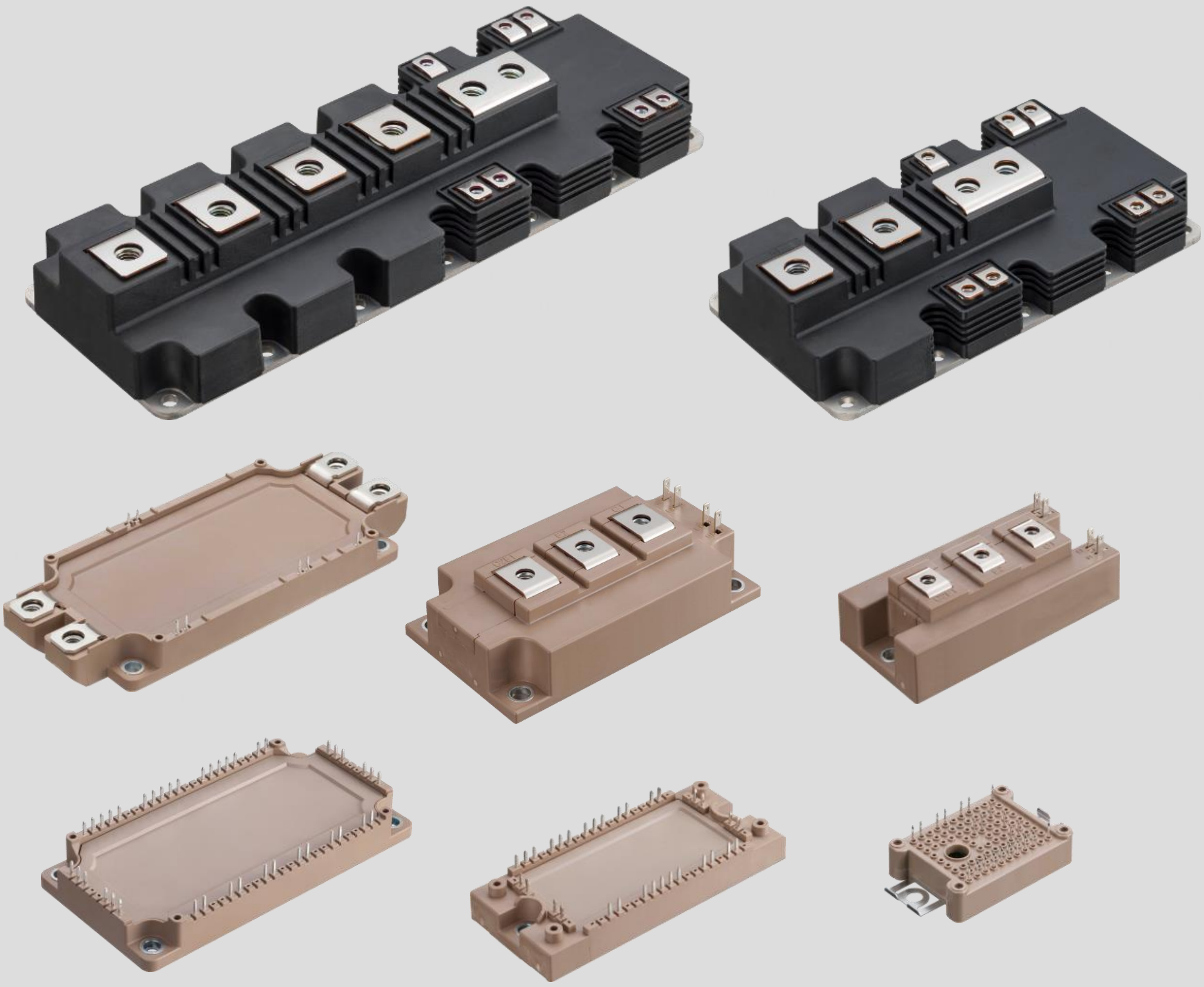

Fuji IGBT Module

Application Manual

March, 2023

Fuji Electric Co.,Ltd.

⚠ Cautions

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Chapter 10 EMC Design of IGBT Module

This chapter describes the EMC design guidelines for IGBT modules.

1. General Information of EMC in Power Electronics Equipment

Recently, EMC countermeasures coping with European CE Marking and Japanese VCCI (Voluntary Control Council for Interference by Information Technology Equipment) standards are essential in designing power electronics equipment such as PDS (Power Drive System) and UPS (Uninterruptible Power Supply) using IGBT modules.

EMC stands for Electro Magnetic Compatibility, which is classified into EMI (Electro Magnetic Interference) and EMS (Electro Magnetic Susceptibility). EMI is the adverse effects that electronic devices have on peripheral equipment, and it is also called Emission. There are two kinds of EMI, one is conducted emission that leaks to power line and the other is radiated emission that radiated as electromagnetic wave. EMS is the immunity performance of electronics equipment against disturbance, such as electromagnetic wave, voltage sag, electrostatic discharge, EFT/burst and lightning surge from the surrounding and it is also called Immunity. This can be simplified as shown in Fig.10-1.

Since IGBT modules are capable of high-speed switching of several hundreds of volts and amps in 500ns or less, reducing both conducted emission and radiated emission is important when designing power electronics equipment.

In this chapter, effects of IGBT modules switching, which is likely to cause troubles to other equipment (EMI characteristics), and the countermeasures are introduced.

- **EMC**
  - **EMI**
    - **Conducted emission**
    - **Radiated emission**
  - **EMS**
    - **Electromagnetic wave**
    - **Instantaneous voltage drop/voltage sag**
    - **Electrostatic Discharge(ESD)**
    - **EFT/Burst**
    - **Lightning surge**

Fig. 10-1 Classification of EMC

1.1 EMI performance

IGBT modules are used in a wide range of application field and power including home appliances such as air conditioners and refrigerators, automobiles and traction system, as well as industrial. Here, we introduce the EMI standards for variable speed drives such as general-purpose inverters, which is one of the main application of IGBT modules.

(1) Conducted emission (noise terminal voltage)

In IEC61800-3, the limits (QP (Quasi-Peak) values) of conducted emission for PDS is shown in Fig. 10-2.

The limits in the standard are classified into Category C1, applied for equipment used in commercial area, and Category C2 and C3, applied for equipment used in industrial area. Industrial PDS are designed to meet Category C3 limits.

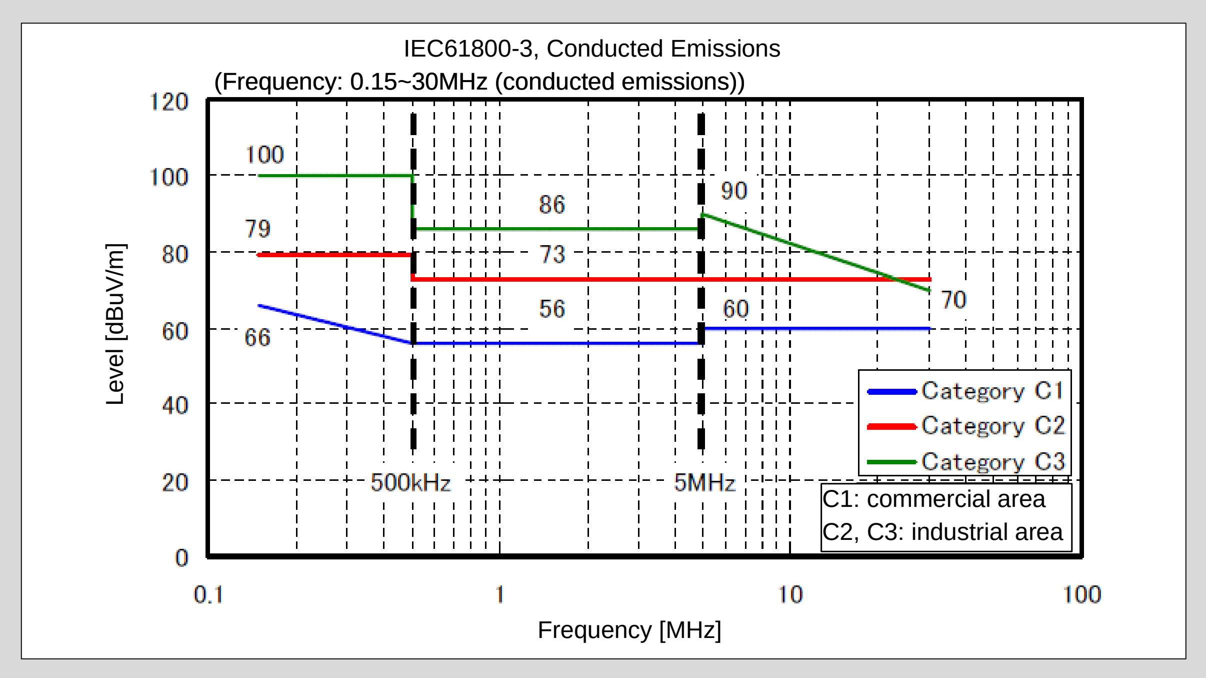


Fig. 10-2 Limits of conducted emissions in IEC61800-3

(2) Radiated emission

Fig. 10-3 shows the limits of radiated emission (radiated noise) for each category.

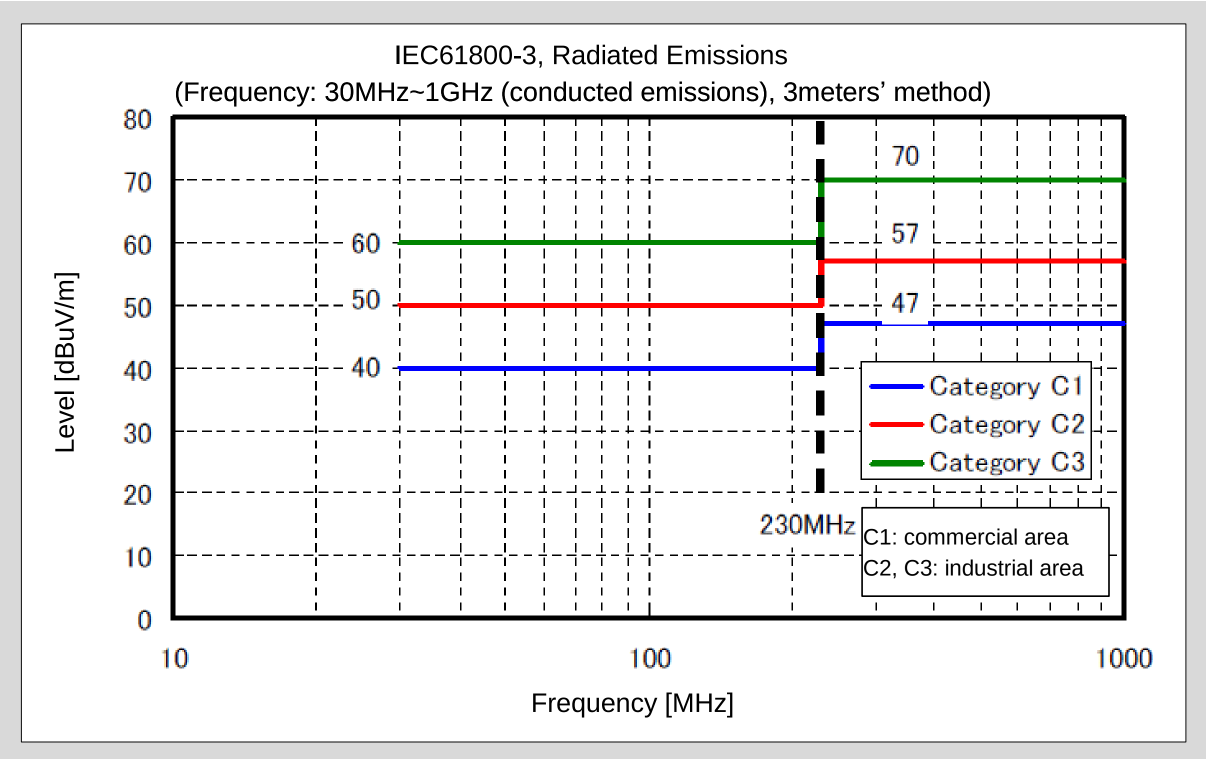


Fig. 10-3 Limits of radiated emissions in IEC61800-3

The category classification is defined as shown in Fig. 10-4.

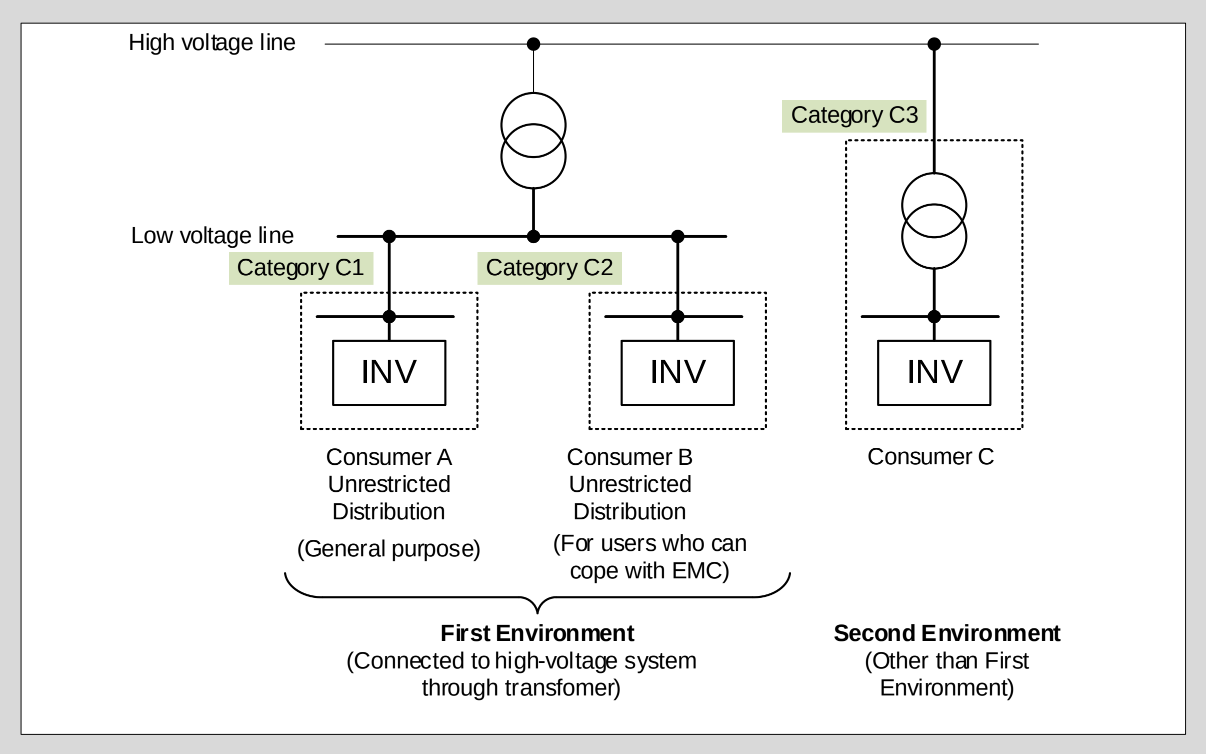


Fig. 10-4 Category classification in IEC61800-3

2. EMI Countermeasure Design for Inverters

2.1 Common mode and normal mode noise

The propagation path of conducted emission is mainly classified into two types, normal mode and common mode.

The normal mode noise is generated by high d*v*/d*t* and d*i*/d*t* due to switching of IGBT, and appears at AC input and output terminals. The path of the normal mode noise is shown in Fig. 10-5.

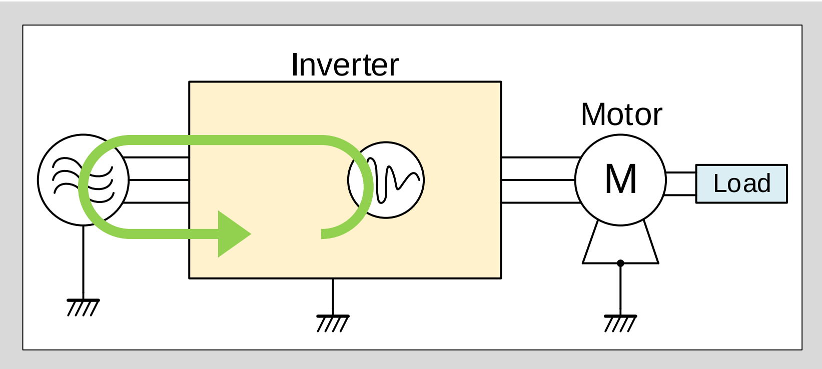


Fig. 10-5 Path of normal mode noise

On the other hand, the common mode noise is generated by potential fluctuation against ground caused by switching, which charge and discharge stray capacitance that exists between the main circuit and ground and in the transformers. Noise current is propagated through the ground line. The path of common mode noise is shown in Fig. 10-6.

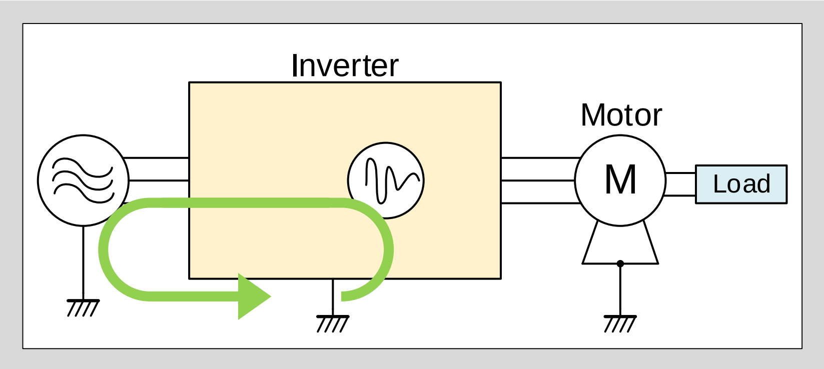


Fig. 10-6 Path of common mode noise

In actual equipment, there is impedance imbalance in the wiring of each phase (e.g. R/S/T phases), thus normal mode noise may be converted to common mode noise via the ground line (Fig. 10-7), or vice versa. Therefore, it is very difficult to separate the noise through the normal mode path and the noise through the common mode path in actual noise spectrum. As a general precaution, it is necessary to prevent unbalanced wiring of each phase as much as possible.

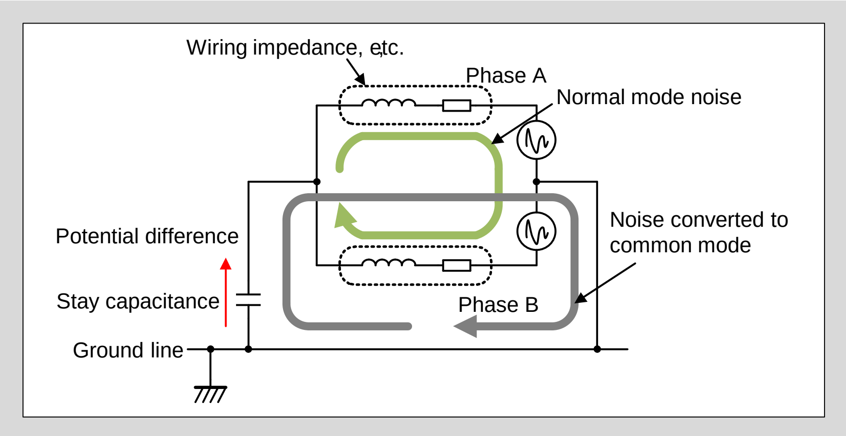
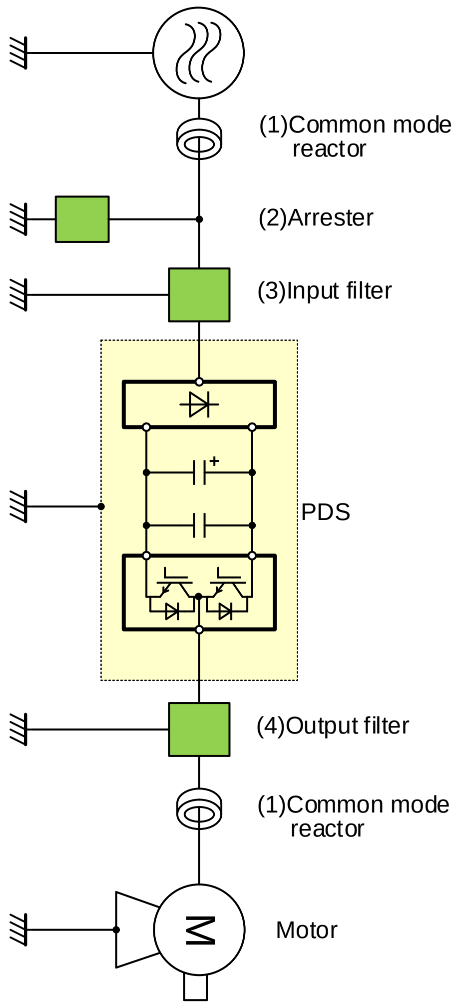


Fig. 10-7 Conversion from normal mode noise to common mode noise

2.2 Countermeasures against EMI noise in PDS

Fig. 10-8 shows example of countermeasures against noise in PDS. It is possible to suppress noise (mainly harmonic current and conducted emission) generated by the PDS by inserting countermeasure components such as commercial noise filters and reactors.



The effect of each components are as follows.

(1) Common mode reactor
This is a reactor of the common mode to be inserted into the input/output line. It is effective in suppressing noise up to the several MHz band.

(2) Surge protective device (Arrester)
This is installed to protect the PDS from induced common mode and normal mode lightning that flows from the input power line.

(3) Input filter
Composed of L, C, and R, it suppresses noise flowing out to the input power line.
Various products with different noise attenuation characteristics are available in the market, thus proper selection should be made in accordance with the specification and purpose.
Since attenuation effect may be inferior depending on the installation method, proper wiring and installation in accordance with the instruction manual is required.

(4) Output filter
This is used to suppress surge voltage applied to the motor and to suppress induced noise in the output cable.

Fig. 10-8 Noise countermeasures for PDS

Such filters installed outside the PDS as described above are generally effective in suppressing noise in the 100kHz to several MHz band, but may be less or not effective for higher bands (conducted emissions above 10MHz and radiated emissions above 30MHz). This is because there are limits to the frequency characteristics of filters, thus in order to effectively suppress noise over a wide range of frequency, it is necessary to install optimum filters for each frequency band.

One of the causes of noise around 10MHz to 50MHz is thought to be due to the resonance associated with switching caused by the inductance and stray capacitance around the IGBT modules inside the PDS.

The following section describes the mechanism of noise generation around the IGBTs and the countermeasures.

2.3 Mechanism of noise generation attributable to IGBT module characteristics

Fig. 10-9 shows the block diagram of a typical PDS. AC power source is rectified into DC by rectifier diodes, and then reversely converted into AC by high frequency switching of the IGBT in the inverter portion, thereby achieving variable speed driving of the motor. The IGBT modules and rectifier diodes are mounted on a heat sink, and in some cases this heat sink is a part of the PDS body, thus it is normally grounded for safety reasons.

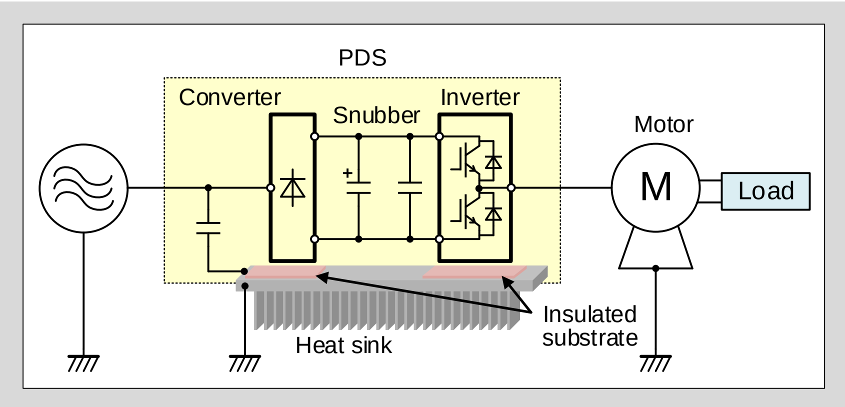


Fig. 10-9 Example of power drive system

In this system , the metal base of IGBT module mounted on a heat sink and the electric circuit side such as IGBT chip are insulated by an insulating substrate with high thermal conductivity (for the detailed structure of the module interior, refer to Chapter 1). In addition, a snubber capacitor is connected to the inverter circuit to suppress surge voltage.

In particular, stray capacitance and stray inductance that exist in IGBT modules and electrical components can have a large impact in high frequency bands of MHz order, such as radiated and conducted emission. Fig. 10-10 shows a schematic diagram of a PDS in the high frequency band of hundreds of kHz to tens of MHz. There is stray inductance of tens to hundreds nH on the wiring around the IGBT module, and stray capacitance of hundreds pF exists on the insulating substrate. Also, junction capacitance exists at the PN junction of the IGBT itself.

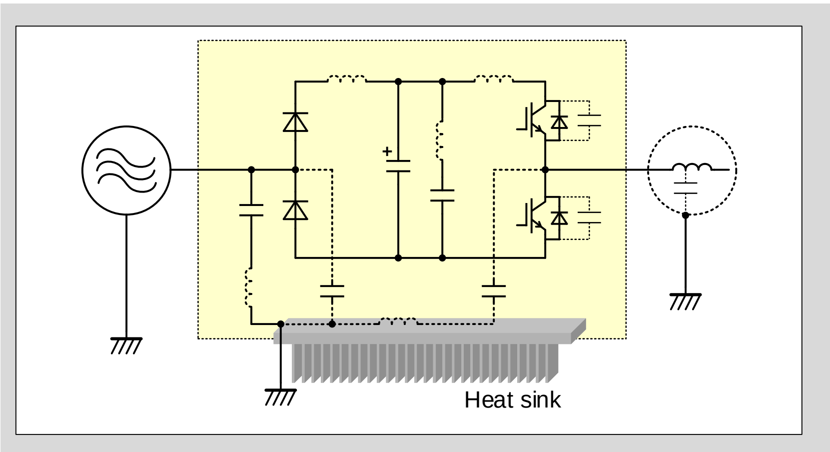


Fig. 10-10 Equivalent circuit considering stray L and C

For example, if the wiring stray inductance is 200nH and the stray capacitance of the substrate is 500pF, and if they form a loop, the resonance frequency f_o of the loop is calculated as Fig. 10-11.

$$f_O = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{200nH \times 500pF}} \approx 16MHz$$

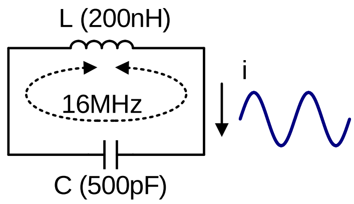


Fig. 10-11 Resonance phenomenon between stray inductance and stray capacitance

If IGBT switching becomes a trigger and resonant current of 16MHz flows in the loop, the resonant current will generate conducted emission and radiated emission. In the case shown in Fig. 10-10, common mode noise current of 16MHz flows through the insulating substrate of the IGBT module to the ground line, and is propagated to the power supply and appears as conducted emission peak. If this resonance frequency becomes 30MHz or higher, it will be observed as radiated emission peak.

Table 10-1 shows examples of stray capacitance and inductance values of each circuit component.

Table 10-1 Examples of stray capacitance and inductance values for each circuit components

Circuit components	Stray capacitance	Stray inductance	Remarks
Between P and N terminals of IGBT module	-	20 ~ 40nH	
IGBT chip	100 ~ 200pF	-	Voltage dependency is large
Snubber capacitor	-	20 ～ 40nH	
Insulating substrate	500 ~ 1000pF	-	
Electrolytic capacitor	100pF	-	Between internal electrode and mounting metallic band
Reactor with iron core	50 ~ 200pF	-	Reactor works as a capacitor at several MHz or higher
Varistor	100 ~ 200pF	-	Stray C is smaller as voltage rating is higher
Motor	13000pF	-	Example of 3φ15kW motor
Shielded 4-core cable	Hundreds of 100pF	Hundreds of nH ~ several μH	Per 1m
Busbar	-	Hundreds of nH	About 100nH per cm

In an actual system, these components are connected in a complicated manner, and unintended LC resonant circuit may be formed. During IGBT switching, resonance occurs in these LC circuits, which is measured as conducted emission and radiated emission peak.

Table 10-2 and Fig. 10-12 show resonance loops that tend to cause the peaks in conducted and radiated emissions.

Table 10-2 Example of resonance frequency and loop in PDS

No.	Frequency	Conducted/radiated	Normal/common	Path
(1)	1 ~ 4MHz	Conducted	Common	Motor capacitance ~ wiring inductance
(2)	5 ~ 8MHz	Conducted	Common	DCB substrate capacitance and wiring inductance
(3)	10 ~ 20MHz	Conducted	Common	DCB substrate capacitance and wiring inductance
(4)	30 ~ 40MHz	Radiated	Normal	Device capacitance ~ snubber capacitance

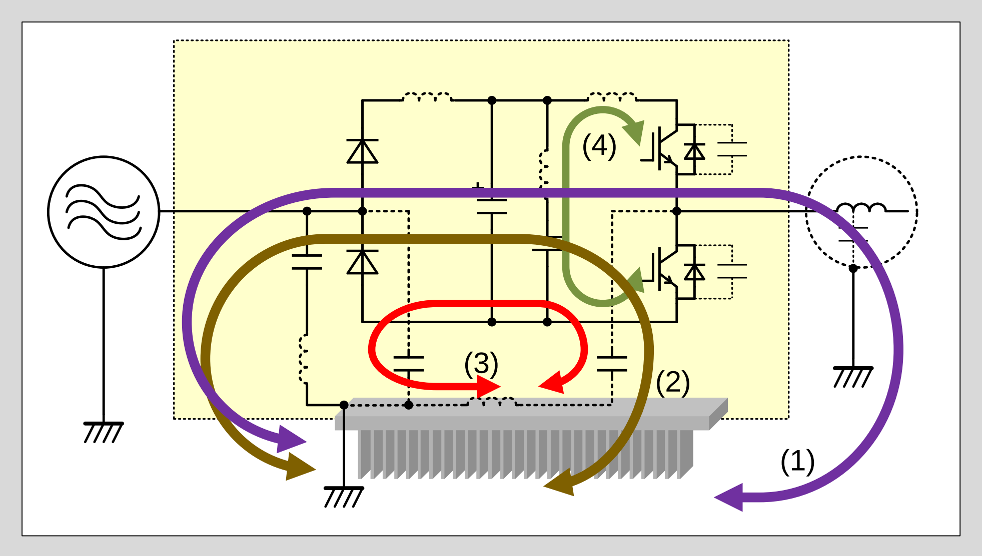


Fig. 10-12 Example of path in Table 10-2

The wire length (inductance) and stray capacitance vary depending on the system configuration, but approximate resonance frequency can be estimated by roughly estimating the inherent stray L and C values of the target system.

2.4 Frequency bands affected by IGBT module characteristics

As aforementioned, the frequency of the conducted emission for a PDS such as general-purpose inverter is 150kHz to 30MHz. Fig. 10-13 shows an example of measured conducted emission in PDS. As shown in Fig. 10-13, the conducted emission is highest around 150kHz, and as the frequency becomes higher, it is mildly attenuated.

This spectrum of conducted emission shows the harmonics of the rectangular switching waveform at the carrier frequency (several kHz to 20kHz), therefore it is almost unaffected by the switching characteristics of the IGBT module itself. This is because, as shown in Fig. 10-14, the voltage rise time and fall time during IGBT module switching are about 50 to 200ns, which is equivalent to frequency of 2 to 6MHz, and in the frequency band lower than this, spectrum of conducted emission does not depend on the difference between the rise time and fall time of the IGBT module

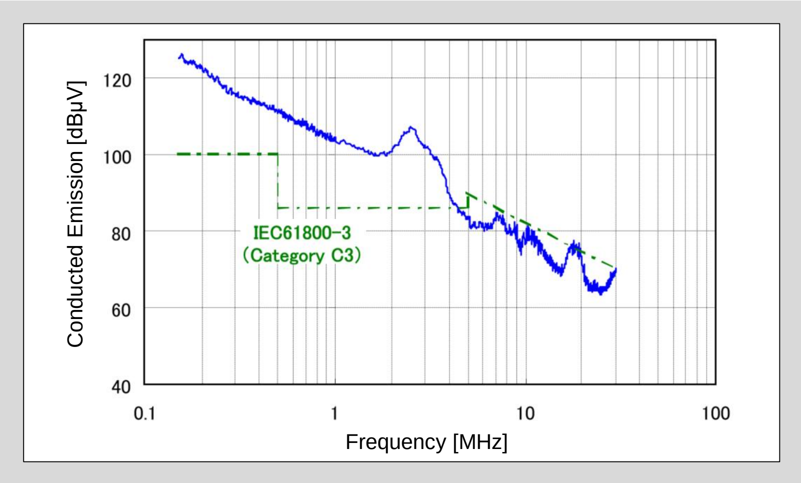


Fig. 10-13 Example of conducted emission of PDS

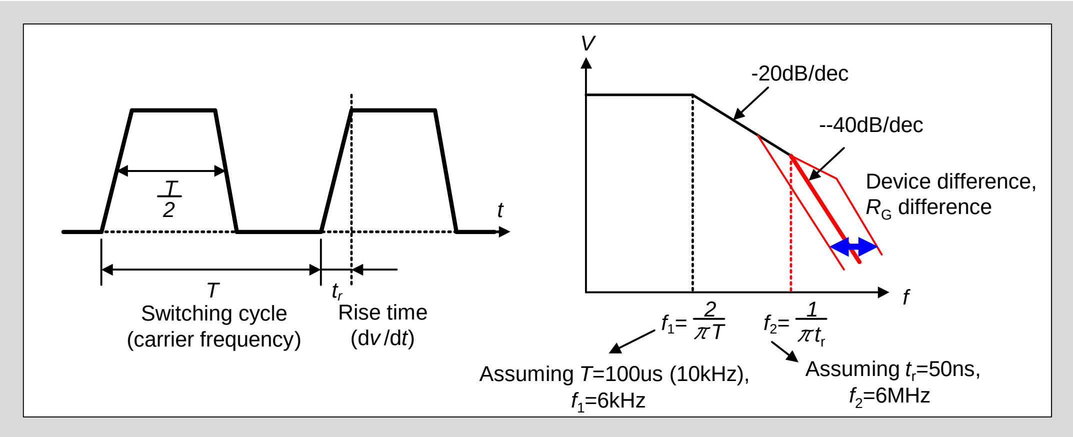


Fig. 10-14 IGBT voltage waveform and frequency spectrum

Fig. 10-15 shows an example of measurement results of radiated emission (30MHz~). Like the conducted emission, the radiated emission become the highest around 30MHz, which is the lowest frequency of the standard, and tend to attenuate as the frequency becomes higher. As shown in Fig. 10-15, the noise spectrum due to IGBT switching does not have a sharp peak like those seen in CPU clocks, but a relatively broad characteristics.

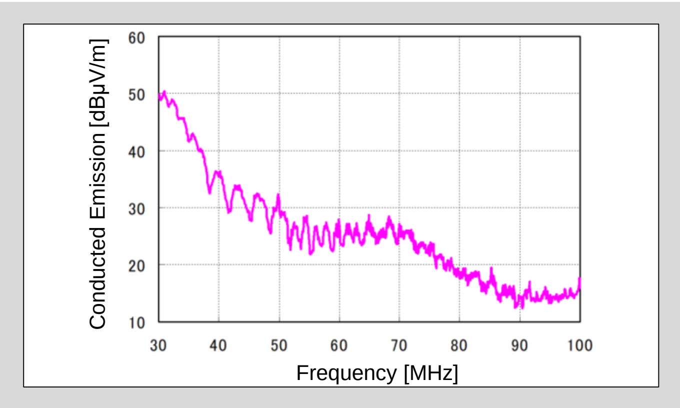


Fig. 10-15 Example of radiated emission spectrum

3. EMI Countermeasures in IGBT Modules Application

3.1 Measures against emission

3.1.1 Filter installation

As countermeasure against conducted emission, it is common to install a filter on the AC power supply input side to prevent the noise current generated by the inverter from flowing out to the AC power line. The filter is composed of *L* and *C* elements, and the cutoff frequency of the filter is designed that sufficient attenuation will be obtained for the target standard value. Since various filters for emission suppression are commercially available, a proper one should be selected according to the relevant standard and required current.

Fig. 10-16 shows the suppression effect of an input filter designed to comply with Category C2 of IEC61800-3. The conducted emission, which was about 125dBμV at 150kHz without the filter, is attenuated to 70dBμV, thus clearing the standard value with a margin of several dBμV.

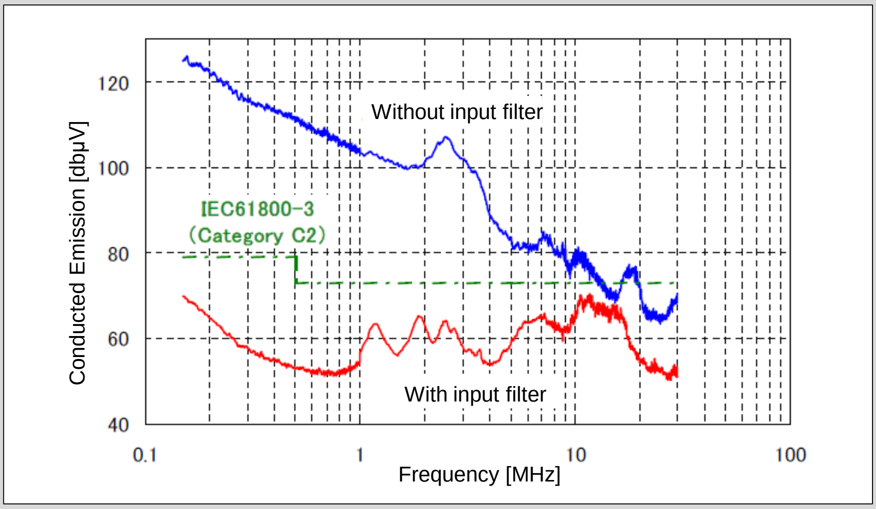


Fig. 10-16 Example of conducted emission in 3φ200V/37kW PDS (QP value)

3.1.2 Cautions when applying filters

In the case of an ideal filter, the attenuation becomes larger as the frequency increases. However, in an actual filter, ideal attenuation characteristic can no more be obtained above a certain frequency as shown in Fig. 10-17. This is because as aforementioned, stray RLC exist in parts used for the filter circuit, and the attenuation effect tends to decrease at the frequency band above 1MHz as shown in Fig. 10-16.

Furthermore, the peak occurs in the high frequency band around 10MHz, and so the margin against the standard is the smallest. Depending on the measuring environment, the level around 10MHz may rise and exceed the standard value.

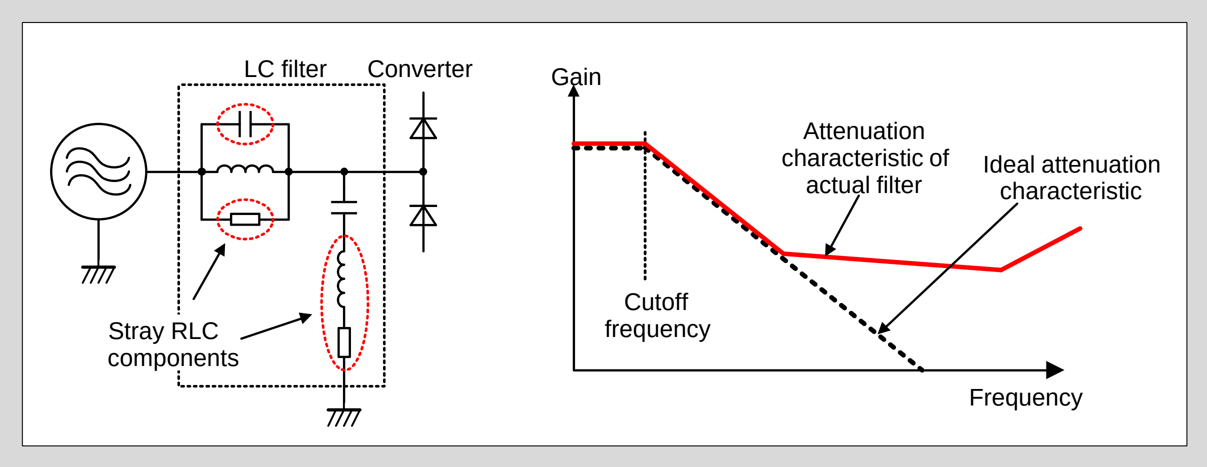


Fig. 10-17 Attenuation characteristics of ideal filter and actual filter

One factor that causes the emission peak occurs in the 10MHz or higher band described in the previous section is the resonance via the insulating substrate of the IGBT module. Assuming that the stray capacitance of the insulating substrate and stray inductance of main circuit are such values as shown in Fig. 10-11, the peak value of conducted emission will occur at 16MHz. The LC values of a loop that resonates at frequency of 10MHz or higher are in the order of hundreds of pF and hundreds of nH, and may be caused by the capacitance of the IGBT chip, insulating substrate capacitance, and wiring inductance inside the package. Fig. 10-18 shows an example of common mode circuit model of resonance via the DCB substrate.

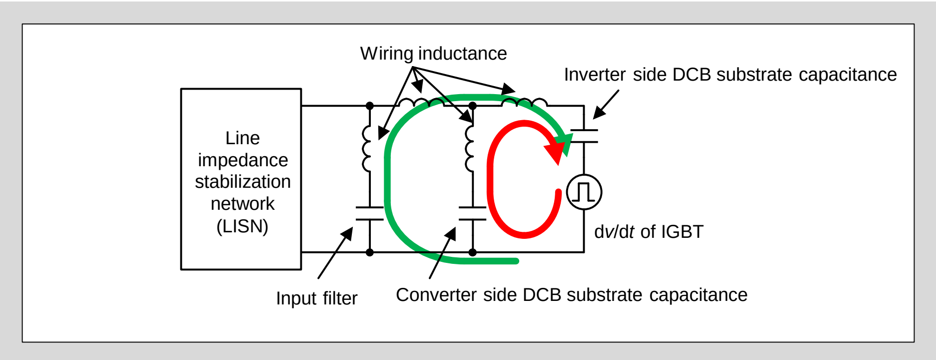


Fig. 10-18 Example of circuit model of resonance via IGBT insulating substrate

This shows the resonance between the inductance of the capacitor connected as an input filter and the DCB substrate capacitance of inverter side module, and the resonance between the converter and the inverter module. When filter or varistor is added as emission countermeasure, it should be noted that peak may occur due to the resonance with the stray L and C of the filter.

3.1.3 Measures against conducted emission of IGBT modules

In order to reduce the peak occurring in the high frequency band of conducted emission spectrum as described above, it is necessary to:

a. Decrease IGBT switching d*v*/d*t*

b. Increase the impedance the resonance loop to suppress the resonance current

However, there are the following demerits.

a. IGBT loss will be increased when d*v*/d*t* is decreased.

b. Simply increasing/decreasing the constants of L and C will result in shifting the resonance frequency, and it is difficult to decrease the peak value. It is impossible to eliminate the stray L and C components structurally and physically.

(1) Measures against conducted emission by adjusting gate resistance

Fig. 10-19 shows an example of conducted emission spectrum of PDS in which the IGBT 7MBR75U4B120 is applied (with input filter). From Fig. 10-19, it can be observed that the conducted emission peak around 10MHz is suppressed by about 5dBμV when the gate resistance is doubled and tripled from the standard value of 22Ω. However, even if the gate resistance is doubled or more, the suppression effect is small, thus it is necessary to judge the suppression effect considering the demerit of increased switching loss.

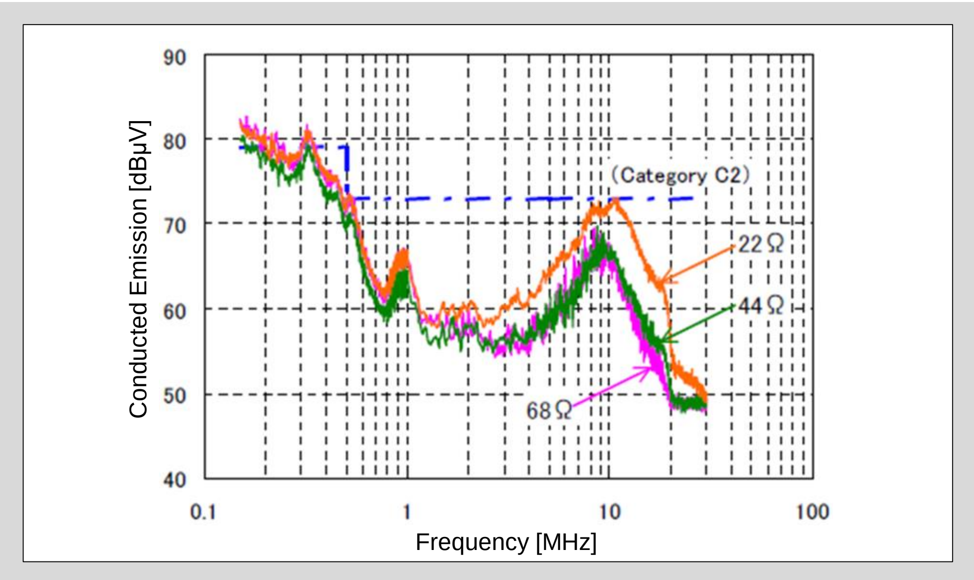


Fig. 10-19 Example of conducted emission spectrum with different gate resistance

(2) Suppression of resonance with ferrite core

The ferrite core is one of the component that is often used for emission suppression. Its equivalent circuit is normally shown as a series circuit of L and R (Fig. 10-20). The characteristics of the ferrite core as magnetic material (L component: μ‘, R component: μ“) is shown in Fig. 10-21.

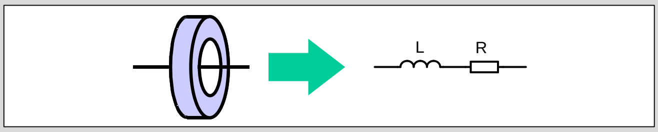


Fig. 10-20 Equivalent circuit of ferrite core

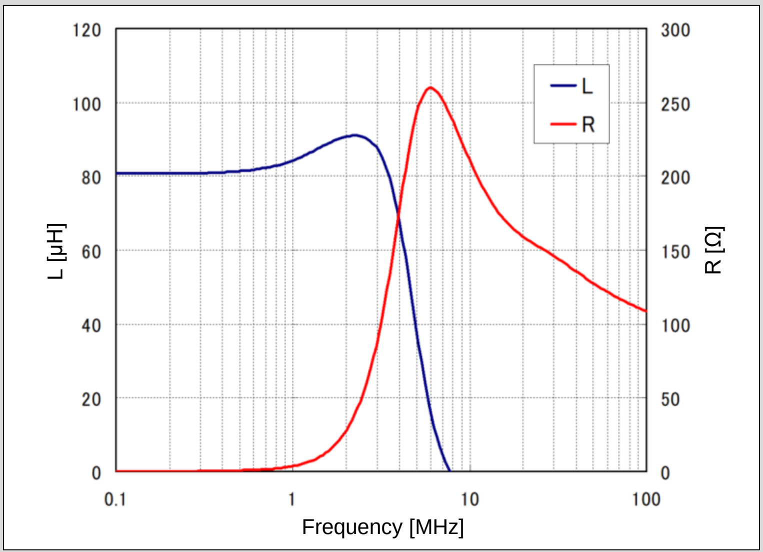


Fig. 10-21 Example of ferrite core impedance (L, R) characteristics

If the ferrite core is inserted into the resonance loop that produces the emission peak described above, the circuit model will be as shown in Fig 10-22.

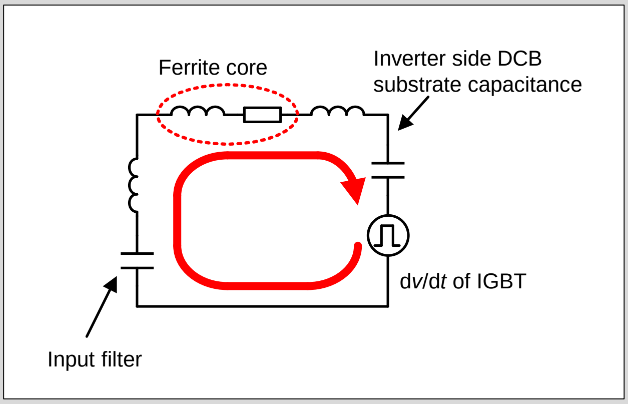


Fig.10-22 Equivalent circuit when ferrite core is inserted

By selecting a ferrite core material with optimum impedance characteristics according to the loop constant (resonance frequency), it is possible to suppress the emission peak by damping the resonance.

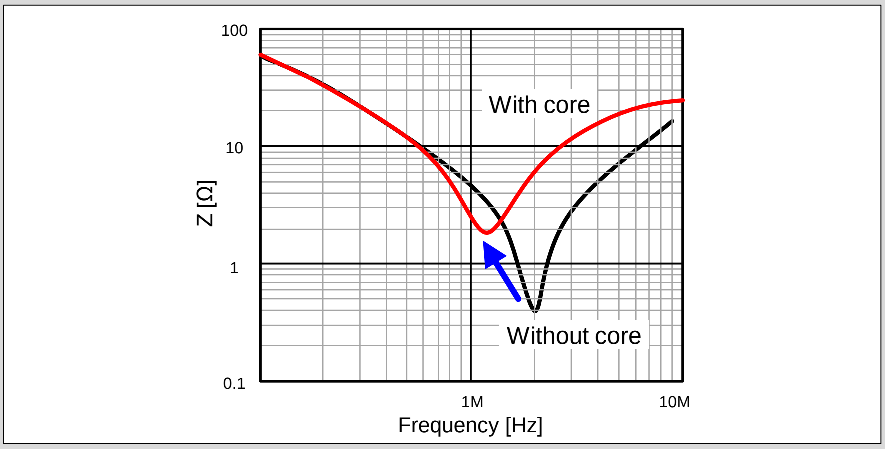


Fig. 10-23 Impedance characteristics of resonance loop with and without core

Fig. 10-23 shows the impedance characteristics of the resonance loop with and without core. At the resonance point, the impedance is lowest and a large resonance current flows, causing a peak in the conducted emission. By inserting the core, the impedance is increased, and the conducted emission can be effectively suppressed by damping the resonance.

Fig. 10-24 and Fig. 10-25 show an example of inserting the ferrite core in the PDS main circuit and the suppression effect, respectively.

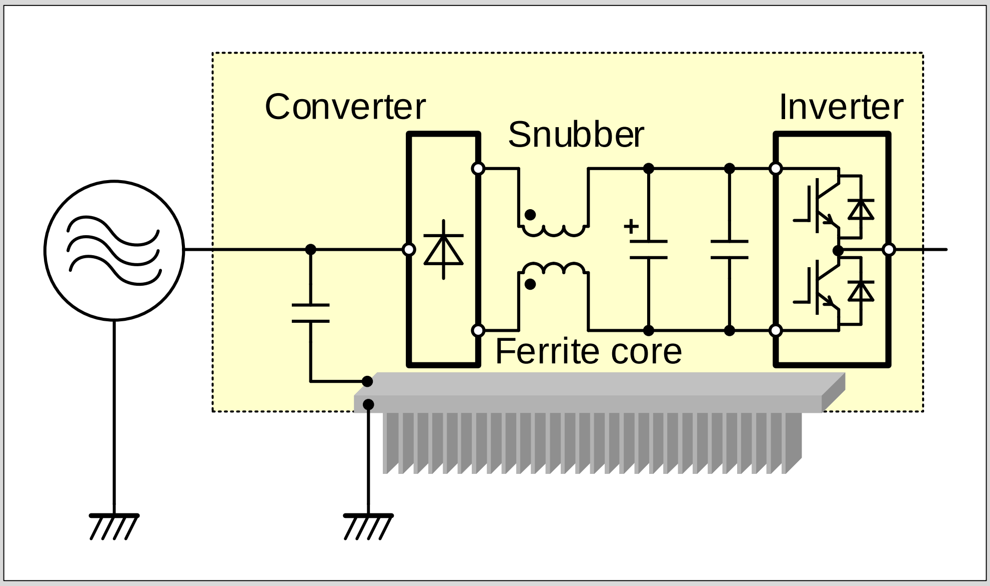


Fig. 10-24 Example of countermeasure using ferrite core

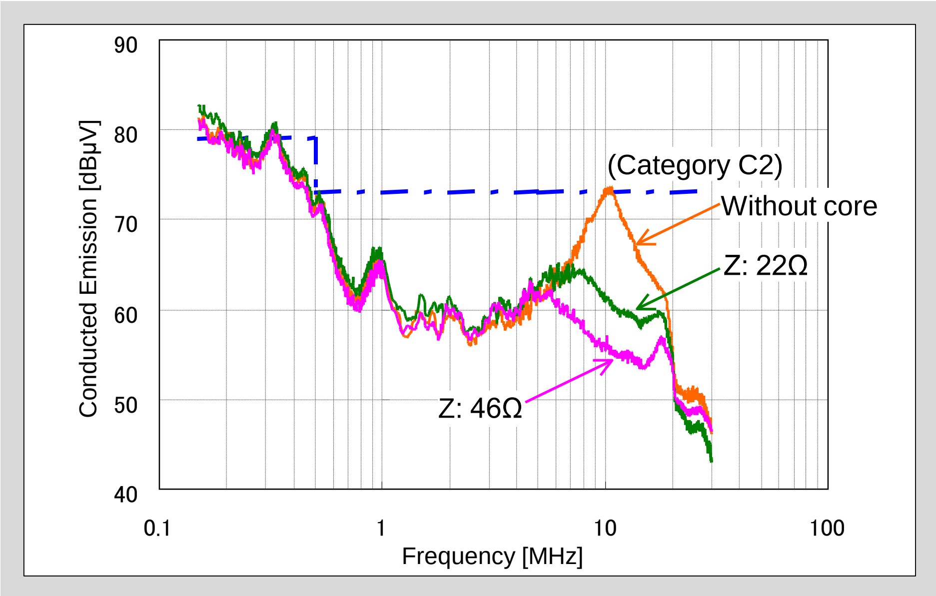


Fig. 10-25 Conducted emission measurement result

Since the loop impedance when no measure is taken is about 8Ω, peak reduction of about 10dB can be achieved by increasing it to about 30Ω by means of the ferrite core.

Unlike the gate resistance method, applying the core can reduce the emission without increasing the IGBT loss.

3.1.4 Measures against radiated emission of IGBT module

The main cause of radiated emission is considered to be the high frequency LC resonance caused by the device junction capacitance and wiring stray inductance (mainly the module internal wiring, and wiring between the module and snubber capacitor, refer to Fig. 10-26) that is triggered by high d*v*/d*t* that occurs during the IGBT turns on (reverse recovery of the FWD on the opposite arm). This is the same generation mechanism as the peak in the conducted emission described above.

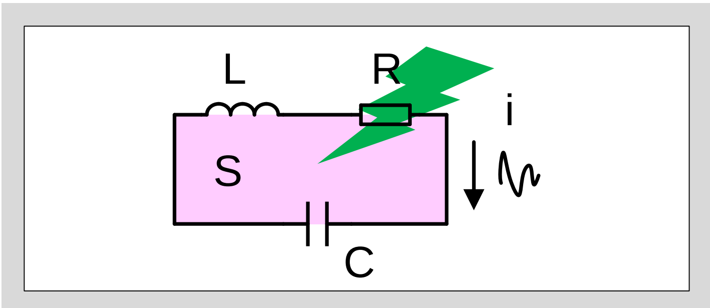


Fig. 10-26 Loop composed of IGBT module and snubber C

Generally, the far electric field E_f at frequency f radiated from a small current loop (the aforementioned LC loop here) placed in a free space is given by the following equation.

$$Ef = \frac{1.32 \times 10^{-14}}{r} \cdot S \cdot If \cdot \sin\theta \qquad \text{(1)}$$

r: distance from loop, *S*: area of loop, *If*: loop current, *θ*: angle from loop surface

From equation (1), it is known that *Ef* is inversely proportional to the distance from the loop and proportional to the loop area and loop current.

The current value *If* is given by the following equation.

$$If = \frac{E}{Z} \qquad \cdots\cdots(2)$$

E: voltage spectrum of IGBT switching waveform (Fig. 10-14), Z: loop impedance

From the above equation, the following measures may be considered to reduce radiated emission.

[1] Increase the distance from the loop
[2] Decrease the loop area S
[3] Decrease the loop current
  [3]a. Decrease the switching voltage spectrum
  [3]b. Increase the loop impedance

As for [1], the measurement at a distance of 10m or 3m is specified in the standard, therefore the practical measures are [2] or [3].

(1) Decrease the loop area S

As described above, the high frequency noise current induced during switching is the resonant current of the LC loop formed by the device capacitance and the snubber capacitor (path [4] in Fig. 10-12).

For 2-Pack medium/large capacity modules, it is necessary to minimize the radiation area of the loop by connecting the snubber capacitor directly to the terminals. This is also effective from the viewpoint of surge voltage suppression during switching.

Pin terminal type modules such as 6-Pack and PIM types are mostly mounted on the power board, but it is important for the snubber capacitor to be placed as close to the P/N terminal pins as possible.

(2) Decrease the voltage spectrum

As described above, the voltage spectrum during IGBT/FWD switching is shown in Fig. 10-27.

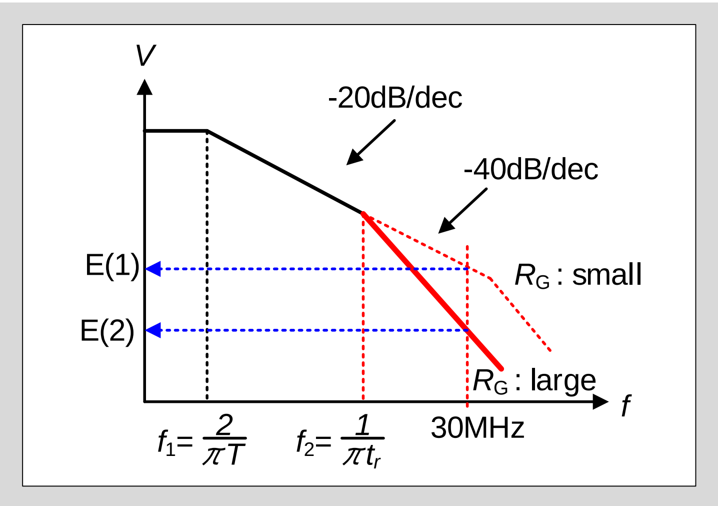


Fig. 10-27 IGBT switching voltage waveform spectrum

Conventionally, increasing the gate resistance to decrease the switching speed has been generally applied as a countermeasure. This lower the frequency of f_2, and reduce the spectrum above 30MHz as shown in Fig. 10-27. In comparison with the voltage component E(1) at 30MHz when R_G is small and the dv/dt is large, the voltage component when R_G is large and dv/dt is small becomes smaller like E(2). Since E(1), E(2) are equivalent to E in equation (2), reducing the dv/dt results in suppressing the noise current *If*.

Fig. 10-28 shows an example of radiated emission dependence on gate resistance. By setting the gate resistance value to about twice the value described in the specification, the radiated emission can be greatly suppressed. However, if the radiated emission is suppressed by adjusting the gate resistance, switching dv/dt becomes slower, and switching loss increases. As a result, depending on the operating conditions of the equipment, the temperature may rise and the junction temperature may exceed the rating, thus evaluation is required.

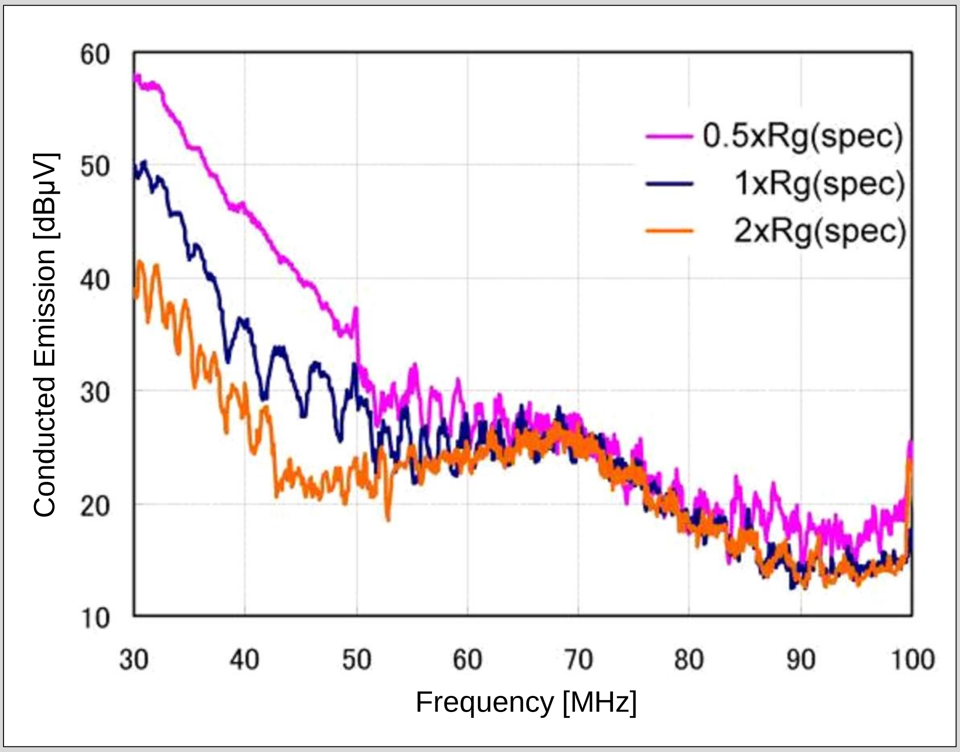


Fig. 10-28 Radiated emission dependence on gate resistance (7MBR100U4B-120)

3.1.5 Summary

As described above, the EMI generated by IGBT switching (especially high frequency conducted emission at 10MHz or higher, and radiated emission) is caused by the resonance of stray L and C existing in the IGBT itself and on its peripheral circuit. These stray L and C components cannot be reduced to zero in principle and physically. Therefore, it is important to accurately identify the loop resonance that cause these problems and take proper countermeasures.