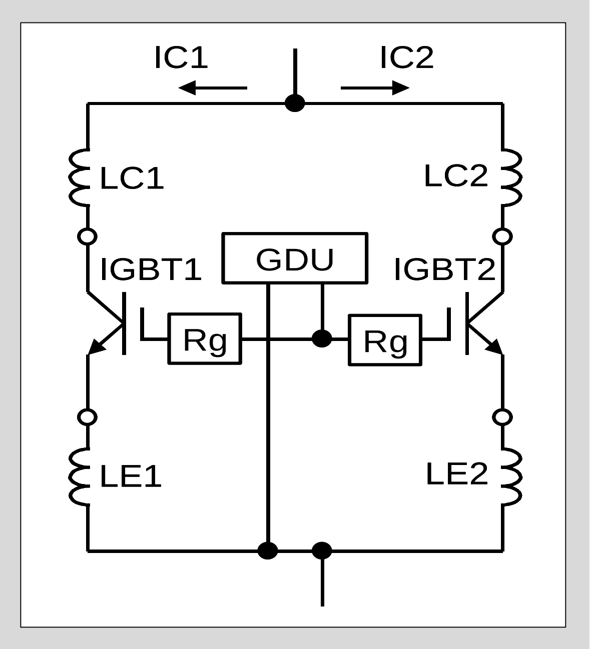


Fig.2-11 Equivalent circuit at parallel connection in consideration with main circuit wiring inductance

5.3.2 Gate drive circuit

In the case of using separated gate driving units (GDU) for each IGBT, there is concern that the switching timing may vary due to variations such as the delay time of the circuit. Therefore, it is recommended that all the paralleled modules are driven by just one GDU. By using this setup, it is possible to reduce the variation in switching time caused by the gate drive circuit. However, if the modules in parallel are operated by the same driving circuit, there are concerns such as switching speed is lowered due to insufficient drive capability. This may make the gate control impossible. Therefore, please select the driver capability accordingly.

Also, when using a single gate drive circuit, parasitic oscillation may occur during rise of the gate voltage depending on the wiring inductance and the IGBT input capacitance. Therefore, the gate resistances of each IGBT should connected individually to the respective gates (please refer to Fig.2-12). Also an additional emitter line resistor can help to suppress this oscillation. Keep in mind that the voltage drop caused by these resistors may cause a device malfunction.

When the emitter wiring of the gate drive circuit is connected to different positions in the main circuit wiring, L_{E1} and L_{E2} become unbalanced as shown in Fig. 2-11. This leads to an unbalanced transient current sharing. Normally, IGBT modules have an auxiliary emitter terminal for the gate drive circuit, and the internal drive wiring is even. Therefore, by using this auxiliary terminal to drive the gate, transient current imbalance inside the module can be suppressed. It is recommended to drive the IGBT with the auxiliary terminal.

However, even if the gates are driven by using the auxiliary emitter terminals, if the emitter wiring from the gate drive circuit to each module is long and non-uniform, it will cause current imbalance.. Therefore, please make sure that the wiring of the gate drive circuit to each module connected in parallel is the shortest possible with equal length. We recommend to use tightly twisted wires for the gate drive circuit and keep them as far away from the main circuit wiring as possible. This will reduce the possibility of mutual induction (especially by the collector current).

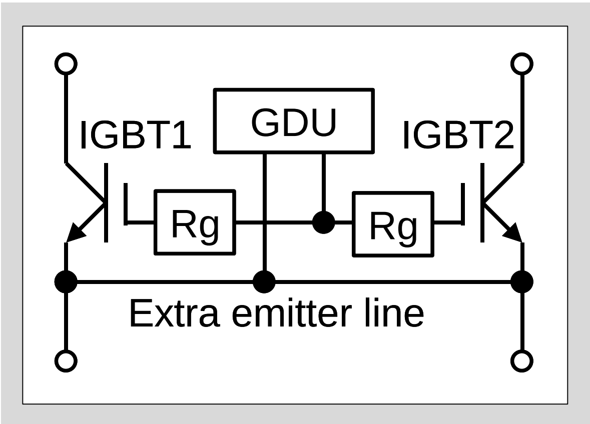


Fig.2-12 Wiring gate drive unit

6. EMI

Fig.2-13 shows the radiation noise comparison of a 1700V SiC hybrid module with a conventional Si module.

While the collector current decreases, the radiation noise increases for the conventional Si module, whereas it decreases for the SiC hybrid module. In the region below 300A, the peak value of the radiation noise of the SiC hybrid module is equivalent to that of the conventional Si module.

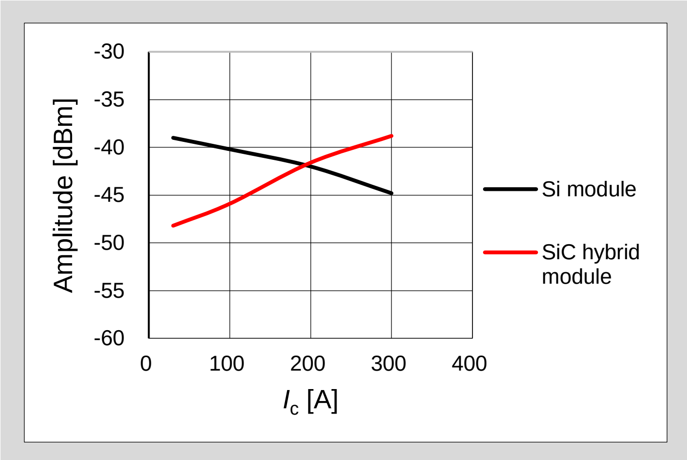


Fig.2-13 Collector current dependence of radiation noise

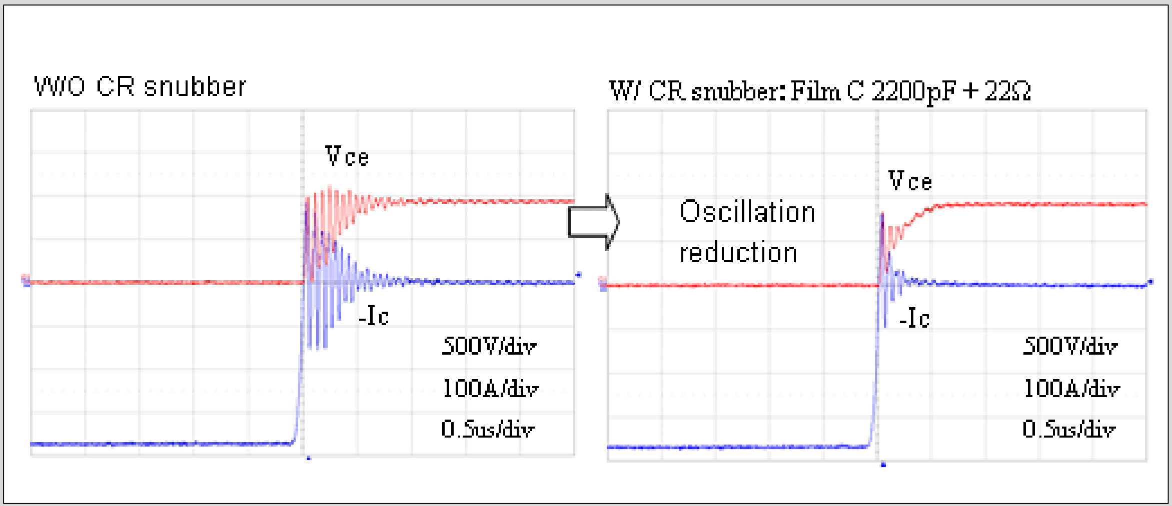
Reference

2) H. Wang, et al., “1700V Si-IGBT and SiC-SBD Hybrid Module for AC690V Inverter system”, International Power Electronics Conference (IPEC-Hiroshima 2014-ECCE=ASIA), pp.3702-3706

7. Method of Suppressing Waveform Oscillation

Fig.2-14 shows an example of the turn-off waveform of the SiC-SBD.

The waveform oscillation can be suppressed by adding a CR snubber between the collector and the emitter of the hybrid module.



(a) without CR snubber (b) with CR snubber

Fig.2-14 Suppression of waveform oscillation by CR snubber circuit

※Patent pending