# Measures against Radiation Noise (in Voltage Resonant Circuits with IGBT)

## Description

Inverter systems using voltage resonant circuits are widely applied mainly for cooking appliances such as IH rice cookers, IH cookers and inverter microwave ovens. These equipment requires more attention to the conduction noise conducted through the PCB or wiring and the radiation noise emitted into the space, which are caused by the high-speed switching operation of transistors. In recent years, the noise emitted from the equipment and the immunity of the equipment to the noise from outside have become increasingly stringent.

This application note reports on the analysis of radiation noises from IH rice cookers and IH cookers using IGBT in voltage resonant circuit, and specific circuit measures and their effectiveness.

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# 1. Electromagnetic noise

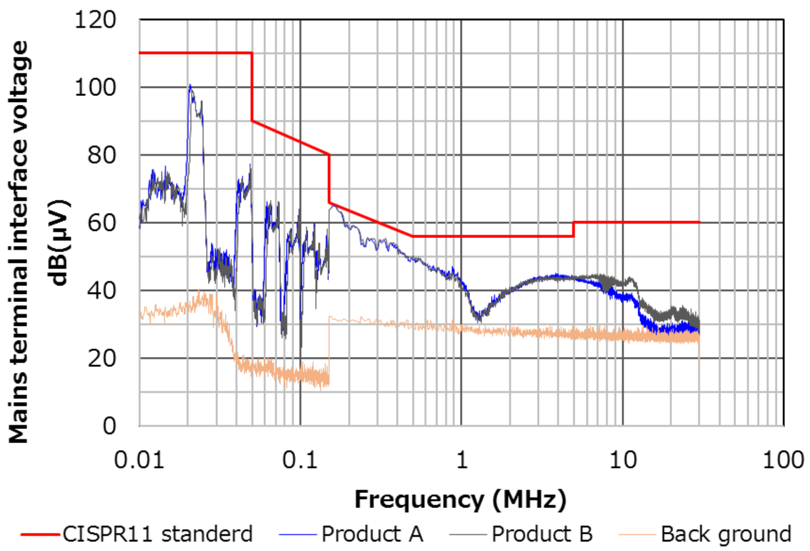
## 1.1. Electromagnetic Noise and Affect of IGBT Operation

In general, noise related to electronic equipment includes noise emission occurred when electrical equipment operates and affect other equipment, and noise immunity that is affected by other equipment and power supply lines.

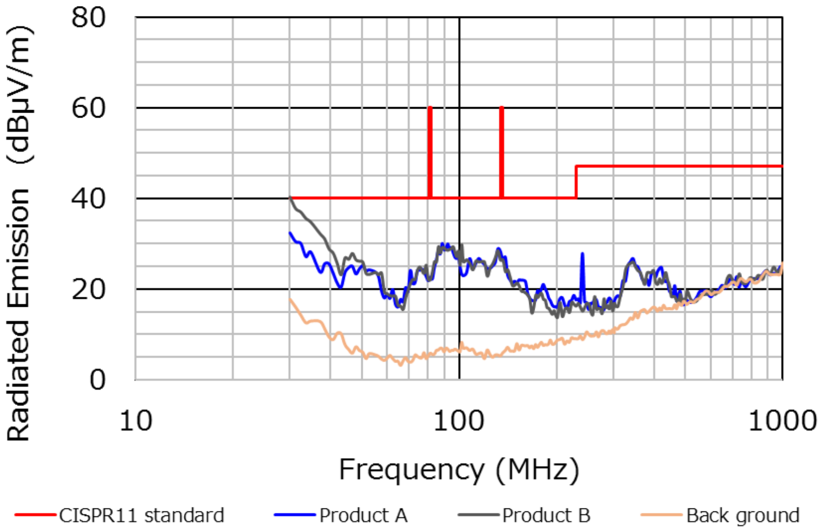
The former is classified into EMI (Electromagnetic Interference) and the latter is classified into EMS (Electromagnetic Susceptibility). These two are collectively called EMC (Electromagnetic Compatibility). This EMC is regulated in various countries, and International Special Commission on Radio Interference CISPR standard is the center of the standard. (commonly known as Comité International Spécial des Perturbations Radioélectriques)

This time, we will report on analyzing the switching performance that affects the EMI of IH (Induction Heating) applied equipment using IGBT (Insulated Gate Bipolar Transistor) as a switching transistor and measures lowering the EMI level. EMI has conduction noise directly conducted from the power supply lines and PCB pattern, and radiation noise transmitted as radio waves in the space. It is known that the former is mainly determined by PCB and filter design of equipment, and the latter is affected by switching operation of transistors.

This application note reports on IGBT switching behavior and radiation noise. Figure.1-1 shows measurement result of conduction noise and radiation noise when different IGBT are installed in a tabletop IH-cooker. There is no significant difference in conduction noise due to differences in IGBT components, but there is a significant difference in radiation noise. To suppress radiation noise, it is essential to suppress noise generated by IGBT. The magnitude of radiation noise is expressed in Mains terminal interface voltage (dBμV/m).




a) Example of conduction noise (actual measurement)




(b) Example of radiation noise (actual measurement)

**Figure. 1-1 Relation Tabletop IH-cooker Noise and IGBT**

## 1.2. Radiation Noise Standards

CISPR was established in France in 1934 as one of the special subcommittees of the IEC (International Electro technical Commission). CISPR11 (Industrial, scientific and medical equipment), CISPR14(household appliances, electric tools and similar equipment) and CISPR15 (electrical lighting and similar equipment), and other standards have been defined for each application field, in order to prevent radio interference caused by the electronic equipment and to ensure a unified of measuring methods and tolerances. IH-cooking appliances are specified in CISPR11 (Tolerances and Methods of Measuring Interference from Industrial, Scientific and Medical Equipment).

The revision of the international standard CISPR11 (2009-5th) + No. 1 (2010) was also applied to the Japan domestic Electrical Appliances and Materials Safety Act (J55011 H27), and there were changes to the standards related to radiation noise. Figure.1-2 shows the new and old standard values. New standards have changed to more stringent standard.

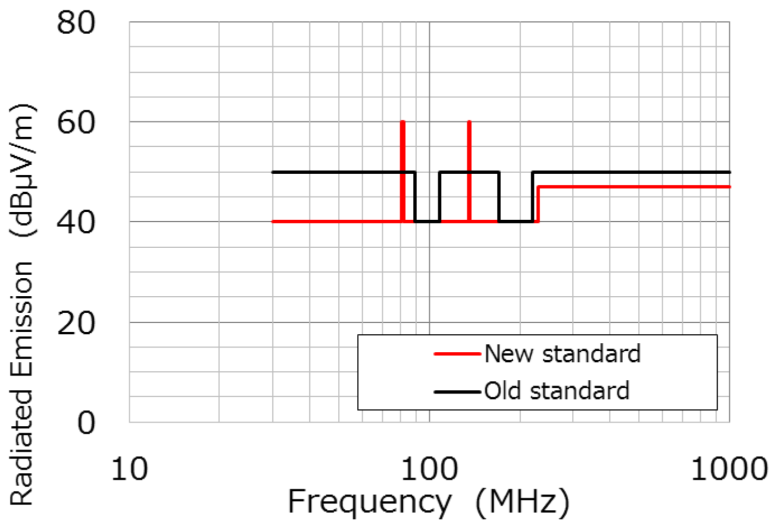



**Figure. 1-2 Old and New Radiation Noise Standard**

## 1.3. Actual Measurement Examples and Standards of Radiation Noise of IH Cooker and IH Rice Cooker

Power Loss of switching transistors including IGBT is mainly caused by conduction loss due to voltage drop during current conduction and switching loss at turn-on and turn-off. Switching transistors are achieving lower power loss as generations advance. The switching loss is determined by the function of applied voltage, current, switching time, and frequency. In order to reduce switching losses, high-speed switching performance that realizes shorter switching time is required. On the other hand, this high-speed switching performance leads steeply change of current and voltage, which is disadvantageous in terms of suppressing the noise of equipment.

Figure.1-3 shows the standard and actual measured values of radiated emission using an IH rice cooker as an example. Products A and B, which have achieved low-loss due to their high-speed switching performance, but exceeded CISPR11 standard around 32MHz. Therefore, some measures must be taken to lower the noise level. Reducing radiation noise is becoming increasingly important.

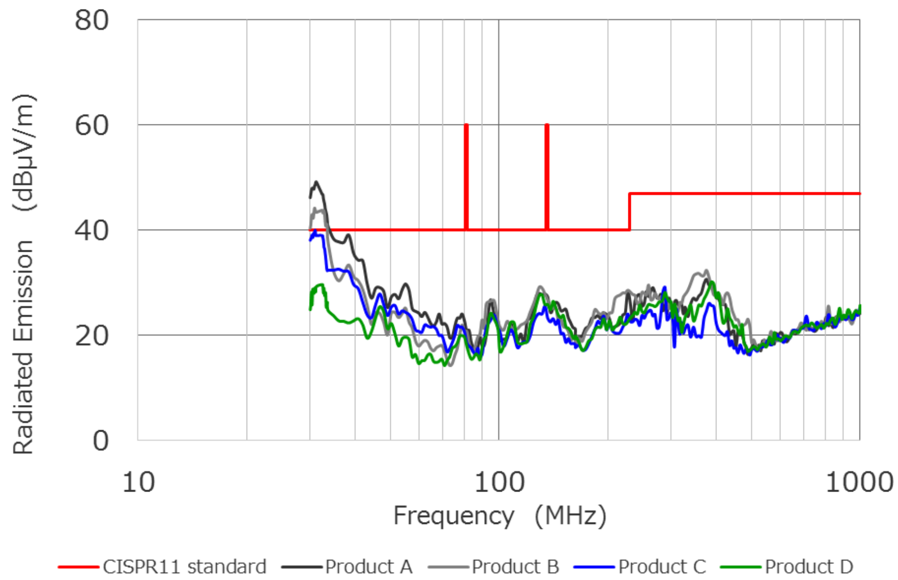



**Figure. 1-3 Differences in Radiated Emission in IH Rice Cooker by IGBT Products (Actual Measurement)**

# 2. Voltage Resonant Circuits and Major Factors of Radiation Noise

## 2.1. Voltage resonant circuit

The voltage resonant circuit consists of a switching IGBT ($Q_1$), a free whiling diode (FWD), and an LC parallel circuit ($L_r$, $C_r$), which is applied in IH rice cookers, IH cookers, and inverter microwave ovens. Figure.2-1 shows a typical voltage resonant circuit using a IGBT with a bridge-connected diode and main capacitor ($C_m$).

Figure.2-2 shows the wave form of voltage and current applied to the switching IGBT.

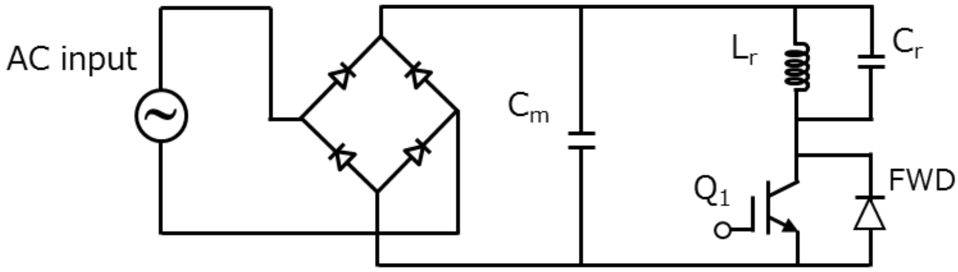



**Figure. 2-1 Voltage Resonant Circuits Using IGBT**

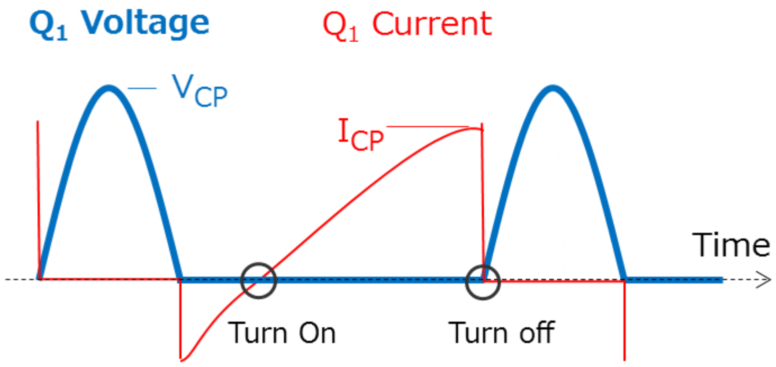
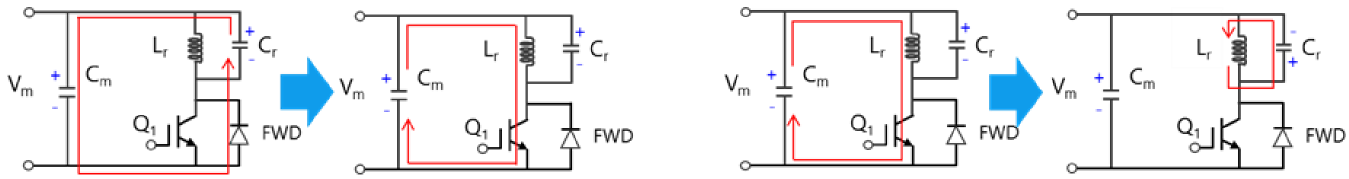



**Figure. 2-2 Current and Voltage Waveforms of IGBT in Voltage Resonant Circuit**

Figure.2-3 shows the operation of IGBT in the voltage resonant circuit. At turn-on, Voltage and Current of IGBT is nearly zero and radiation noise are rarely issues. At turn-off, radiation noise is generated because IGBT currents steeply move toward zero. The differences between IGBT components are also significant.




(a) Operation at turn-on (b) Operation at turn-off

**Figure. 2-3 Operation of IGBT in Voltage Resonant Circuit**

Refer to GT20N135SRA Application Note (November 2019) for more information on the operation of the Voltage Resonant Circuit.)

### 2.2. Relation between switching characteristics of IGBT and radiation noise

Figure.2-4 shows the typical turn-off switching waveform of the voltage resonant circuit shown in Figure 2-1. The gate signal is turned off, and the gate-emitter voltage $V_{GE}$ of IGBT drops. After $t_1$ Collector-Emitter Voltage $V_{CE}$ rises. Here, the voltage rise of $V_{CE}$ differ from typical inductance load indicated by a broken brown line, which is suppressed by resonant capacitor $C_r$ as solid brown line. The collector current $I_C$ begins to decrease after $t_2$ and it becomes zero when $V_{GE}$ reaches the gate-emitter cutoff voltage $V_{GE(OFF)}$. Therefore, the current change of the collector current $I_C$ can be thought of as Equation (1).

For the collector current change rate at turn-off

$$-dic/dt \fallingdotseq \frac{I_{CP}}{t_3}$$ ---------------------------------------------- Equation (1)

On the other hand, in $t_3$ period shown in Figure. 2-4(b), the following characteristics are seen in the waveform.

Gate-emitter voltage ($V_{GE}$) ------------------- After $t_2$ period, the behavior of the V-shape (once falls to nearly zero and returns) is observed.
Collector-emitter voltage ($V_{CE}$) -- Voltage elevation like bump
AC Powering Cable Current ------ Noise swinging positively and negatively is seen

The mechanism of the radiation noise here is considered that the noise generated by the switching operation of the device propagates inside the circuit and radiates to the outside by reaching the input AC-cable. The Voltage elevation like bump on $V_{CE}$ waveforms are considered due to the di/dt during turn-off and the parasitic inductance inside device and it to be related with radiation noise.
Also, it is commonly known that a large change in the collector current $-di_C$ /dt is detrimental to noise. To suppress radiation noise, it is necessary to increase $t_3$ duration in Equation (1). Equation (4) shows an approximation of $t_3$ interval.

The amount of gate charges in $t_3$ period ΔQ ($t_3$) is expressed as follows.

$$\Delta Q(t_3) = \int_0^{t_3} i_g \ \ dt$$

It is transformed from {Q = I × t} to { t = Q ÷ I}.

$$t_3 = \frac{\Delta Q(t_3)}{i_g}$$ ---------------------------------------------------- Equation (2)

For the gated current $i_{g\,(Vgp)}$ when $V_{GE}$ reaches $V_{gp}$ .

$$i_{g(Vgp)} = \frac{V_{gp}}{R_G + r_g}$$

The gate current $i_{g(VGE(OFF))}$ when $V_{GE}$ reaches $V_{GE(OFF)}$.

$$i_{g(V_{GE(OFF)})} = \frac{V_{GE(OFF)}}{R_G + r_g}$$

Assuming that the average gate current $i_{g\ (avg)}$ during $t_3$ period is the average of $i_{g\ (Vgp)}$ and $i_{g\ (VGE(OFF))}$.

$$i_{g(avg)} = \frac{i_{g(Vgp)} + i_{g(VGE(OFF))}}{2}$$

$$i_{g(avg)} = \frac{V_{gp} + V_{GE(OFF)}}{2 \times (R_G + r_g)} \quad \text{------------------------- Equation (3)}$$

Substitute equation (3) by replacing $i_g$ in equation (2) with $i_{g(avg)}$

$$t_3 = \frac{\Delta Q(t_3)}{i_{g(avg)}}$$

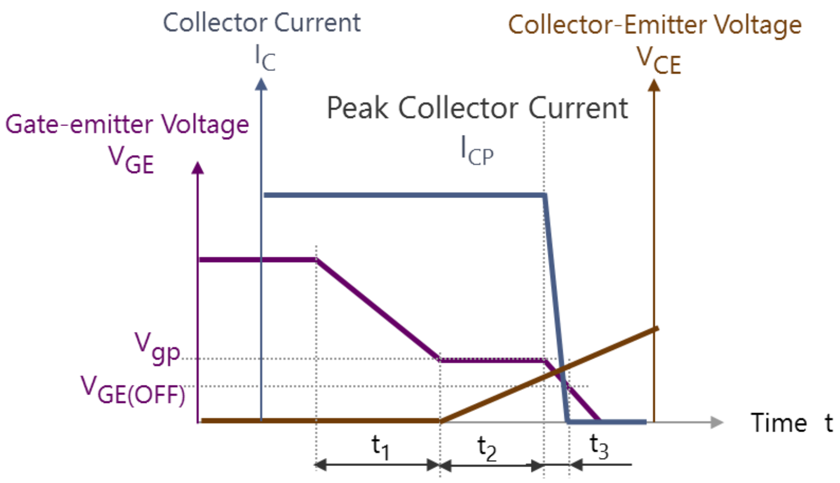
$$t_3 = \frac{2 \times \Delta Q(t_3) \times (R_G + r_g)}{V_{gp} + V_{GE(OFF)}} \quad \text{--------------------------- Equation (4)}$$

$R_G$ : External resistance for gate drive
$r_g$ : Internal gate resistance of IGBT
$i_g$ : Gate current

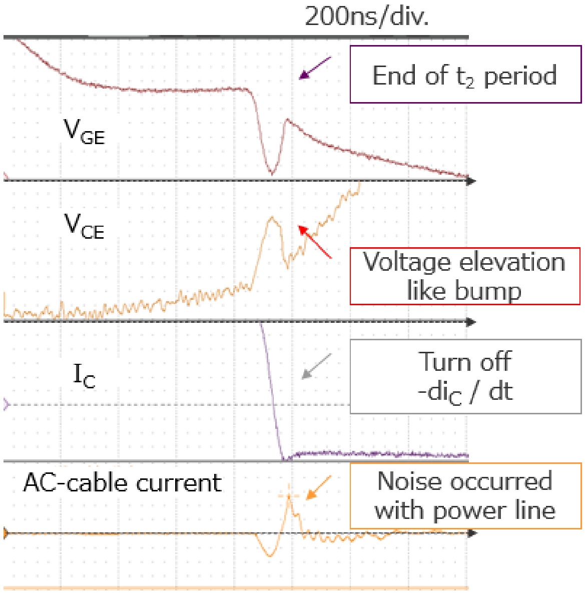
From Equation (4), as a measure to increase $t_3$,

(1) Increase the value of resistance $R_G$ for IGBT gate drive.
(2) Inserting an Additional capacitor $C_G$ between Gate and Emitter.
(3) Adding an Inductance $L_E$ to Emitter

These could be considered as counter measures shown in Figure 2-5.

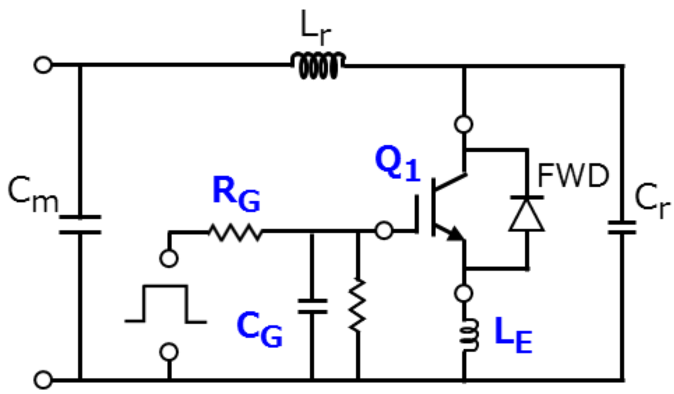



(a) Overall turn-off waveform definition




(b) Example of turn-off waveform (actual measurement)

**Figure. 2-4 Example of switching waveform at turn-off in voltage resonant circuit**




$C_m$ : Main capacitor
$L_r$ : resonant inductance
Cr : resonant capacitor
$Q_1$ : Switching IGBT
$R_G$ : External resistance for IGBT gate drive.
$C_G$ : Additional capacitor between Gate and Emitter
$L_E$ : Additional Inductance to Emitter

**Figure. 2-5 Countermeasures for radiation noise in voltage resonant circuit21**

**Counter measures for radiation noise**

# 3. Counter measures for radiation noise

## 3.1. Counter measures

As described above, it is essential to suppress the noise generated by the switching operation of the transistors in order to suppress radiation noise. Voltage elevation like bump on $V_{CE}$ wave form, it is considered that are generated by the product of the parasitic inductance in the circuit and di/dt during turn-off. It is important to be suppresses the factors generated by switching of IGBT in order to suppress the radiation noise. Following 3 circuit counter measures could be considered.

(1) Increase the value of resistance $R_G$ for IGBT gate drive.
(2) Inserting an Additional capacitor $C_G$ between Gate and Emitter.
(3) Adding an Inductance $L_E$ to Emitter

## 3.2. External resistance $R_G$ for gate drive

Figure. 3-1 shows the radiated emission when the external resistance $R_G$ for IGBT gate-drive used in IH rice cooker is changed. The radiated emission, which was 48dBμV/m at $R_G$ = 62 Ω, it was improved to 35dBμV/m by increasing $R_G$ to 160 Ω.

In this way, the external resistance $R_G$ for gate-drive is closely related to the radiated emission. It can be dealt with by changing value of $R_G$ without changing the circuit configuration, but it will simply increase the switching time and increases the turn-off loss in proportion to the value of $R_G$ .

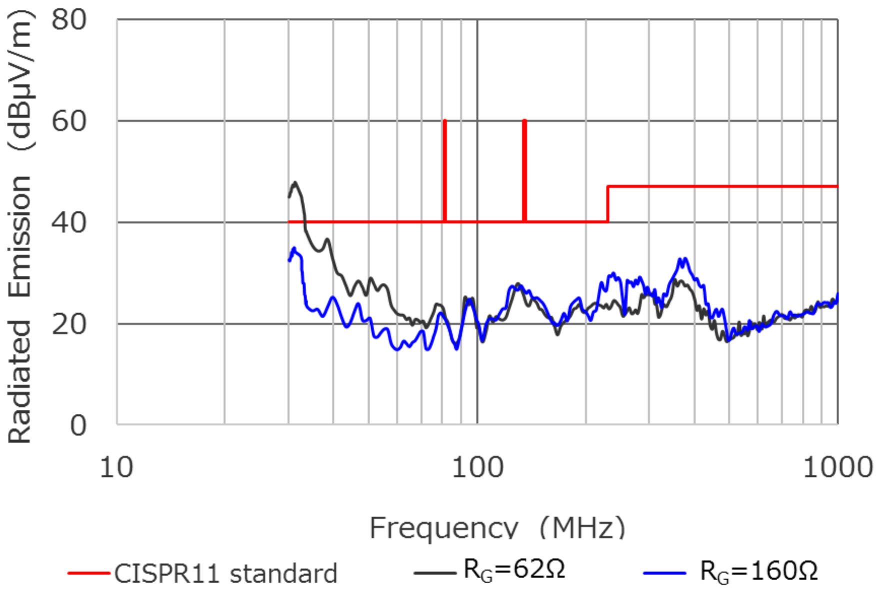



**Figure. 3-1 Radiated emission by Changing $R_G$ in IH Rice Cooker (Actual Measurement)**

### 3.3. Additional Capacitor $C_G$ between Gate and Emitter

Figure. 3-2 shows the change in radiated emission when a capacitor is inserted between the gate and emitter of IGBT used in IH rice cooker. In this test, the peak was observed at about 42dBμV/m in the early condition without additional $C_G$. However, we can observe the improvement about 7dBμV/m at 470pF, about 10dBμV/m at 940pF (470pF×2), and more than 10dBμV/m at 1410pF. IGBT used for this test has an input capacitance $C_{ies}$ about 1500pF. For additional $C_G$ values, we recommend the similar value as $C_{ies}$ value a reference.

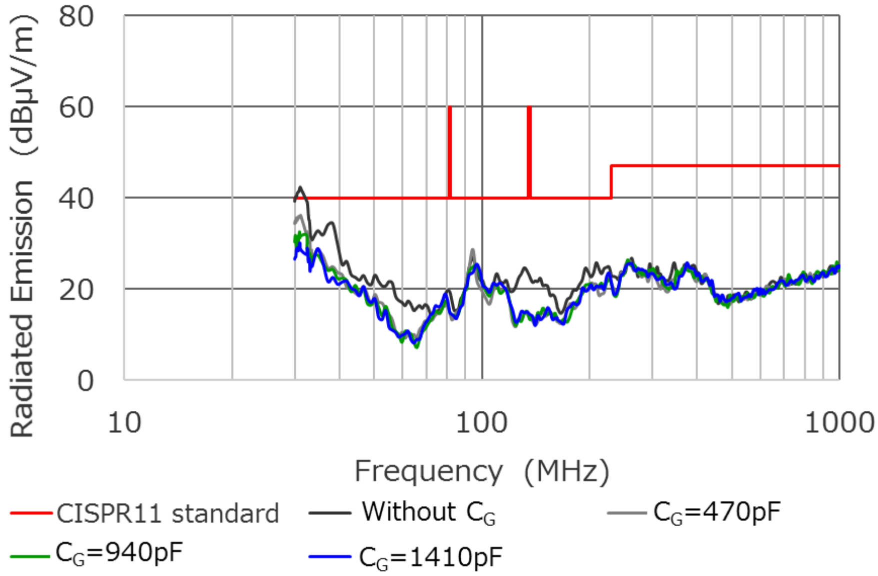



**Figure. 3-2 Radiated Emission by inserting $C_G$ in IH rice cooker (actual measurement)**

### 3.4. Additional Inductance $L_E$ to Emitter

Figure. 3-3 shows the change in radiated emission when an inductance $L_E$ is added to the emitter of IGBT used in the IH-cooker. the peak was observed at about 40dBμV/m (30MHz) in the early condition without additional $L_E$. However, we can observe the improvement about 10dBμV/m at 40nH, reduced to 30 dBμV/m.

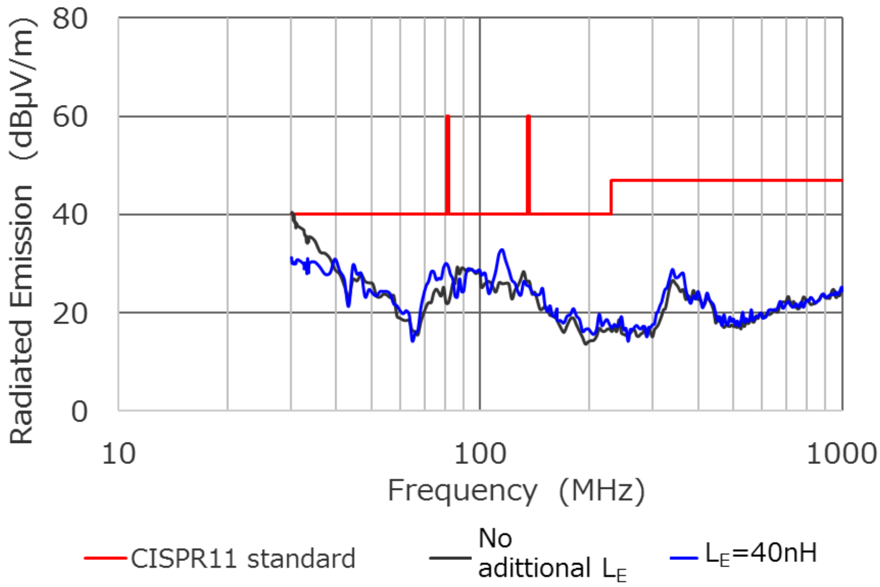
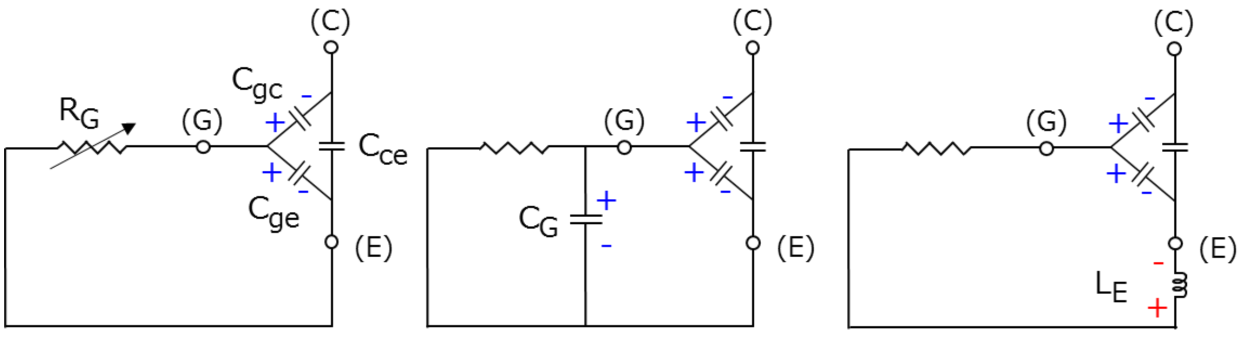



**Figure. 3-3 Radiated Emission by adding $L_E$ in IH rice cooker (actual measurement)**

### 3.5. Effectiveness and Issues of Each Counter Measures

Three circuit measures are considered in terms of their impact on switching characteristics. Figure.3-4 shows simple model as IGBT is replaced by capacitor. In the illustration, the Gate, Collector and Emitter terminals of the IGBT are represented by (G) (C) (E).




(a) Change $R_G$ Value (b) Insert $C_G$ (c) Add $L_E$

**Figure. 3-4 Simple model to study counter measures to suppress radiation noise and issues on switching characteristics.**

(1) Increase value of the external resistance $R_G$ for IGBT gate-drive.

As shown in Figure. 3-4(a), duration of discharge stored charge in $C_{gc}$ and $C_{ge}$ will be longer. As the result, switching duration for the entire from $t_1$ to $t_3$ shown will be longer in Figure. 2-4(a). $t_3$ is longer, and radiated emission is reduced, on the other hand, $t_2$ is also longer and switching loss is increased.

(2) Inserting an additional Capacitor $C_G$ between Gate and Emitter of the IGBT

As shown in Figure. 3-4(b), It does not affect discharge from $C_{gc}$, although the switching $t_{1,}$ $t_3$ in Figure.2-4(a) is longer, since there is no change in $t_2$, the effect on switching loss is smaller than that of the measure by $R_G$.

(3) Adding an Inductance $L_E$ to IGBT Emitter

As shown in Figure.3-4(c), the gate bias is affected only when the emitter current changes. During $t_3$ shown in Figure.2-4(a), the voltage shown in Figure.3-4(C) is generated at both ends of $L_E$ due to the current change. Voltage acts to positively bias the gate and emitter, reducing radiated noise by delaying IGBT turn-off. The voltage generated at $L_E$ is applied between gates and emitter of IGBT so that it is necessary to take care to not exceed the absolute maximum rating at $V_{GES}$.

### 3.6. Noise Reduction Study by Simulation

the following three circuit measures have been explained using measured data as a method of reducing radiation noise.

(1) Increase value of the resistance $R_G$ for IGBT gate drive.
(2) Inserting an Additional capacitor $C_G$ between Gate and Emitter.
(3) Adding an Inductance $L_E$ to Emitter

Verifying the effect on radiation noise by actual measurement requires a lot of time and effort because it needs to examine many combinations and conditions. Pre-simulation makes it efficient if it is possible so that a metric related to the radiation noise was investigated from the switching waveform.

Here, the noise generated by the switching operation of IGBT propagates inside the circuit and influence to the AC-cable and it radiates to the outside.

The voltage elevation like bump on $V_{CE}$ waveform are due to the product of di/dt during turn-off and the parasitic inductance of the circuit and it is considered to be related to radiation noise. Looking at $V_{CE}$ waveform shown in Figure. 2-4(b), we examine the relation with the radiated emission when $R_G$ condition is changed. The following figure defines "$\Delta V_{CE}$" on $V_{CE}$ waveform.

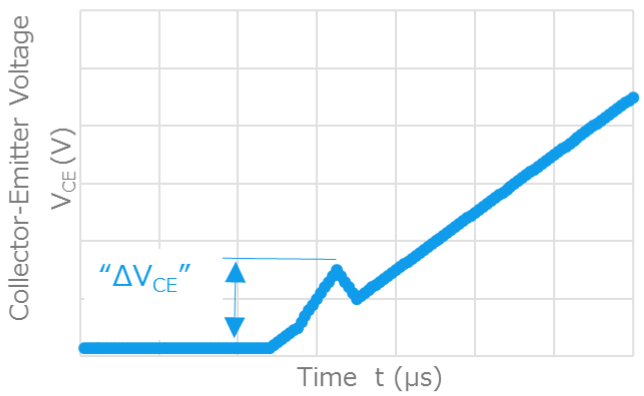



**Figure. 3-5 Defining $V_{CE}$ Waveforms Related to radiated emission**

Figure. 3-6 shows the peak and mean values of radiated emission and $V_{CE}$ waveform (elevation like bump). Positive relationship between both are seen, the smaller the peak of $V_{CE}$ ($\Delta V_{CE}$ thereafter), the smaller radiated emission.

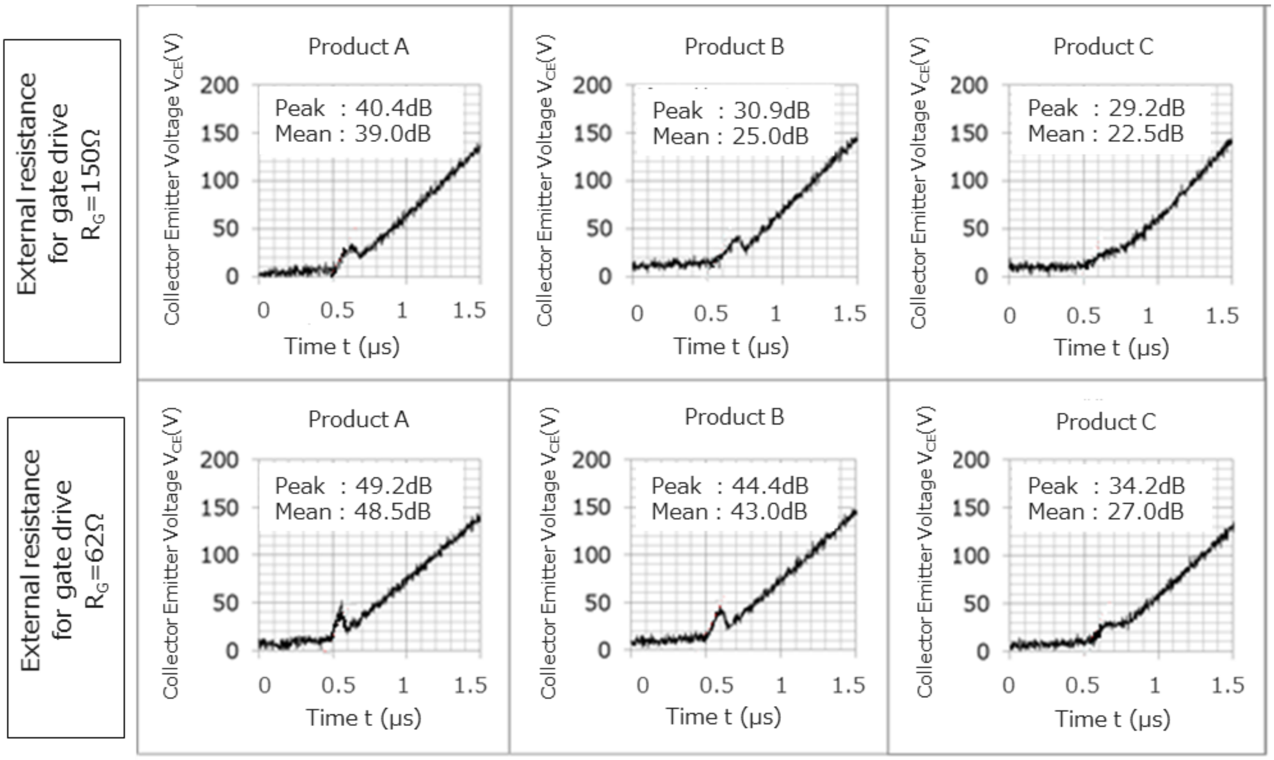



**Figure. 3-6 "$\Delta V_{CE}$" waveforms and radiated emission (actual measurement)**

Referring the actual IH cooker circuit, a circuit model is created as shown in Figure.3-7 and simulation was performed to study conditions to reduce the "$\Delta V_{CE}$" (= low radiated emission).

A screen of simulation software is indicated below. The item name is different from usual because special symbol can't be used by software.

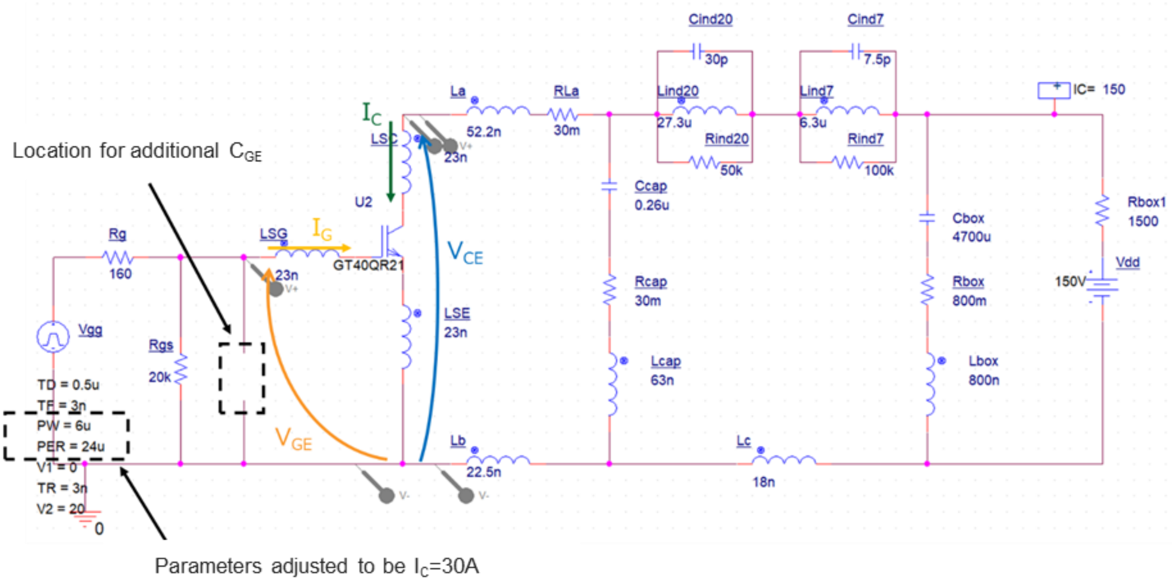



**Figure. 3-7 Model of Voltage Resonance Circuit for IH Rice Cooker (Simulation)**

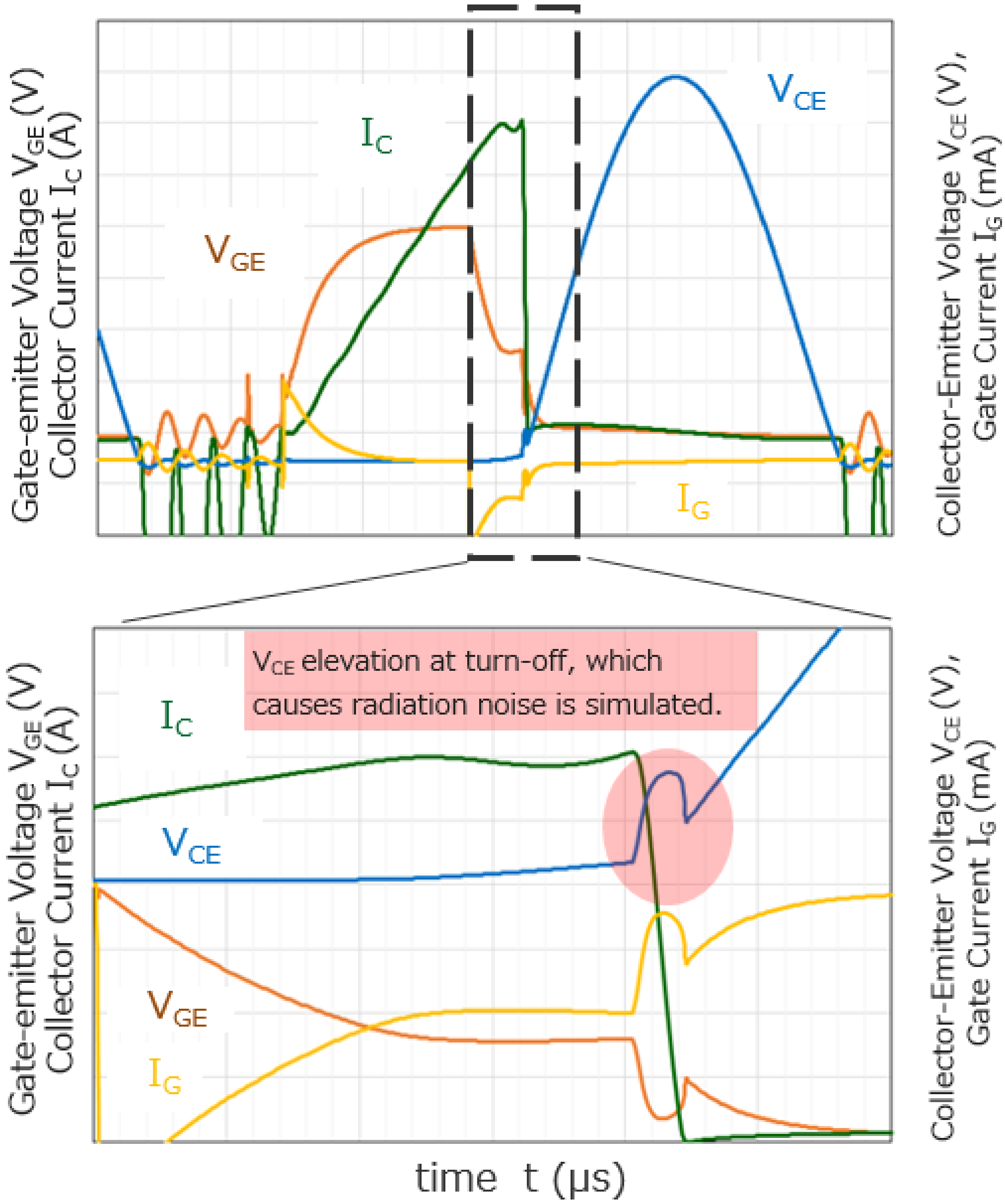



**Figure. 3-8 Voltage Resonance Waveform for IH Rice Cooker (Simulation)**

It is generally known that changing the external resistance $R_G$ for gate-drive affects the turn-off loss. Therefore, we confirmed not only the radiated emission but also the effect on the switching loss. Increasing $R_G$ can reduce the "Δ $V_{CE}$" but the turn-off loss is significantly increased.

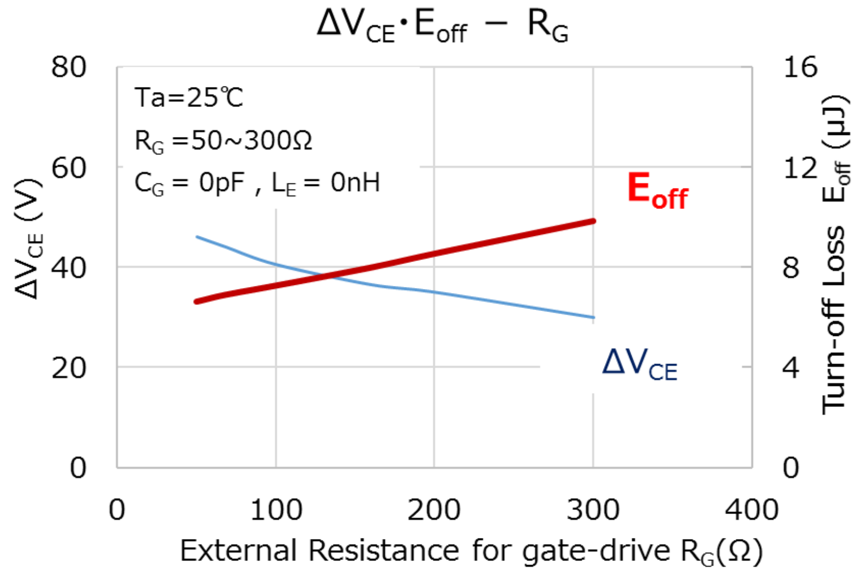



**Figure. 3-9　$R_G$ Effects on Turnoff Loss and "Δ $V_{CE}$" (Simulation)**

On the other hand, increasing $C_G$ and $L_E$ can improve the radiation noise without significant increase of turn-off loss. In particular, $L_E$ has little effect on turn-off loss. But it is necessary to take care for the voltage induced by the emitter current and additional Inductance.

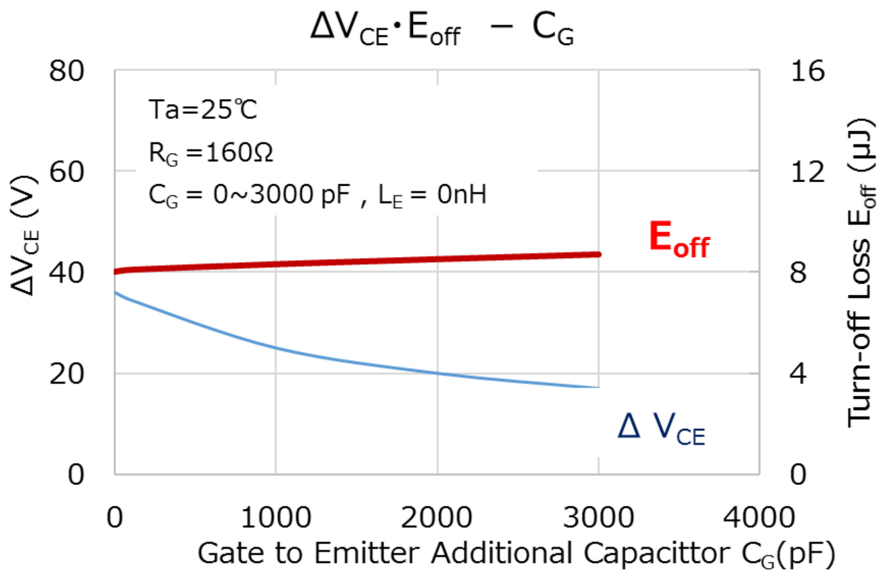



**Figure. 3-10　$C_G$ Effects on Turnoff Loss and "Δ $V_{CE}$" (Simulation)**

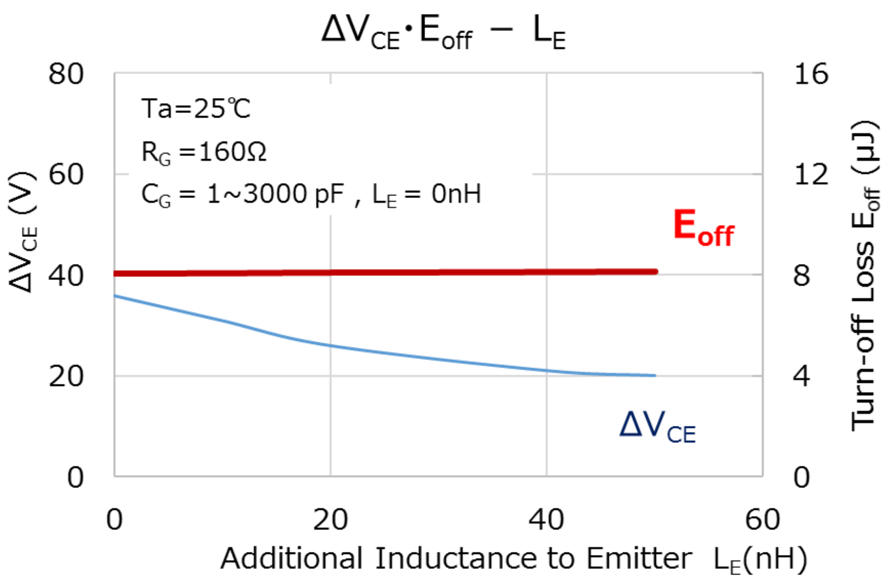



**Figure. 3-11 $L_E$ Effects on Turnoff Loss and "Δ $V_{CE}$ " (Simulation)**

At the turn-on of the voltage resonant circuit shown in Figure. 2-3(a), in normal operation, the terminal voltage of the resonant capacitor $C_r$ is same as the voltage of the main capacitor $C_m$, the current that flows through resonant inductance $L_r$ rises from zero.

On the other hand, $C_r$ voltage is zero or near when the power is turned on, large short-circuit current flows through $C_r$, this short current and parasitic inductance create an overvoltage between the gate and emitter of IGBT. Figure.3-12 shows an example of the waveform when the IH rice cooker is turned on. Collector current peak value during normal operation might be 40A, which jumps up to nearly 130A at power on.

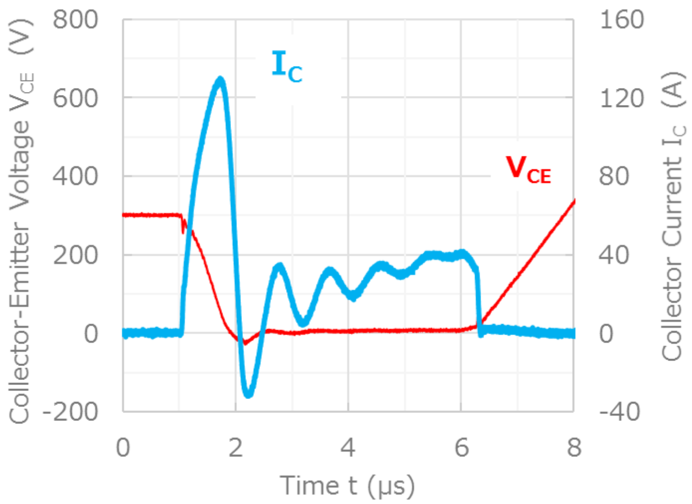
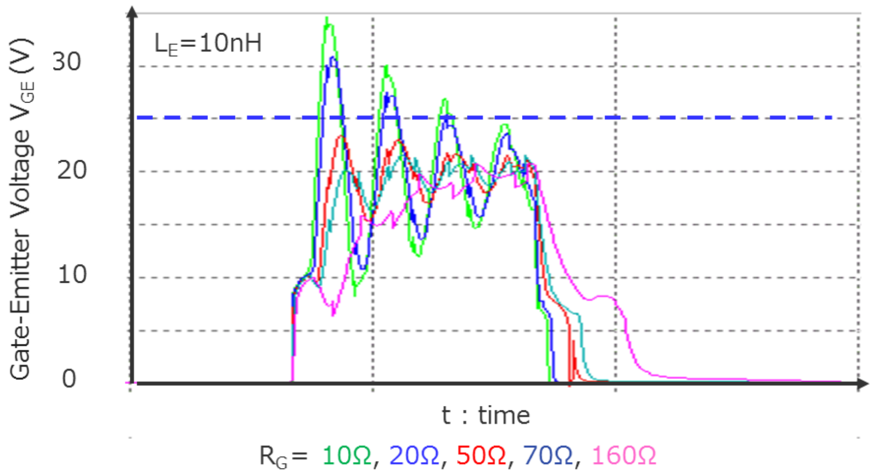


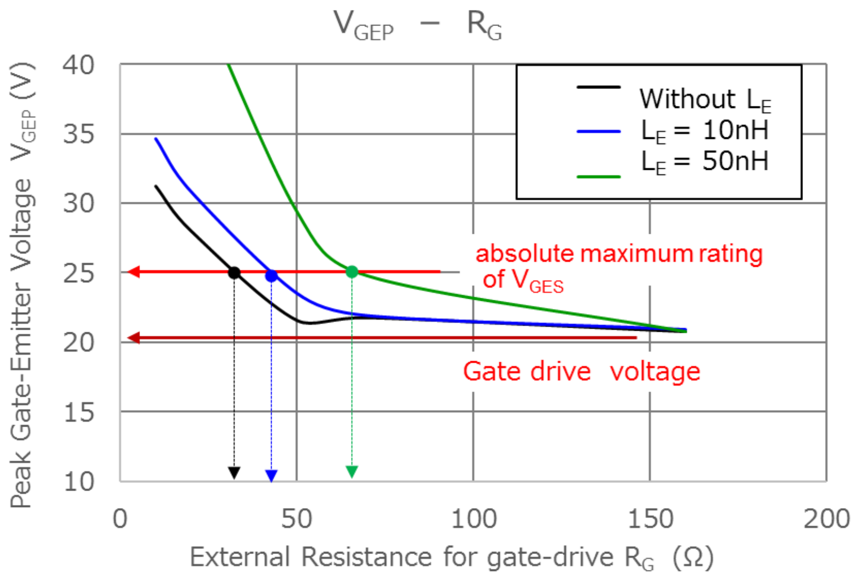

**Figure. 3-12 Example of waveform at power on (actual measurement)**

In Figure.3-13 shows simulation results of the relation between the gate-emitter voltage waveform and external resistance $R_G$ for gate-drive. When additional inductance $L_E$ is inserted, the surge voltage generated between gate and emitter due to the short-circuit current which becomes large, it may exceed the maximum rating $V_{GES}$.

Figure.3-13(a) shows gate emitter waveforms by $R_G$ when $L_E$=10nH inserted. Figure.3-13(b) shows the change of peak value of gate emitter voltage when the power is turned on. When $R_G$ is increased, peak voltage is decreased because short current become to be suppressed. It is necessary to choose $R_G$ value in order to $V_{GE}$ does not exceed the absolute maximum rating of $V_{GES}$.




(a) $V_{GE}$ wave from with $L_E$ = 10nH




(b) $V_{GEP}$ depends on $R_G$ and $L_E$

**Figure. 3-13 Gate-Emitter Voltage at Power-on (Simulation)**

## 4. Summary

For IH-cookers, IH rice cookers, and microwave oven, these cooking appliance with inverter function are using IGBT mainly as switching device. As a tendency of many switching devices, lower switching loss is required for high-efficiency design and easy heat dissipation as well as IGBT.

On the other hand, the radiation noise generated by the equipment due to the high-speed switching may increase and not satisfy the specified standard value.

The magnitude of the radiation noise is expressed as the radiated emission here it is considered to have relation with "$\Delta V_{CE}$" at turn-off.

The $\Delta V_{CE}$ occurs by 2 items multiplication of product in the following.

○ The Internal inductance between the collector emitter of IGBT

○ The di/dt at the time of TURN-OFF

We found, radiation noise can be done small by doing the $\Delta V_{CE}$ value small.

The following (1) (2)(3) were carried out in the circuit simulation to investigate the effect on the turn-off losses and "$\Delta V_{CE}$".

(1) Increase value of the resistance $R_G$ for IGBT gate drive.
(2) Inserting an Additional capacitor $C_G$ between Gate and Emitter.
(3) Adding an Inductance $L_E$ to Emitter

(1) can be handled by changing the resistance value simply without changing the circuit configuration. However, by increasing $R_G$, power dissipation of IGBT is increased proportionally to the value of $R_G$. Although (3) is able to suppress the radiation noise with little influence on the power loss, there is a concern that excessive voltage will be generated at Gate to Emitter when power-on. (2) has a greater effect on the loss than (3), but there are no other major problems. it will be an effective method as circuit solution.

Radiated noise is often verified during the last process of equipment design completion, and the possible solution might be limited. We recommend to consider PCB layout in advance that allows additional inductance or capacitor as measures against noise issues. Counter measures other than RG increase can be investigated more easily by PCB layout consideration in advance.

# Appendix: List of Toshiba IGBT for Voltage-Resonance Application

**Table 1 List of Toshiba IGBT for Voltage-Resonance Applications**

| $V_{CES}$ (V) | Voltage-Resonant Applications for AC100V | | | Voltage-resonant applications for AC220V | | |
|---|---|---|---|---|---|---|
| | to 1100 W | to 1250 W | to 1400 W | to 1900 W | to 2200W | to 2400W |
| 600 | | | | | | |
| 900 | GT50MR21 (6.5G) | | | | | |
| 1000 | | GT50N322A (4G) | GT50N324 (6G) | | | |
| 1050 | GT50NR21 (6.5G) | | | | | |
| 1100 | | GT60PR21 (6.5G) **GT30J110SRA (6.5G New)** | **S1PA7(*) (6.5G New)** | | | |
| 1200 | GT40QR21 (6.5G) | | | | | |
| 1350 | | | | GT40RR21 (6.5G) | **GT20N135SRA (6.5G New)** | **GT30N135SRA (6.5G New)** |
| 1800 | | | | GT40WR21 (6.5G) | | |

4G (4th generation), 6G (6th generation), 6. 5G (6.5th generation), 6. 5G New (6.5th generation New products)

(*:S1PA* indicates the prototype number at the development stage, the official name will be given in mass production.)

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