
Chapter 10

EMC Design of IGBT Module

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In this chapter, EMC measures when IGBT module is applied are introduced.

1 General information of EMC in Power Drive System

Recently EMC measures coping with European CE Marking and Japanese VCCI(Voluntary Control Council for Information Technology Equipment) standards are indispensable in designing power electronic equipments such as Power Drive System(PDS) and Uninterruptible Power Source(UPS) using IGBT modules.

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

Since IGBT modules turn on and off several hundreds of voltage and several hundreds of current in several hundreds nanoseconds, both conducted emission and radiated emission are easily generated due to high dv/dt and di/dt of IGBT module. It is important to reduce those emission when designing power electronics equipments.

In this chapter, effects of switching on others (EMI characteristics), which tend to become troubles in the application of the IGBT module, and countermeasures are introduced.

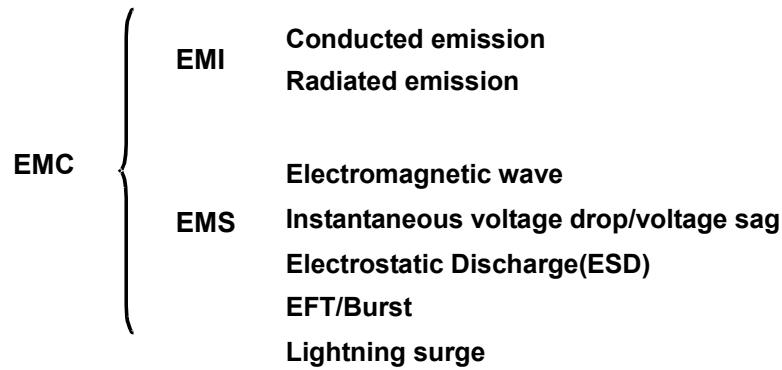


Fig.10-1 Classification of EMC

1.1 EMI performance

The IGBT module is used for equipments in a wide range of application field and power including such home appliance as air-conditioner and refrigerator, automobile and traction system as well as industrial PDS. Here are EMI standards related to PDS including general-purpose motor drive which is one of main application of the IGBT module.

(1) Conducted emission

In IEC61800-3, the limits (QP (Quasi-Peak) values) of the conducted emission are stipulated as shown in Fig.10-2 for PDS (Power Drive System).

The limits in the standard are classified into Category (C1) applied for equipments used in commercial area and Category (C2, C3) applied for equipments used in industrial area, and the industrial PDS are so designed as to clear Category C3 limits.

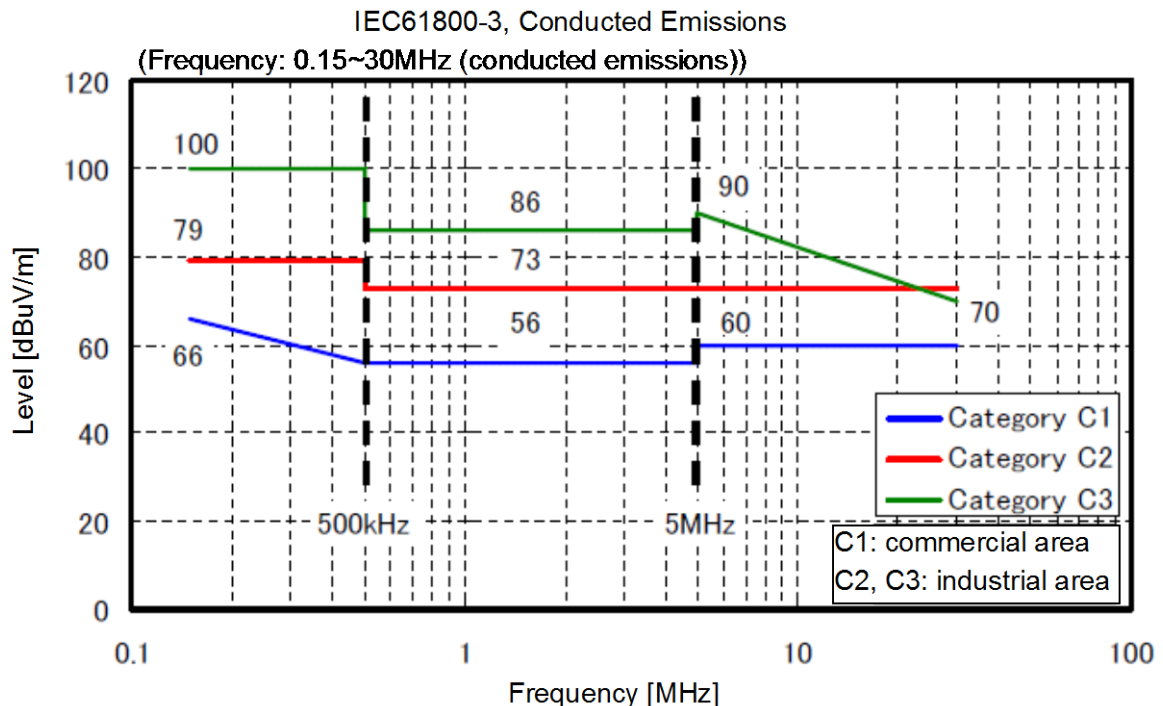


Fig.10-2 Limits of Conducted Emissions in IEC61800-3

(2) Radiated emission

Fig. 10-3 shows the standard limit values of radiated emission for each category. The category classification is defined as Fig. 10-4.

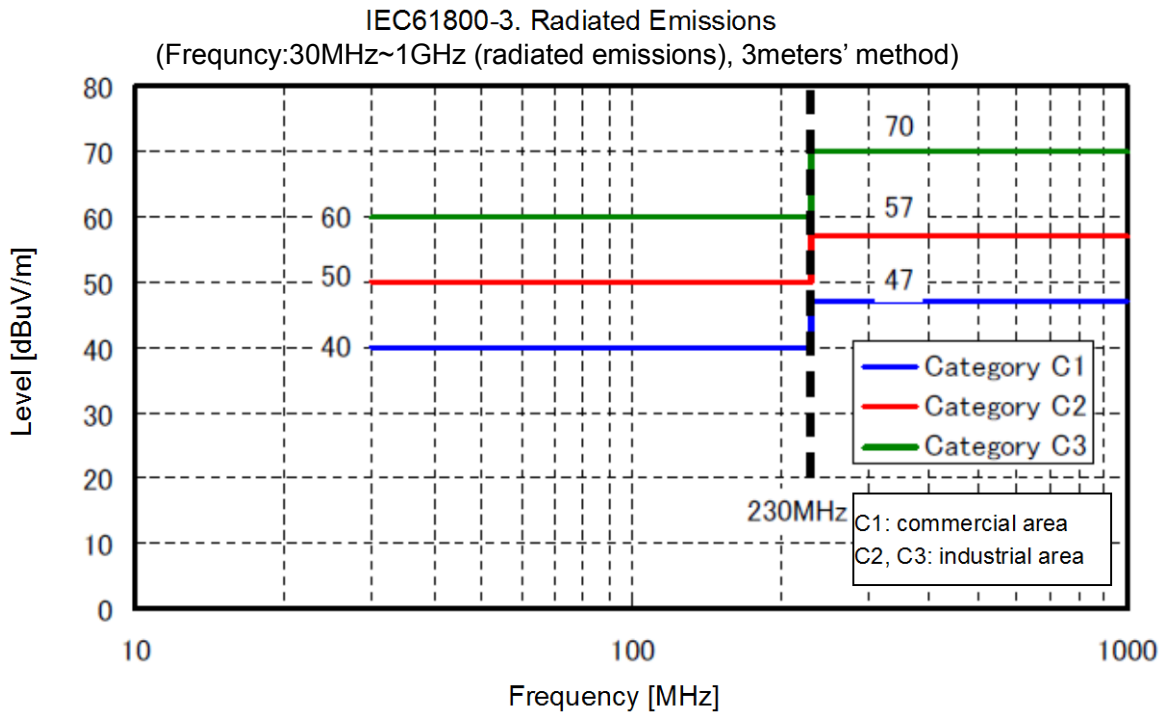


Fig.10-3 Limits of Radiated Emissions in IEC61800-3

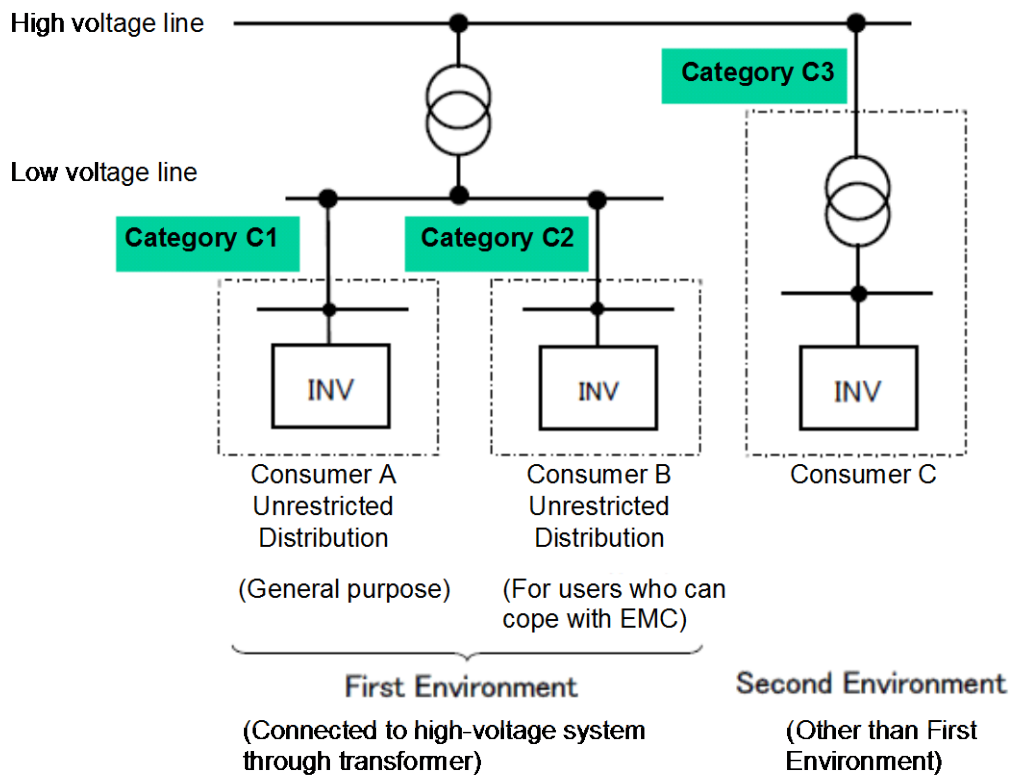


Fig.10-4 Category Classification in IEC61800-3

2 EMI design in Power Drive System

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 dv/dt and di/dt due to switching of IGBT, is propagated in the main circuit and appears as noise at AC input terminal and output terminal. The path of the normal mode noise is shown in Fig. 10-5

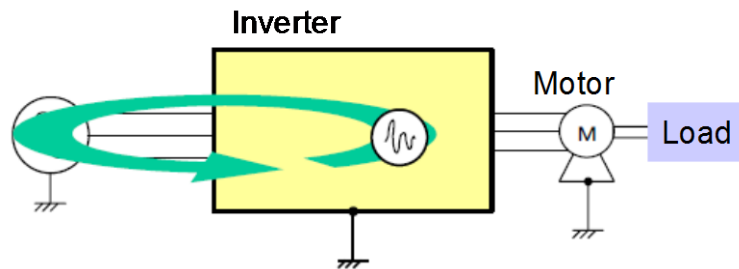


Fig.10-5 Path of Normal Mode Noise

On the other hand, the common mode noise is generated by potential fluctuation against ground due to charge and discharge of stray capacitance existing between main circuit and ground and in the transformer, and noise current is propagated through the ground line. The path of common mode noise is shown in Fig. 10-6.

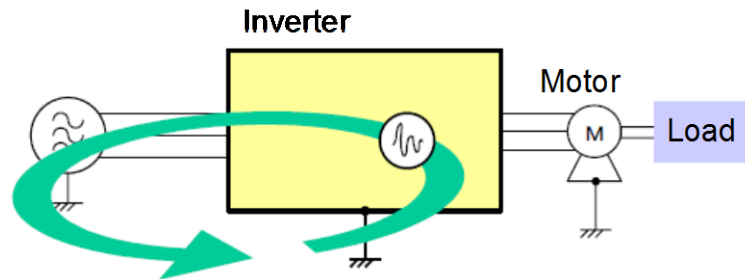


Fig.10-6 Path of Common Mode Noise

With actual equipment, there is impedance imbalance in the wirings of phases (e.g. R/S/T phase), and so the normal mode noise is changed to the common mode noise via the ground line (Fig. 10-7) or reversely the common mode noise is changed to the normal mode noise. In actual noise spectrum, therefore, it is very difficult to separate the noise through the normal mode path and the noise through the common mode path. As general caution, it is necessary to prevent the imbalance as much as possible for the phase wirings.

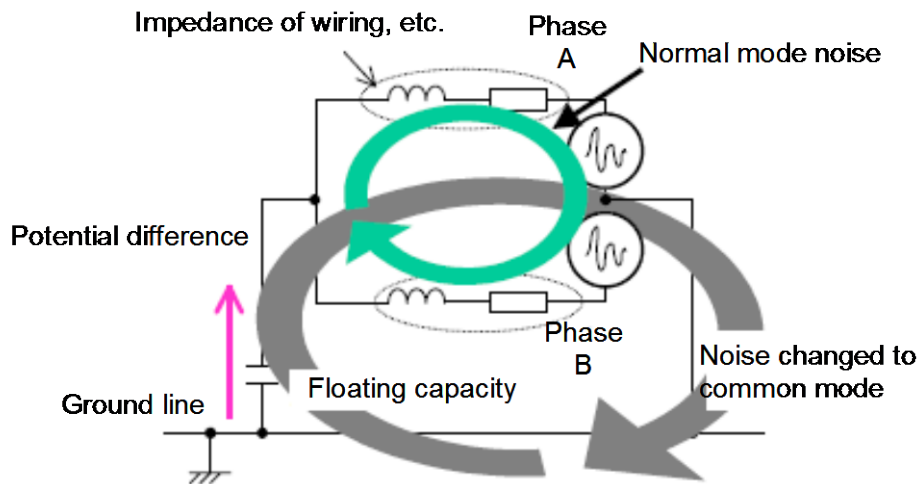
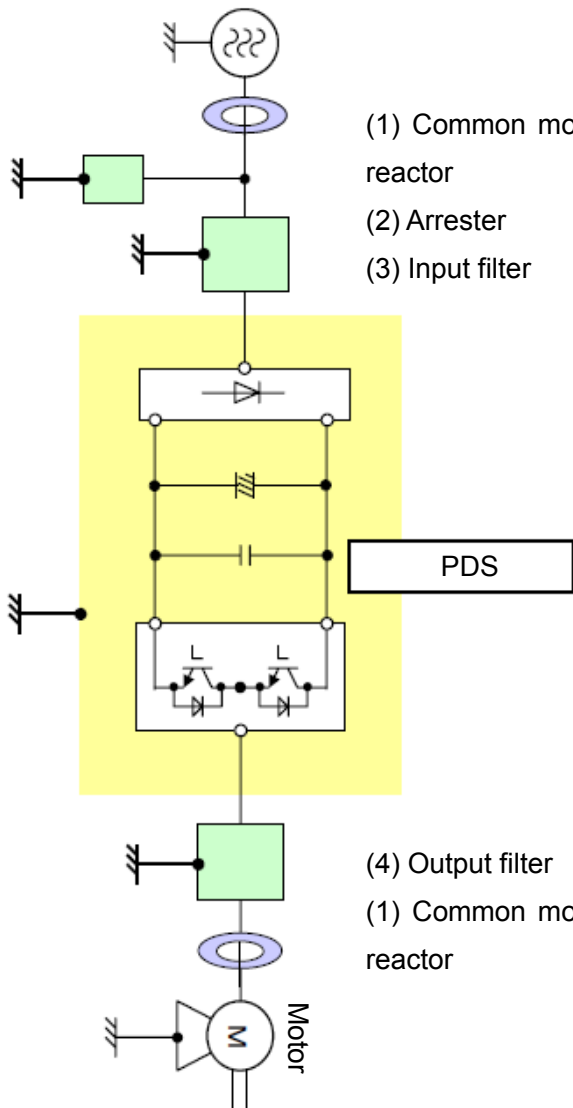


Fig.10-7 Path of Common Mode Noise

2.2 Measures against EMI noise in PDS

Fig. 10-8 shows general measures against noise in Power Drive System(PDS).

It is possible to control noise (mainly harmonics current and conducted emission) occurring in PDS by inserting such countermeasure parts as commercial noise filter and reactor.



The effects of the parts are as follows.

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

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

(3) Input filter
This, composed of L and C, R, controls noise outflowing to the input power line. Various products having different noise attenuation characteristics are available in the market and 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 are required in accordance with the instruction manual.

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

Fig. 10-8 Measures against Noise of PDS

Such filters as described above to be installed outside the PDS are effective for noise control in the bands of 100kHz to several MHz, but may be less or not effective for higher bands (conducted emissions of 10MHz or higher and radiated emissions of 30MHz or higher).

This is because the frequency characteristics of filters are limited, and in order to effectively control emissions over a wide range of frequency, it is necessary to install optimum filters to meet the respective frequency.

2.3 Occurrence mechanism of emission attributable to module characteristics

One of factors to cause emission near the range of 10MHz to 50MHz is wiring inductance and/or stray capacitance around the IGBT module in the PDS, and it is considered that resonance occurs accompanying switching. In this section, the mechanism of emissions occurring around the IGBT and the countermeasures are introduced.

Fig. 10-9 shows the block diagram of a typical power drive system. In this figure, AC power source is rectified into DC by rectifier diodes and then reversely converted into AC by switching at high frequency the IGBT of the inverter portion, thereby achieving variable speed driving of the motor. The IGBT module and rectifier diode are mounted on a cooling fin, and this cooling fin is a part of a PDS body and is normally grounded for safety.

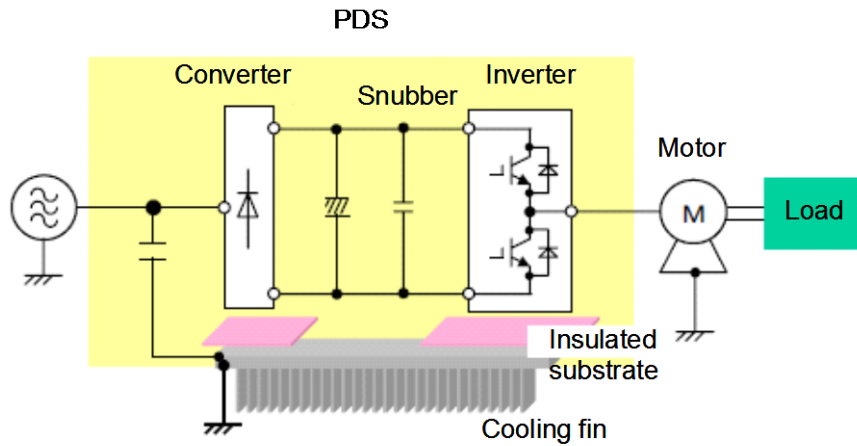


Fig.10-9 Path of Common Mode Noise

In this system, the metal base of IGBT module mounted on a cooling fin and the electric circuit side such as IGBT chip are insulated each other by a highly thermal conductive substrate. (For the detailed structure of the module interior, see Chapter 1)

A snubber capacitor which suppresses surge voltage is connected to the IGBT of the inverter portion.

In the area of MHz order such as radiated and conducted emission, however, the wiring inductance, stray capacitor which are not appeared on circuit diagram may give large effects.

Fig. 10-10 shows a schematic diagram of PDS in such high-frequency bands as hundreds of kHz to tens of MHz. At a high frequency, stray capacitance and stray inductance existing in IGBT module and electrical parts give a very large effect. On the wiring around IGBT module, tens to hundreds nano henry of stray inductance may exist, and on the insulating substrate described above, hundreds piko farad of stray capacitance exists. There exists Junction capacitance at the PN junction of the IGBT itself.

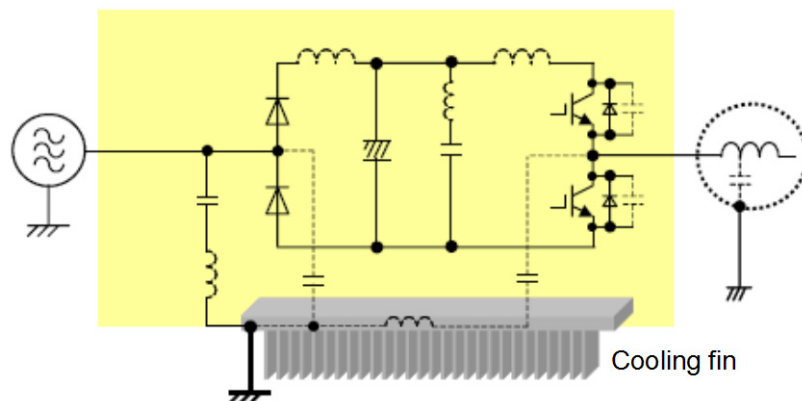


Fig.10-10 Equivalent Circuit Considering Parasitic L/C

Assuming, for example, that the stray inductance of the wiring is 200nH and the stray capacitance of the substrate is 500pF, and if they are looped, the resonance frequency f_0 of the loop is calculated as Fig. 10-11.

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{200\text{nH} \times 500\text{pF}}} \doteq 16\text{MHz}$$

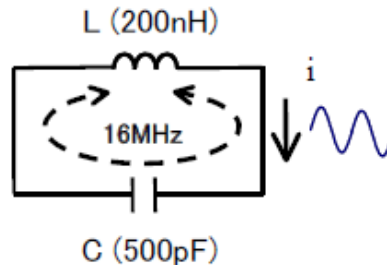


Fig.10-11 Resonance phenomenon between stray inductance and stray capacitance

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

Table 10-1 shows an example of stray capacitance and inductance values of circuit components.

Table 10-1 Example of stray Capacitance and Inductance values in components of PDS

Circuit Components	Stary 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	
Insulated substrate	500~1,000pF	—	
Electrolytic capacitor	100pF	—	Between internal electrode and mounting metallic band
Iron-core reactor	50~200pF	—	At several MHz or higher a reactor works as a capacitor.
Varister	100~200pF	—	The higher voltage resistance is, the smaller stray C is.
Motor	13,000pF	—	Example of 3-phase 15kW induction motor
Shielded 4-core cable	Hundreds of pF	Hundreds of nH ~several micro H	Per meter
Wiring busbar	—	Hundreds of nH	About 100nH per 10cm

In an actual system, these components are connected in a complicated way, and an unintended L-C resonance circuit will be formed. Due to the IGBT switching, resonance current will be occurred in the L-C circuit and will generate peak value of conducted emission and radiated emission.

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

Table 10-2 Example of Resonance Loops in PDS

	Frequency	Conducted/radiated	Normal/common	Path
(1)	1~4MHz	Conducted	Common	Motor capacitance ~ wiring inductance
(2)	5~8MHz	Conducted	Common	DBC substrate capacitance and wiring inductance
(3)	10~20MHz	Conducted	Common	DBC substrate capacitance and wiring inductance
(4)	30~40MHz	Radiated	Normal	Device capacitance ~ snubber capacitor

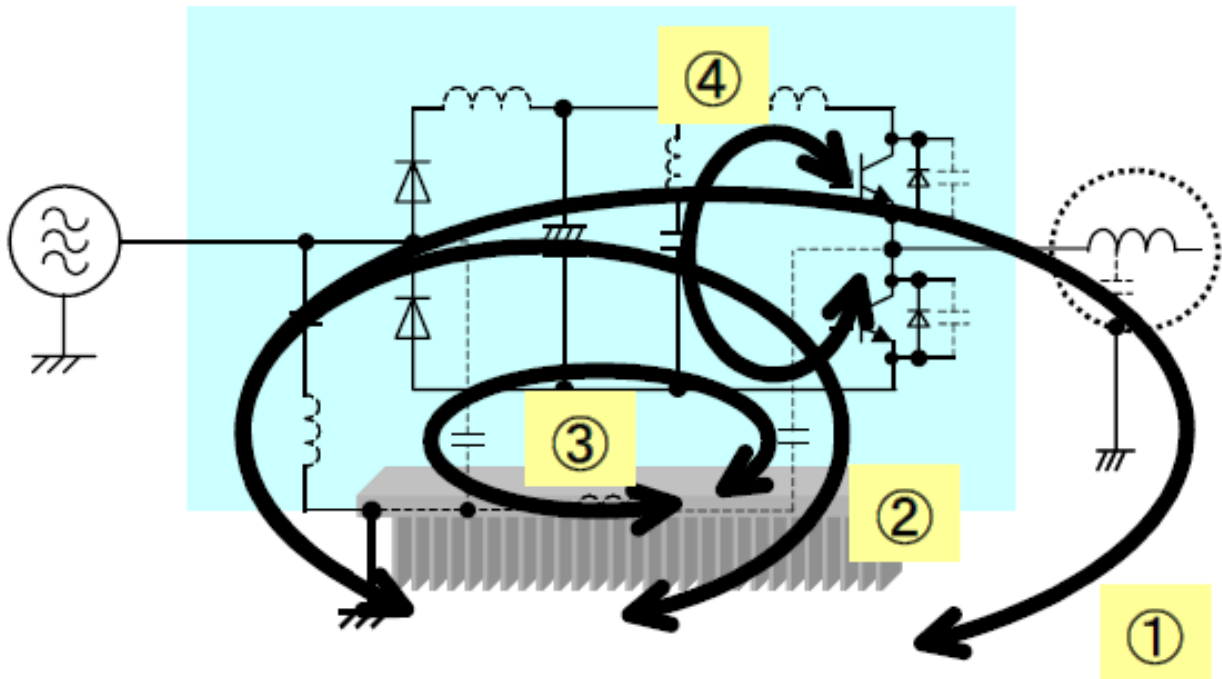


Fig.10-12 Example of Resonance Loops in PDS

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

2.4 Frequency bands affected by IGBT module characteristics

As aforementioned, the frequency of the conduction noise for a power drive system such as general-purpose motor drive is 150kHz ~ 30MHz. Fig. 10-13 shows an example of measured data of the conducted emissions in PDS. As shown in Fig. 10-13, the conducted emission is highest near 150kHz, and as the frequency becomes higher, it is mildly attenuated. In the spectrum of the conducted emissions, the harmonics of rectangular switching waveform at the carrier frequency (several kHz ~ 20kHz) appears, and therefore, it is hardly affected by the switching characteristic of the IGBT module itself. This is because, as shown in Fig. 10-14, the voltage rise time and fall time in the switching of IGBT module are about 50~200 nanoseconds which is equivalent to 2~6MHz in terms of frequency, and in the frequency band lower than this, spectrum of conducted emission does not depend on the rise time and fall time of IGBT module.

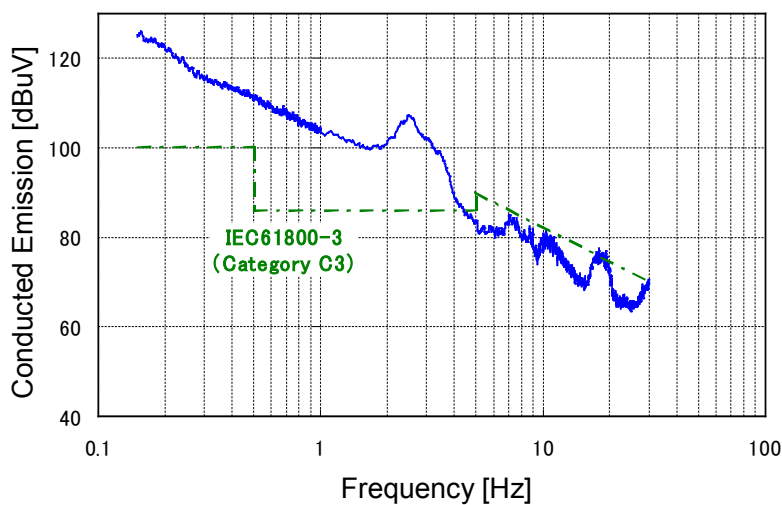


Fig.10-13 Example of Conducted Emission of PDS

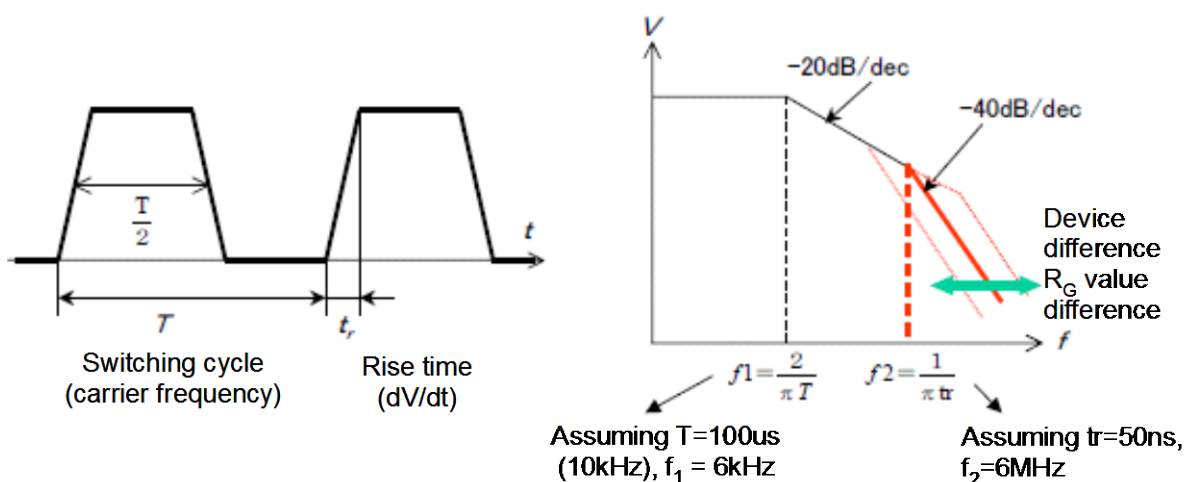


Fig.10-14 IGBT Voltage Waveform and Frequency Spectrum

Fig. 10-15 shows measurement results of radiated emissions (30MHz ~). Like the conducted emissions, the radiated emissions become the highest near 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 switching of IGBT does not have a sharp peak such as the CPU clock but a relatively broad.

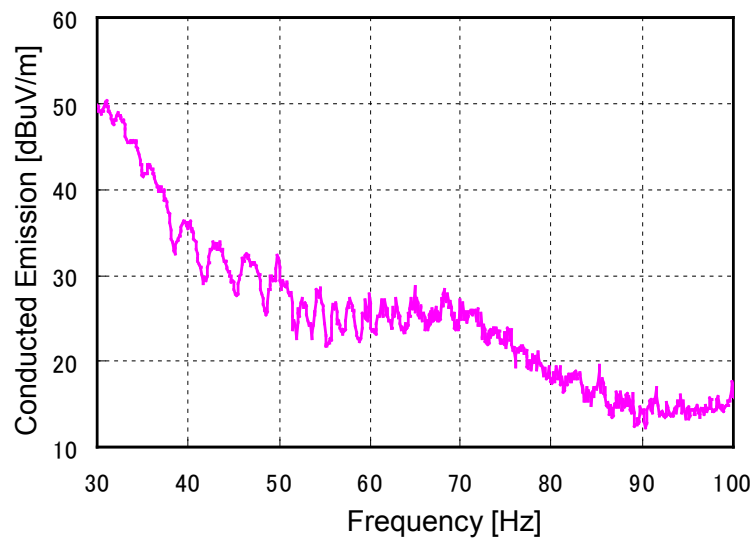


Fig.10-15 Radiated Emission Spectrum of 7MBR100U4B120 with Standard Gate Drive

3 EMI countermeasures in applying IGBT module

3.1 Measures against conducted emissions

3.1.1 Filter installation

Normally as the measures against the conducted emission, an input filter is installed on the input AC side to prevent the noise current produced in the inverter from outflowing to the AC power line. The input filter is composed of L and C elements, and the cutoff frequency of the filter is so designed that sufficient attenuation will be obtained for the target standard value. Since various filters for preventing emission are marketed by magnetic material and capacitor manufactures, a proper one should be selected in accordance with the relevant standard and necessary input current.

Fig. 10-16 shows reducing effects of an input filter designed for Category C2 of IEC61800-3. The conducted emission that was about 125dB μ V at 150kHz without filter was attenuated to 70dB μ V thanks to the filter, thus clearing the standard value with the margin of several dB μ V.

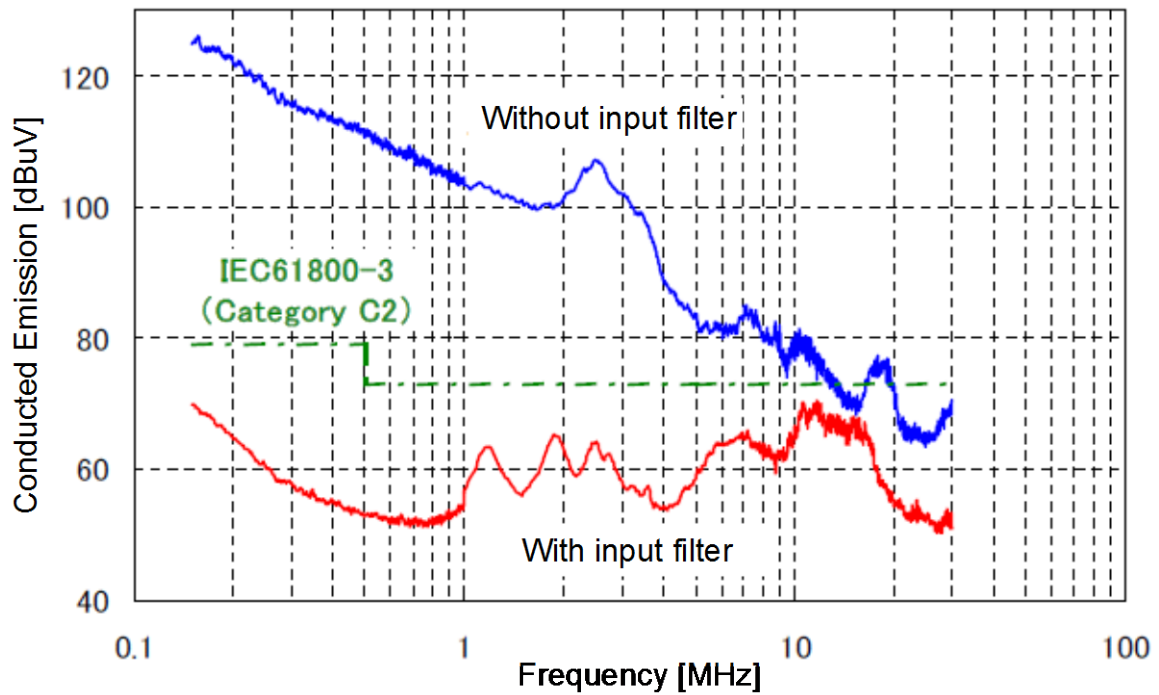


Fig.10-16 Measurement Results of Conducted Emissions in 3-Phase PDS 200V/37kW (QP Value)

3.1.2 Cautions when filter is applied

In case of an ideal filter, the attenuation becomes large as the frequency increases, but in actual filter circuits, ideal attenuation characteristic can no more be obtained at a certain frequency or higher, as shown in Fig. 10-17. This is because, as aforementioned, stray L and C exist in parts used for the filter circuit, and the attenuating effect tends to decrease at the frequency of 1MHz or higher, like the measurement results of conducted emissions shown in Fig. 10-16.

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

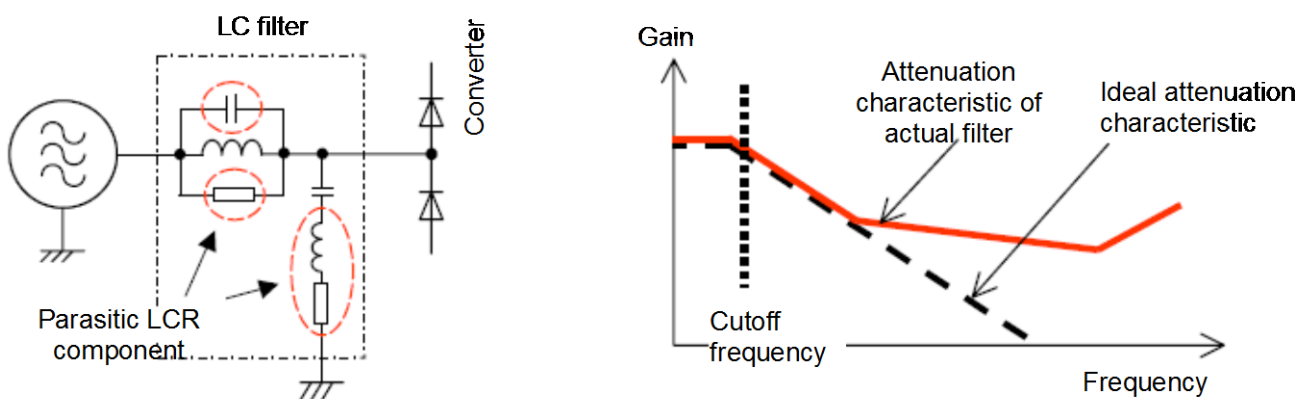


Fig.10-17 Attenuation Characteristics of Ideal Filter and Actual Filter

As one factor of the peak appearing in the band of 10MHz or higher of the conducted emissions, described in the preceding section, the resonance via the insulating substrate of the IGBT module can be cited.

Assuming, for example, that 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 emissions appears at 16MHz. The LC values of a loop that resonates with the frequency of 10MHz or higher are in the order of hundreds of pF and hundreds of nH, and the causes may be the capacitance of 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 DBC (Direct Bonding Copper) substrate.

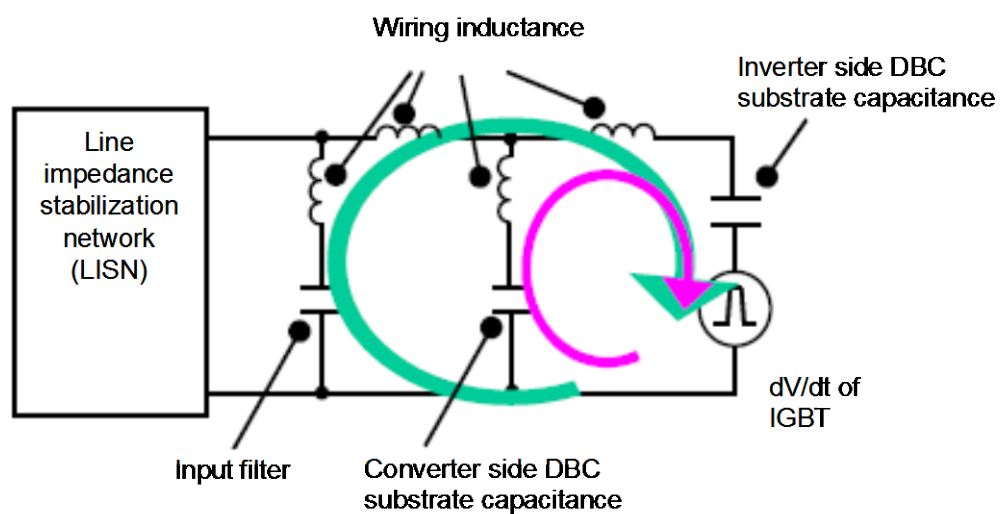


Fig.10-18 Example of Circuit Model of Resonance via Insulating Substrate of IGBT

This shows the resonance between the inductance of capacitor connected as an input filter and the substrate capacitance of inverter side module and the resonance between converter and inverter modules. When the filter or varistor is added to prevent emissions, it should be noted that the peak may appear due to the resonance with the parasitic L/C of the filter.

3.1.3 Measures against conducted emissions caused by IGBT module

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

- [1] to decrease dV/dt of IGBT for switching
- [2] to make resonance current smaller by raising the impedance the resonance loop

But there are such demerits as shown below.

- [1] IGBT loss will be increased when dV/dt is decreased.
- [2] Only increasing/decreasing the constants of L and C will result in moving 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.

3.1.3.1 A measure of conducted emissions by adjusting gate resistance

Fig. 10-19 shows an example of conducted emissions spectrum of PDS (with input filter) applying 7MBR75U4B120. From Fig. 10-19, it is known that the peak near 10MHz of the conducted emissions is controlled about 5 dB μ V when the gate resistance is 2 times or 3 times as big as standard value.

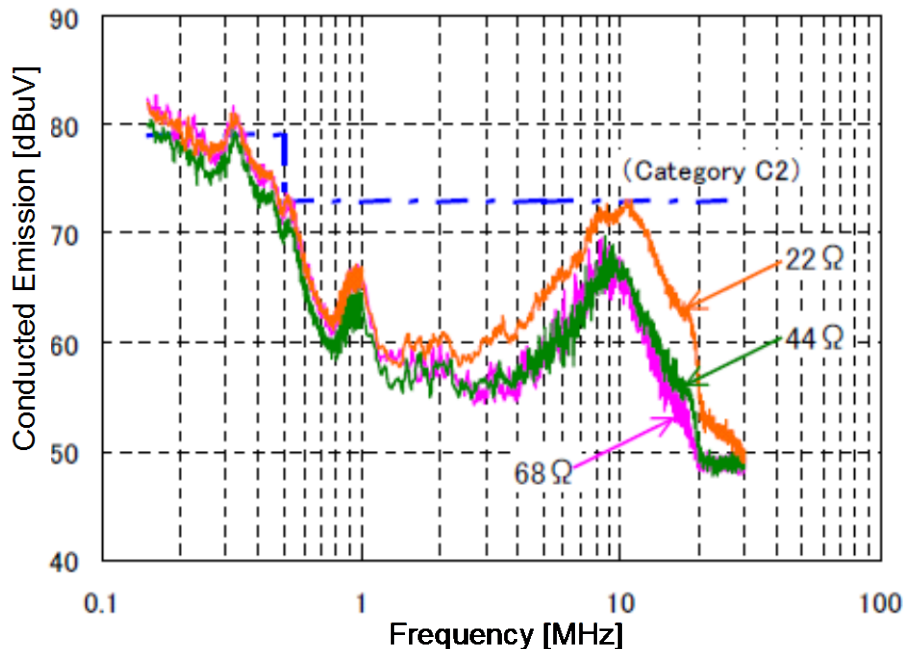


Fig.10-19 Measurement of Conducted Emissions of 7MBR75U4B120

Even if the gate resistance is increased to 2 times or more, the reducing effect is smaller, and so it is necessary to judge the reducing effect considering the demerit of increased switching loss.

3.1.3.2 Controlling of resonance with ferrite core

The ferrite core is one of parts often used for reducing the emissions. Its equivalent circuit is normally shown as a series circuit of L and R. The characteristics of L and R as magnetic material of the ferrite core are as shown in Fig. 10-21.

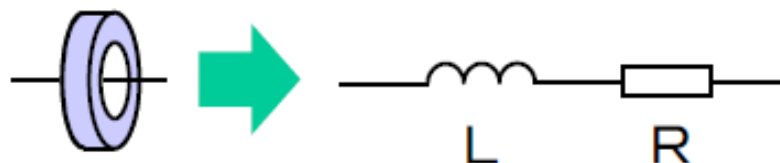


Fig.10-20 Equivalent Circuit of Ferrite Core

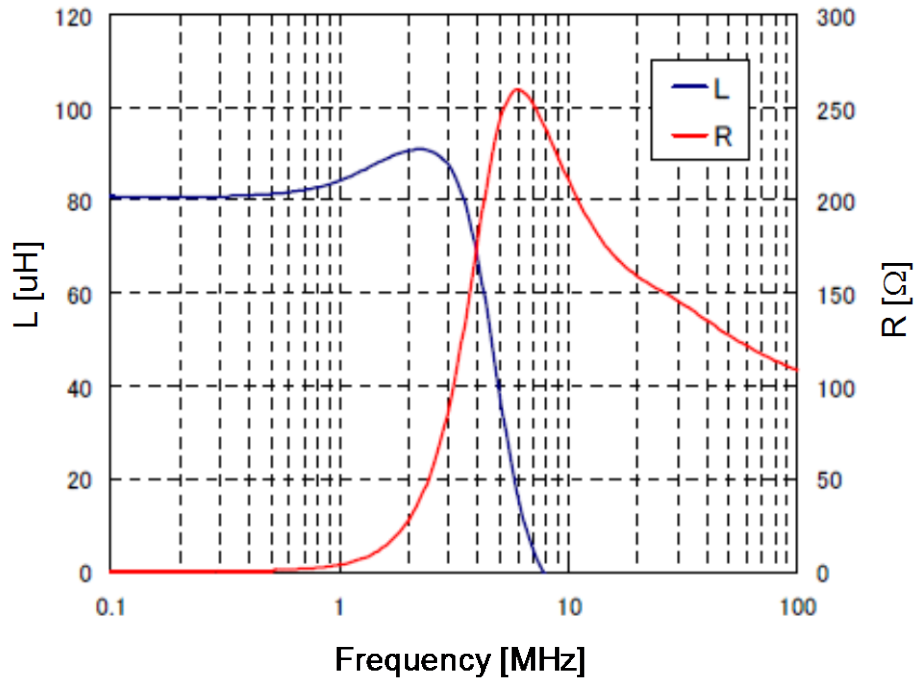


Fig.10-21 Impedance (L, R) Characteristics of Ferrite Core

If this ferrite core is inserted in the resonance loop to produce the noise peak described above, the following circuit model is made.

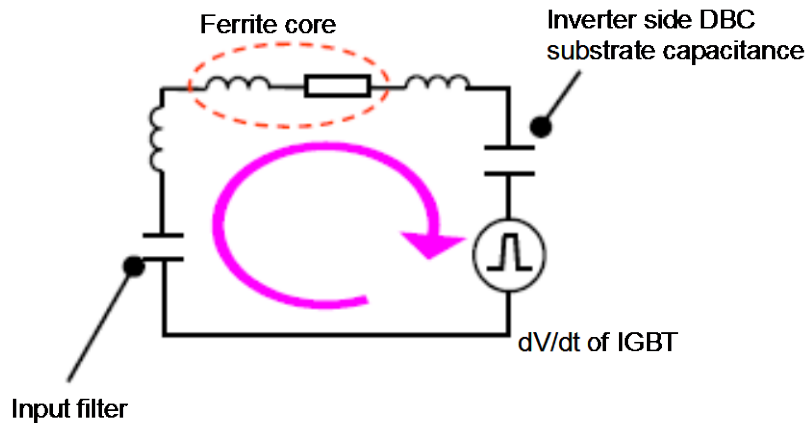


Fig.10-22 Equivalent Circuit When Ferrite Core Is Installed

By selecting a ferrite core material with optimum impedance characteristic in accordance with the constant (resonance frequency) of the loop, it becomes possible to control the noise peak by damping the resonance.

Fig. 10-23 shows the impedance characteristic of the resonance loop before and after the core measure is taken. At the resonance point, the impedance becomes the lowest and large resonance current runs, and so the peak occurs in the conducted emissions. By inserting the core here, the impedance is increased, and by damping the resonance, the conducted emissions can be effectively controlled.

Fig. 10-24 and Fig. 10-25 show an example of inserting the common mode/ferrite core in the PDS main circuit and reducing effects, respectively.

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 emissions without increasing the loss of IGBT. In Fuji's 5th generation IGBT modules, U4 series, the tradeoff between high-speed switching and low-noise characteristic is greatly improved when a core is applied. Furthermore, lower noise of equipment can be achieved without sacrificing the high-speed switching characteristic by arranging the ferrite core effectively. (Various patents are applied)

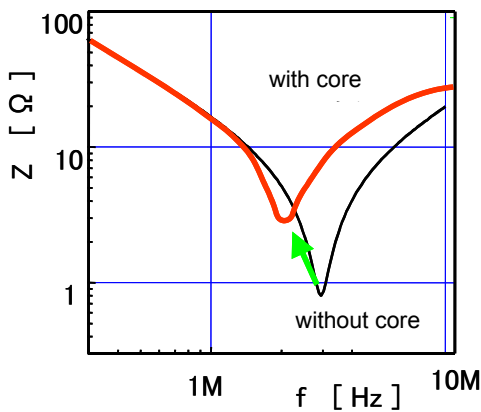


Fig.10-23 Impedance Characteristic of Resonance Loop before and after

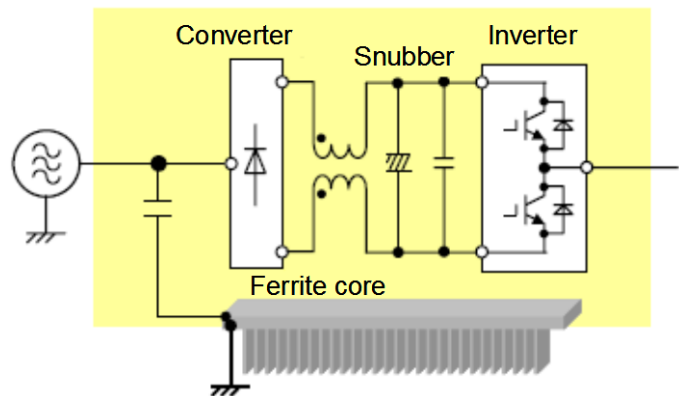


Fig.10-24 Example of Measure by means of Common

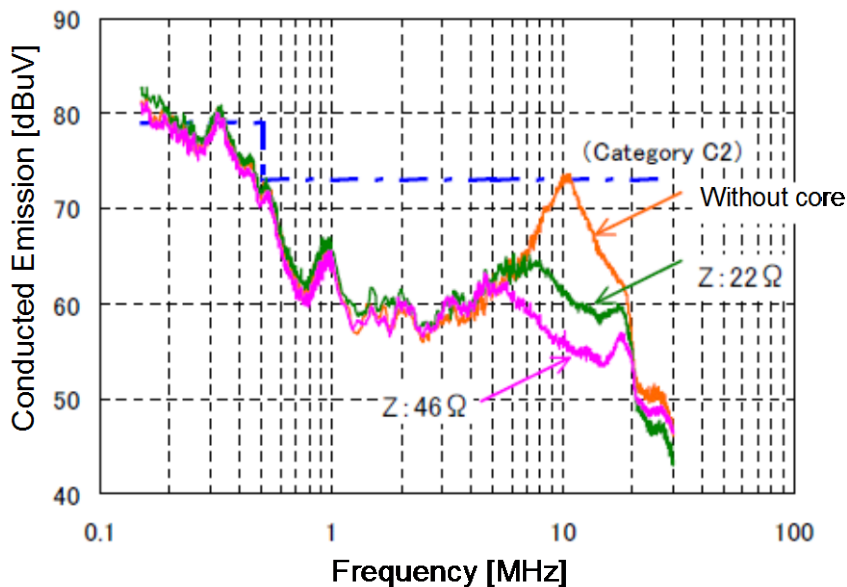


Fig.10-25 Measurement Results of Conducted Emissions

3.1.4 Measures against radiated emissions of IGBT module

The main cause of the radiated EMI emissions is considered to be the high-frequency L-C resonance produced by the junction capacitance of a semiconductor chips and stray inductance on the wiring (mainly the wiring between a module and a snubber capacitor) that is triggered by high dV/dt produced when the IGBT turns on (a FWD on the opposing arm side acts as reverse recovery) (Fig. 10-26). This is the same occurrence mechanism as the peak in the conducted emissions described above.

Generally, the far electric field E_f at frequency f radiated from a very small current loop (aforementioned L-C loop here) placed in a free space is given by the following formula (Maxwell's equations).

$$E_f = \frac{1.32 \times 10^{-14}}{r} \cdot S \cdot I_f \cdot \sin \theta \quad (1)$$

r : distance from loop, S : area of loop,
 I_f : current value of loop, θ : angle from loop surface

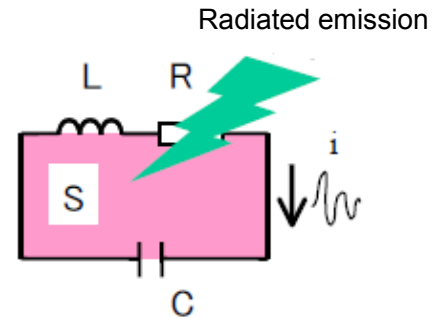


Fig.10-26 Loop formed by a module

From this formula (1), it is known that the E_f is in inverse proportion to the distance from the loop and the loop area is proportional to the loop current.

The current value I_f is given by the following formula.

$$I_f = \frac{E}{Z} \quad (2)$$

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

In order to reduce the radiated emissions, therefore, the following measures may be considered.

- [1] Increasing the distance from the loop
- [2] Decreasing the loop area S
- [3] Decreasing the loop current
 - [3]a Decreasing the spectrum of switching voltage
 - [3]b Increasing the loop impedance

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

3.1.4.1 Reducing loop area S

As described above, the high-frequency noise current induced when switching is the parasitic capacitance of the device and the resonance current of L-C loop formed by the snubber capacitor (path [4] of Fig. 10-12). With medium/large capacity module of 2in1 package class, it is necessary to minimize the radiation area of the loop by screwing the mold type snubber capacitor directly to the terminals. This is also effective from the viewpoint of controlling the spike voltage when switching.

Pin terminal type modules such as 6in1 and 7in1 types are installed on the power substrate in most cases, but it is important for the snubber capacitor to be arranged near the P/N terminal pins as much as possible.

3.1.4.2 Decreasing voltage spectrum

As described above, the spectrum of voltage waveform when IGBT and FWD chips are switching is as shown in Fig. 10-27.

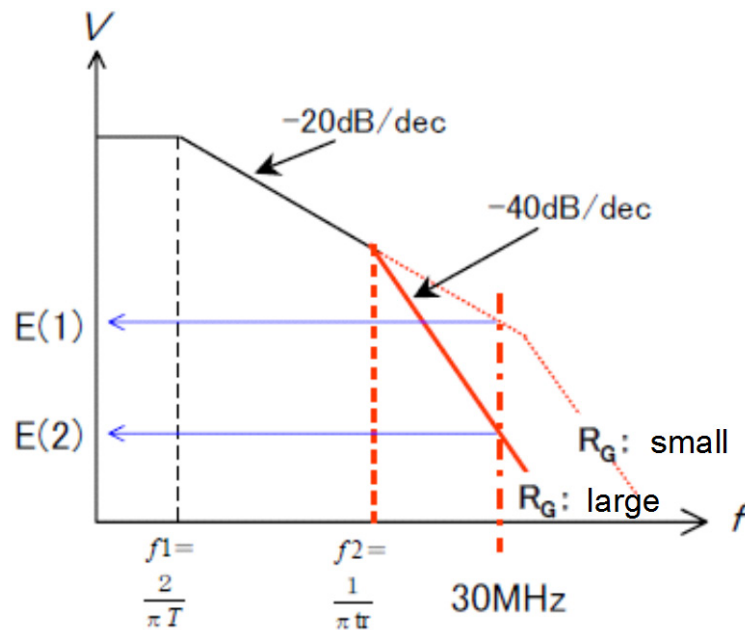


Fig.10-27 Spectrum of IGBT Switching Voltage Waveform

Conventionally, the method to make the rise time t_r slower by increasing the gate resistance has been generally applied, and this means to make lower frequency of f_2 in Fig. 10-27 and reduce the spectrum of 30MHz or higher. In comparison with the voltage component $E(1)$ at 30MHz when R_G is small and the voltage rise and fall time are short (dV/dt is large), the voltage component when R_G is large and dV/dt is small becomes smaller like $E(2)$.

Since $E(1)$, $E(2)$ is equivalent to E in Formula (2), reducing the dV/dt means to control the noise current I_f consequently.

Fig. 10-28 shows the dependency on gate resistance of the radiated emissions of 7MBR100U4B-120. By approximately doubling the standard resistance, the radiated emissions can be greatly controlled. Thus, the radiated emissions can be easily controlled by adjusting the gate resistance for U4 series, and the emission and loss are balanced well.

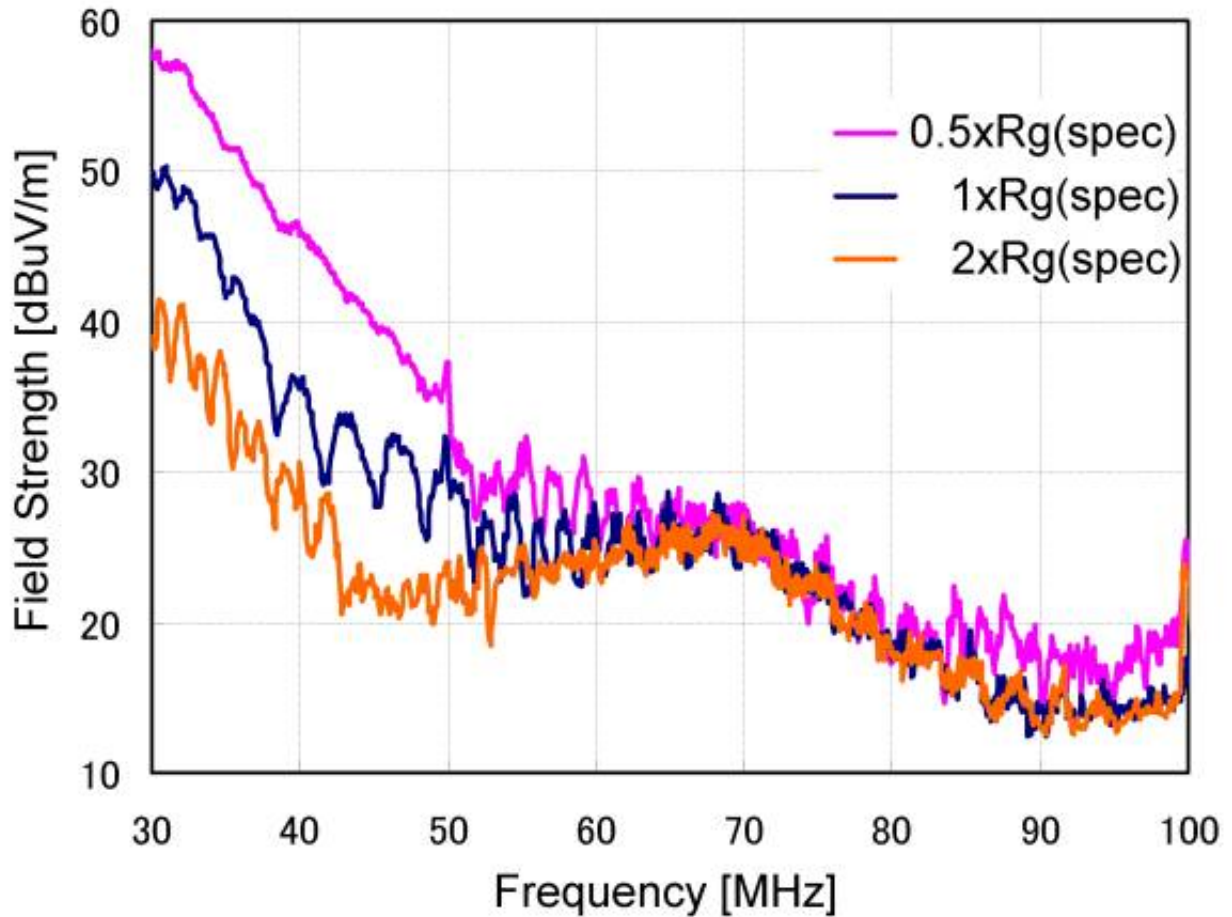


Fig.10-28 Dependency on Gate Resistance of Radiated Emissions of 7MBR100U4B-120

3.1.5 Summary

As described above, the EMI (especially the peak value of high-frequency conducted emission at not less than 10MHz and radiated emission) produced by IGBT switching is generated 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. As the measures against the emissions, therefore, it is important to accurately discover the resonance of the loop to be the problem and take proper measures.

WARNING

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 - Computers
 - OA equipment
 - Communications equipment (terminal devices)
 - Measurement equipment
 - Machine tools
 - Audiovisual equipment
 - Electrical home appliances
 - Personal equipment
 - Industrial robots etc.
5. If you need to use a product in this Catalog for equipment requiring higher reliability than normal, such as for the equipment listed below, it is imperative to contact Fuji Electric Co., Ltd. to obtain prior approval. When using these products for such equipment, take adequate measures such as a backup system to prevent the equipment from malfunctioning even if a Fuji's product incorporated in the equipment becomes faulty.
 - Transportation equipment (mounted on cars and ships)
 - Trunk communications equipment
 - Traffic-signal control equipment
 - Gas leakage detectors with an auto-shut-off feature
 - Emergency equipment for responding to disasters and anti-burglary devices
 - Safety devices
 - Medical equipment
6. Do not use products in this Catalog for the equipment requiring strict reliability such as the following and equivalents to strategic equipment (without limitation).
 - Space equipment
 - Aeronautic equipment
 - Nuclear control equipment
 - Submarine repeater equipment
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