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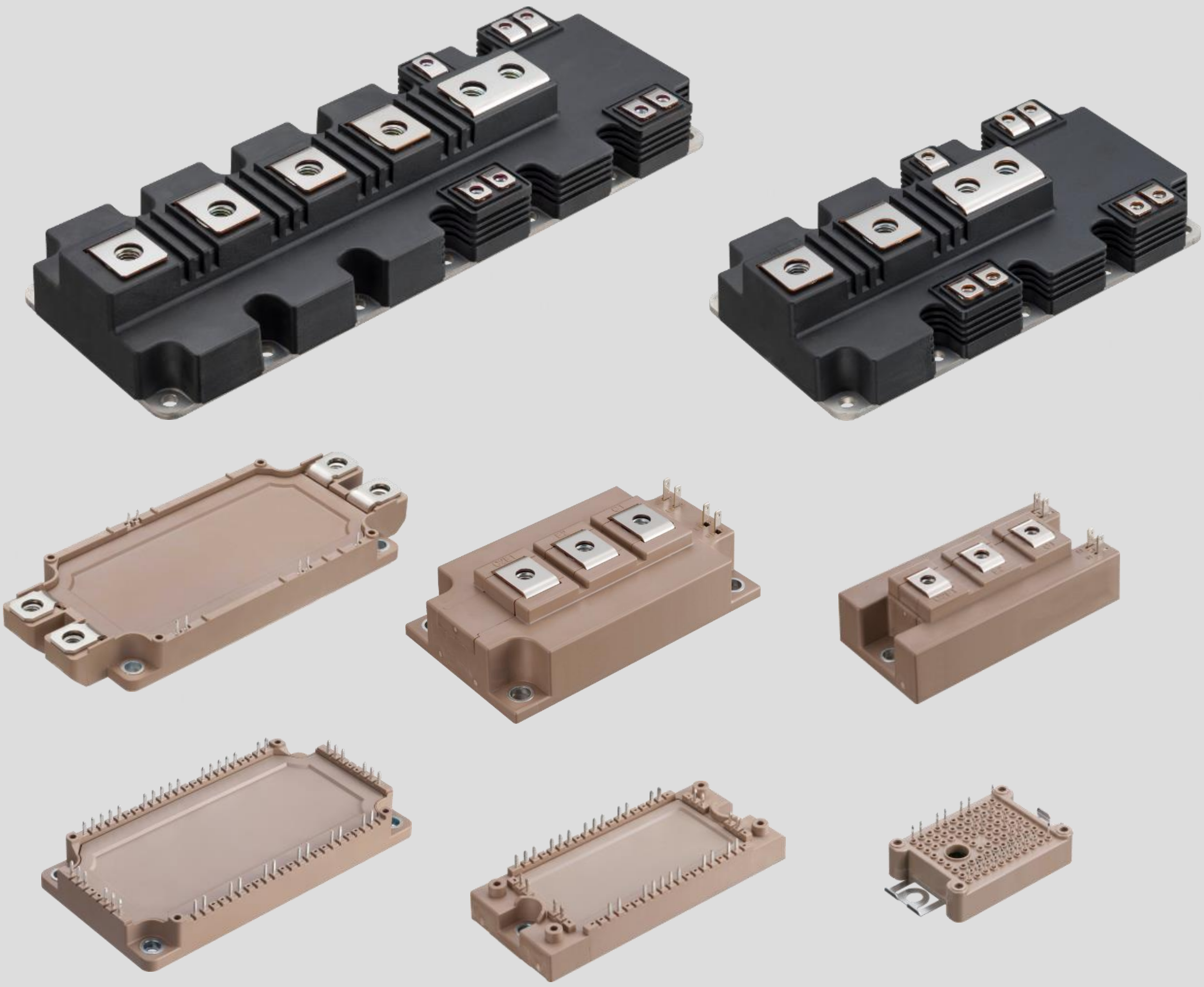

Fuji IGBT Module

Application Manual

March, 2023

Fuji Electric Co., Ltd.

⚠Cautions

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Chapter 9 Evaluation and Measurement

This chapter describes how to evaluate the characteristics of IGBT module, and voltage and current measurement methods.

1. Application Scope

This chapter describes the method of evaluating the characteristics of IGBT modules applied to power electronics equipment with a switching frequency of several kHz to 20kHz and equipment capacity of several hundred VA or more.

2. Evaluation and Measurement Methods

2.1 Overview of evaluation and measurement methods

During development of power electronics equipment, it is necessary to evaluate the characteristics and measure the load of the IGBT modules while they are installed in the equipment. An overview of the evaluation items and measurement methods is shown in Table 9-1.

Table 9-1 Overview of evaluation items and measurement methods

No.	Evaluation item	Measurement item	Measurement methods	Measuring instrument
1	Isolation voltage	Voltage	With the module terminals shorted, apply a voltage between the conductive part and the device frame.	Isolation voltage tester
2	Collector-Emitter voltage		With G-E shorted, apply test voltage to C-E. *If there is possibility that the test voltage may exceed the rating of the components connected to C-E, disconnect those components first.	Curve tracer
3	Collector-Emitter saturation voltage		Measure by connecting a voltage clamping circuit between C-E so that the built-in amplifier of the oscilloscope does not saturate. *Static characteristics can be measured with a curve tracer or pulse h_{FE} meter	Oscilloscope
4	Turn-off surge voltage	Voltage	Measure the C-E voltage directly at module terminals.	Oscilloscope
5	Switching time	Voltage Current	Measure the required voltage and current waveforms according to the switching time definition.	Oscilloscope Current probe
6	Current sharing (parallel connection)	Current	Measure the current flowing through each module.	Oscilloscope Current probe
7	Switching loss	Voltage Current	The product of the current and voltage is integrated over a specified period. (1) Calculate from voltage & current waveforms (2) Use a measuring instrument with math function	Oscilloscope
8	Operation locus		Plot the voltage & current during switching in current-voltage graph.	Oscilloscope
9	Case temperature	Temperature	Measure on the copper base under the chip *The measurement location is point A as shown in Fig. 6-9 in Chapter 6.	Thermocouple
10	Junction temperature		Create a calibration curve for the junction temperature and device characteristics with temperature dependence characteristics (for example, saturation voltage), and measure the characteristics of the device during operation to estimate the junction temperature. *Can be measured directly using an IR camera.	IR camera

2.2 Voltage measurement

Note that voltage measurement during IGBT operation is susceptible to noise caused by high-amplitude, high-speed switching operation.

(1) Measuring instrument and calibration

Both the waveform and the target voltage value are important. Normally, an oscilloscope is used as the measuring instrument, and a voltage probe is used for voltage measurement. The time constant of the voltage divider RC of the probe/oscilloscope vary depending on the oscilloscope/probe combination. Therefore, before using the probe, carry out probe compensation to achieve uniform attenuation across all frequency range by connecting it to the calibration terminal of the oscilloscope.

Set the appropriate sensitivity (generally, 3 to 4 division amplitude on the display screen) and set the input coupling to DC. Exercise caution in selecting the probe, because the adjustment capacitance of the probe and the input capacitance of the oscilloscope must match to enable adjustment. The selection of oscilloscopes and probes are shown in sections 2.5 and 2.6.

(2) Saturation voltage measurement

Generally, while the circuit voltage using IGBT is as high as several hundred volts, the IGBT saturation voltage is as low as several volts. Because the size of the screen of the oscilloscope is limited, increasing the voltage sensitivity in an effort to measure the saturation voltage accurately will result in the display of a waveform that is different from the actual waveform due to effect such as saturation of the oscilloscope built-in amplifier. Therefore, the IGBT saturation voltage during switching operation cannot be measured by directly measuring the C-E voltage of the IGBT with an oscilloscope.

The method to measure the saturation voltage is by adding a voltage clamping circuit as shown in Fig. 9-1.

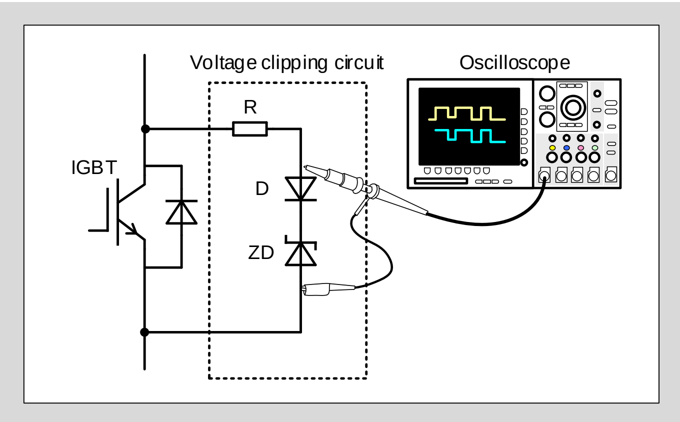


Fig. 9-1 Measurement method of saturation voltage

In Fig. 9-1, the Zener diode (ZD) limits the high voltage when the IGBT is turned off. Generally, a Zener diode with Zener voltage of 10V or less is used. R is a current-limiting resistor. Because most of the circuit voltage is applied to this resistor when the IGBT is turned off, the resistor must have a relatively large capacity. The diode (D) prevents the charges built in the junction capacitance of the Zener diode from discharging, and also prevents a RC filter from being formed by the junction capacitance and the current-limiting resistance.

(3) Surge voltage measurement (Collector-emitter voltage measurement)

While IGBTs offer the benefit of fast switching, the current change rate (-d*i*/d*t*) at turn-off is large, inducing a high voltage in the main circuit wiring inductance (L_S) of the equipment. This voltage is superimposed over the DC circuit voltage and cause a spike voltage to be applied to the module. This voltage is called surge voltage, and it is necessary to confirm that the voltage is within a predetermined voltage margin with respect to the maximum rating of the module.

The surge voltage can be measured at the terminals of the module with an oscilloscope and directly reading the value on the oscilloscope screen. Note the following precautions during measurement.

a. Use a probe and an oscilloscope having a sufficient frequency bandwidth.
b. Adjust the oscilloscope sensitivity and calibrate the probe.
c. Connect the measurement probe directly to the module terminals.

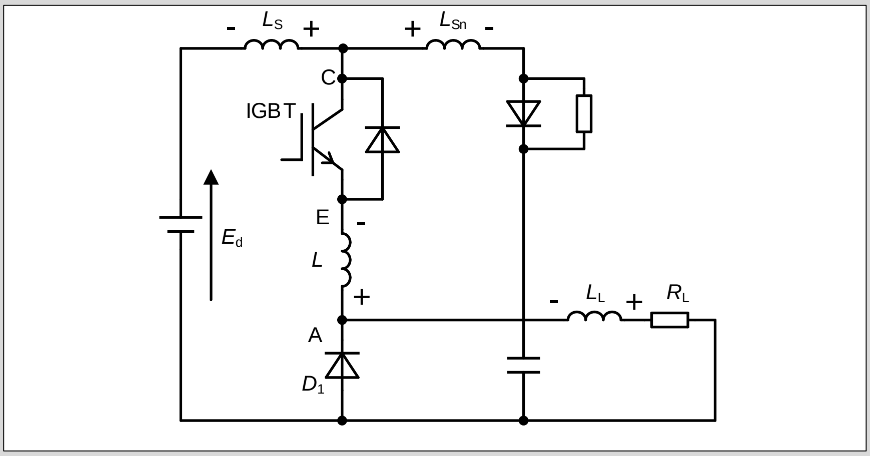


Fig. 9-2 Example of surge voltage measurement circuit

During IGBT turn-off, voltages of the polarity shown in Fig. 9-2 are induced in the circuit inductances of each part of the circuit. Note that in the case where V_{CA} is measured instead of V_{CE}, then a voltage lower than V_{CE} by $-L \cdot di/dt$ will be erroneously measured. Therefore, when measuring the surge voltage of the IGBT, it is necessary to measure it in a state where the influence of the wiring inductance *L* is minimized, such as by connecting the voltage probe directly to the module terminal.

d. Keep the probe measurement leads as short as possible.
e. Keep probe leads away from high d*i*/d*t* areas so that noise interferences are minimized.

When the voltage probe is connected to the switching circuit, the reference potential of the oscilloscope would equal the switching circuit. If there is a large ground potential fluctuation in the switching circuit, common-mode current would flow through the power line of the oscilloscope, which may cause the internal circuit to malfunction. Noise interferences can be verified by the following methods.

a. Consider whether the measured waveform can be logically explained.
b. Comparing with waveforms measured on a battery-powered oscilloscope that is less susceptible to noise interferences.

(4) Gate voltage measurement (Gate-emitter voltage measurement)

The V_{GE} can be directly measured with an oscilloscope similar to the surge voltage. However, since the IGBT gate is a capacitive load and the voltage probe also has capacitive impedance, do not attach or detach the voltage probe during measurement. The same precautions as for the surge voltage measurement are required.

2.3 Current measurement

Current probes are used for current measurement. However, in practical device, the main circuit is compact in order to reduce wiring inductances L_S and simplify the structure. Thus, the wiring needs to be extended to measure the device current. A current transformer can be used to minimize the wiring extension. In addition, the use of current transformers is also necessary due to the limited measuring capacity of the current probe.

Current probe can measure current while maintaining insulation from the conductive part, but in addition to being an electromagnetic induction-based detector, the signal level is low that it is susceptible to induction caused noise interferences. Care should be taken against noise interferences.

(1) Current detectors

Table 9-2 shows the examples of current detectors.

Table 9-2 Current detectors

No.	Product name	Model	Brand	Remarks
1	DC current probe (Dedicated amplifier and power supply required)	Model A6302	Tektronix	Maximum circuit voltage: 500V ~20A at DC~50 MHz Peak pulse current: ~50A
2		Model A6303		Maximum circuit voltage: 700V ~100A at DC~5MHz Peak pulse current: ~500 A
3	AC current probe	Model P6021		Maximum circuit voltage: 600V ~15Ap-p at 120Hz~60MHz Peak pulse current: 250A
4		Model P6022		Maximum circuit voltage: 600V ~6Ap-p at 935Hz~120MHz Peak pulse current: 100A
5	ACCT	Varied	Pearson	~35MHz
6	Rogowski coil current probe	CWT	PEM	Current range: 300mA~300kA Bandwidth: 0.1Hz~16MHz

(2) Current probe sensitivity check

Before making any measurements, it is necessary to check the probe sensitivity.

Current probe can be calibrated using the oscilloscope calibrator output or using an oscillator as shown in Fig. 9-3. The measurement method in Fig. 9-3 uses a known resistance *R* (non-inductive) to measure the voltage *e* across *R* to obtain the current *i*. Compare the current *i* and the waveform of the current probe to calibrate. If the current *i* is too small, sensitivity can be increased by increasing the number of primary winding of the current probe.

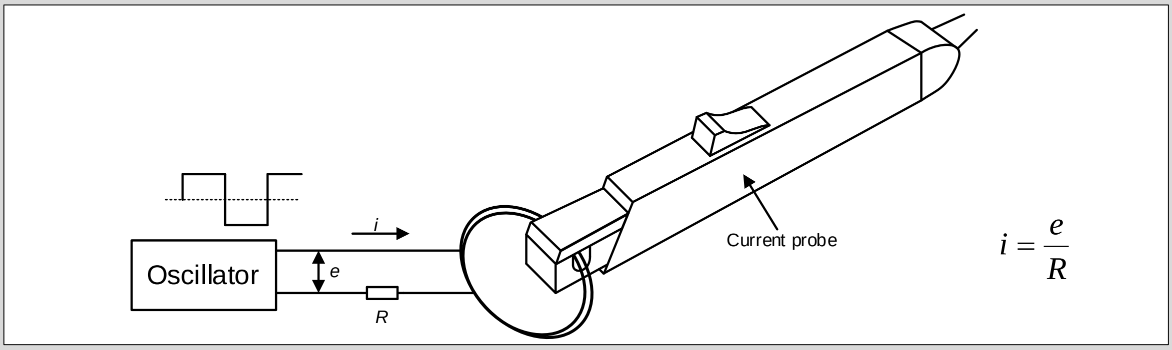


Fig. 9-3 Current probe calibration method

(3) Current measurement method

Using a two parallel connection as example, Fig. 9-4 shows where current transformers (CT) are inserted to measure the current. When measuring the current on the positive side of T_{11}, measure the secondary side current of CT_1 with a current probe. For T_{12}, measure the secondary side current. The total current on the positive side (sum of T_{11} current and T_{12} current) can be measured with the same current probe by aligning the directions of the secondary side currents of CT_1 and CT_2 and measuring them at once. Refer to sections 2.6 and 2.7 for the application of current probe and current transformer.

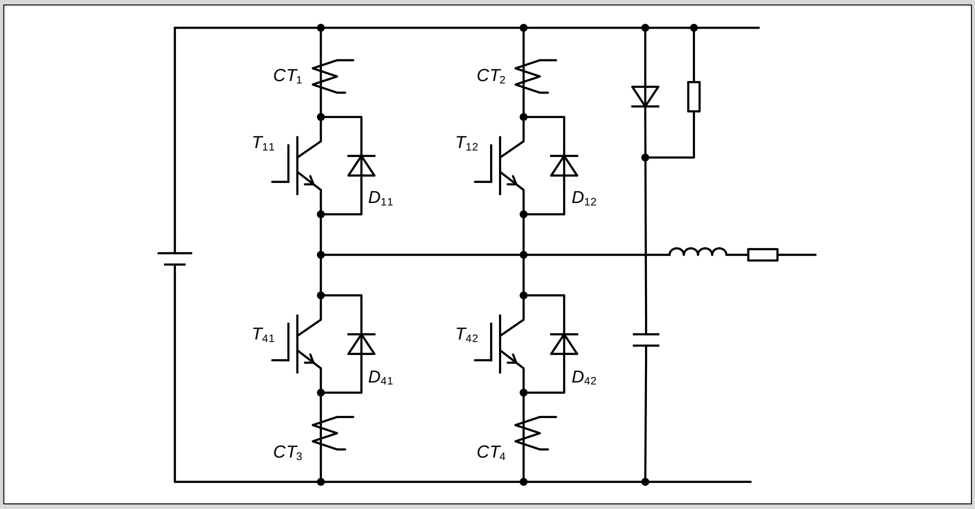


Fig. 9-4 CT insert position and current measurement method

2.4 Switching loss measurement

Switching loss is the loss generated during the period from the start of switching to the end of switching operation and reaching a steady-state. For example, the turn-on loss is the loss that is generated from V_{GE} is above 0V until V_{CE} reaches the saturation voltage.

The switching loss is generally expressed in terms of energy generated per instance of switching.

Fig. 9-5 shows example of switching waveform and switching loss. To measure switching loss, the current and voltage waveforms must be measured correctly. Note that when current and voltage are measured simultaneously, the common-mode current flowing from the voltage probe may cause the current waveform to be distorted. The presence or absence of this common-mode effect can be determined by comparing the current waveforms before and after the voltage probe is connected. If the current waveform is distorted, inserting a common-mode choke into the voltage probe cable and the oscilloscope power cable (by winding the cable around a core with excellent high frequency characteristics) as shown in Fig. 9-6 will reduce the waveform distortion.

In addition, the settings of reference 0V and 0A is important. Note that when using an AC current probe, the position of 0A varies depending on the current value and the conduction ratio.

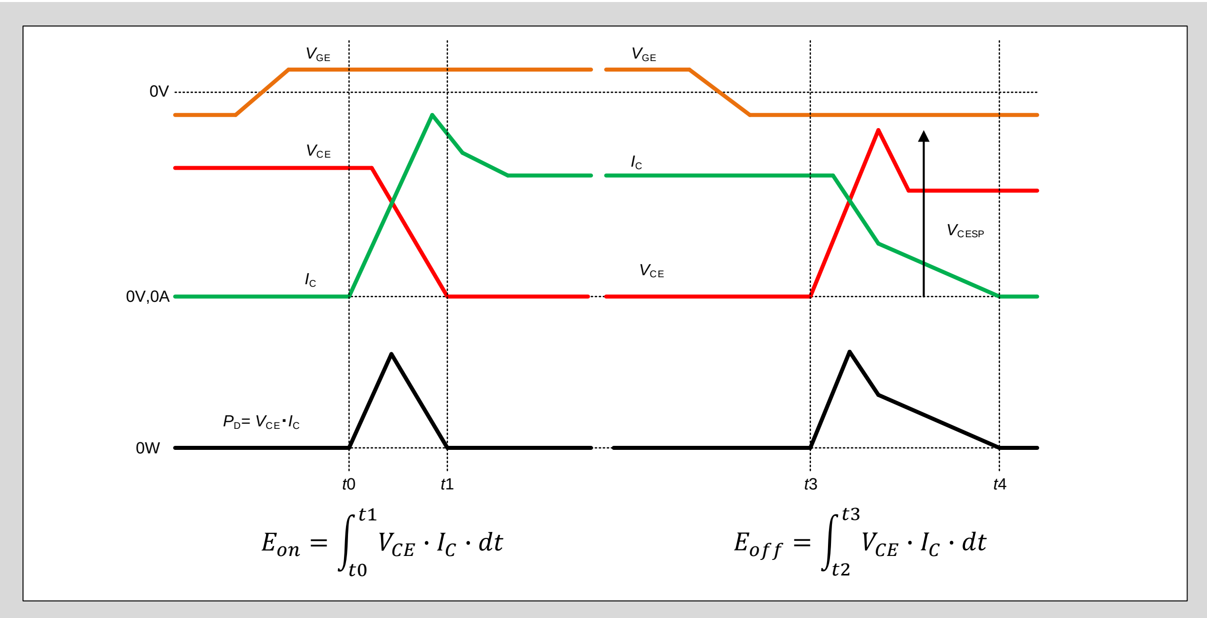


Fig. 9-5 Switching loss

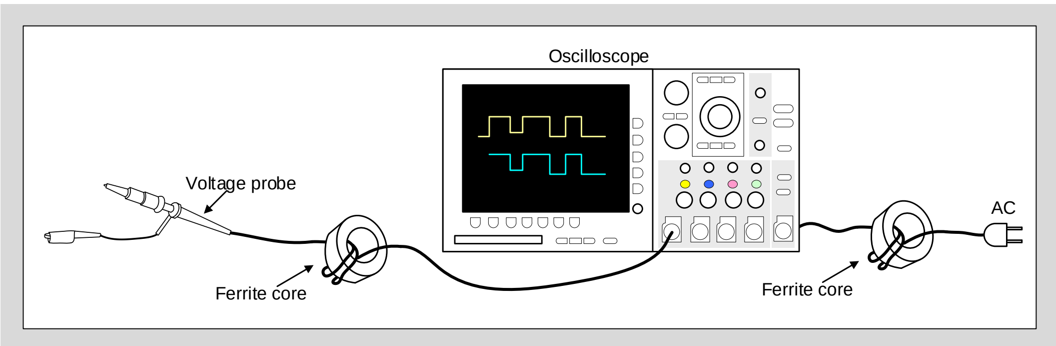


Fig. 9-6 Inserting common mode choke

2.5 Selecting oscilloscopes

Because oscilloscopes vary in terms of functionality and performance, it is important to select the right oscilloscope to suit the measurement items required and the rate of change in the signal to be measured. This section outlines the signal source rise time and the frequency bandwidth requirements for the oscilloscopes.

(1) Relationship between the rise time of a pulse waveform and the frequency bandwidth

The rise time of a pulse waveform is defined as the time needed for the voltage to change from 10% to 90% as shown in Fig. 9-7.

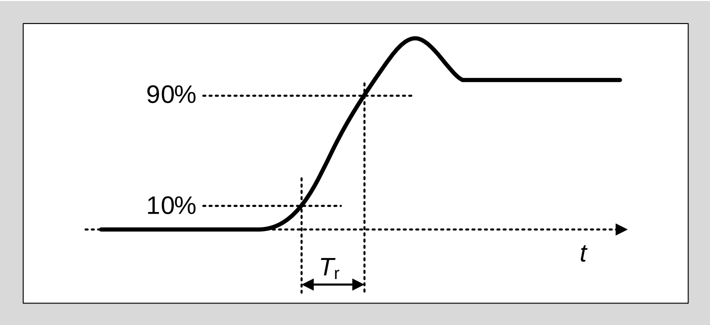


Fig. 9-7 Definition of the rise time of pulse waveform

Assuming that the rise time is T_r and the frequency at which -3dB is attained is F_{-3dB}, the following equation can be expressed.

$$T_r \cdot F_{-3dB} \fallingdotseq 0.35 \qquad \text{(1)}$$

(2) Signal source rise time T_{r1} and oscilloscope selection

Fig. 9-8 shows the rise time of each component in an actual measurement system.

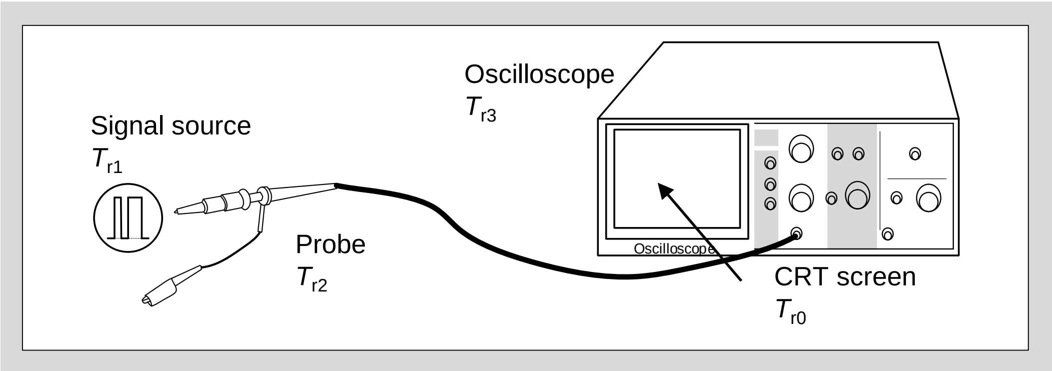


Fig. 9-8 Measurement system and rise time of each component

The rise time T_{r0} of the waveform displayed on the CRT screen of the oscilloscope is determined by the rise time of each component and is given by the following equation.

$$T_{r0} = \sqrt{T_{r1}^2 + T_{r2}^2} \qquad \text{(2)}$$

A correct reproduction of the waveform of the signal source is accomplished by setting T_{r0} = T_{r1}. Assuming that:

$$\varepsilon = \frac{T_{r0} - T_{r1}}{T_{r1}} \times 100(\%) \qquad k = \frac{T_{r2} + T_{r3}}{T_{r1}} \qquad \cdots\cdots(3)$$

the relationship between ε and k is shown in Table 9-3, obtained using equation (2)

Table 9-3 Waveform measurement errors and rise time of signal source and measuring instrument

ε (%)	1	2	3
k	7	5	4

For example, to measure a signal with a rise time of 3.5ns with ε = 3%, the combined rise time of the probe and oscilloscope should be less than 1/4 (3.5 / 4 = 0.87ns) of the rise time of the signal source. If the rise time of the probe is ignored, solving equation (1) gives the required bandwidth of the oscilloscope as $0.35/0.87\times10^{-9}$ = 4×10^{8}, or 400 MHz. Accordingly, an oscilloscope having a frequency bandwidth of 400 MHz or above must be used.

Thus, the oscilloscope to be used should be selected according to the rise time of the signal.

2.6 Selecting probes

As mentioned before, there are voltage probes and current probes. This section describes the basics for selecting probes and the precautions on their use.

2.6.1 Voltage probes

(1) Rise time

As described in section 2.5, it is necessary to consider the frequency bandwidth of the probe to be used in accordance with the rise time of the signal. The concept of probe selection is similar to the concept of oscilloscope selection and is omitted here.

(2) Effect of the signal source impedance and probe capacitance on the rise time

Fig. 9-9 shows the electrical equivalent circuit of the measurement system, in which R_1 and C_1 denote the output impedance and capacitance of the signal source, respectively, and R_2 and C_2 denote the input impedance and capacitance of the oscilloscope, respectively.

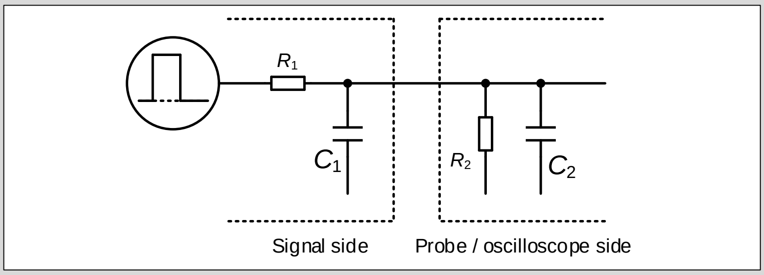


Fig. 9-9 Electrical equivalent circuit of the of measurement system

The rise time T_r of the RC filter can be expressed by

$$T_r = 2.2 \cdot R \cdot C$$

In the case of Fig. 9-9, R and C can be expressed as follows.

$$R = \frac{R_1 \cdot R_2}{R_1 + R_2} \qquad C = C_1 + C_2$$

The following facts become apparent from these relationships:

a. The higher the output impedance of the signal source, the longer the rise time becomes.

b. The larger the capacitance of the probe or oscilloscope, the longer the rise time becomes.

For example, if the signal of a signal source (R_1 = 500Ω, C_1 = 2 pF) is measured using an ordinary passive 10:1 probe (C_2 = 9.5 pF, R_2 = 10 MΩ), while the rise time is 2.2 ns when the probe is not connected, the rise time is 12 ns when the probe is connected, resulting in a significant error.

(3) Probe selection

Table 9-4 shows the guideline for selecting probes and precautions according to the measurement objectives.

Table 9-4 Guideline for selecting probes according to the measurement objectives

Objective / Item	Amplitude	Rise time, etc.	Phase difference
Probe requirements	High input impedance in the working frequency bandwidth.	Sufficient frequency bandwidth against signal source rise time.	Low input capacitance. Matched cable lengths and characteristics
Precautions	The pulse width should be at least 5 times the time constant of the probe or oscilloscope. Select a signal source with lowest impedance possible as the measurement point.	The pulse width should be at least 5 times the time constant of the probe or oscilloscope. Select a signal source with lowest impedance possible as the measurement point.	Measure the probe-to-probe time difference in advance. *A 3.5ft probe has a delay of 5ns.

(4) Precautions

Correct signal measurement requires an understanding of the probe characteristics and selection of the appropriate probe. Key items to consider when selecting a probe are listed below.

a. Is the probe suitable for the measurement objectives?
b. Is the frequency bandwidth of the probe correct for the measurement?
c. Is the maximum input voltage (withstand voltage) sufficient?
d. Will the loading effect of the probe cause a false reading? (optimal measuring point selection)
e. Is the ground (earth wire) connected properly?
f. Are there mechanical or physical strains?

When measuring high-speed switching pulses, resonance may occur due to the ground lead inductance and probe capacitance, especially in wideband oscilloscopes. Shortening the ground lead and grounding the probe tip can reduce this resonance. The necessary adapters are usually included as accessories.

In addition, multiple probes may each have their ground lead to prevent induction noise interferences as shown in Fig. 9-10. However, in this case, the potential at the points where the ground leads are connected must be equal.

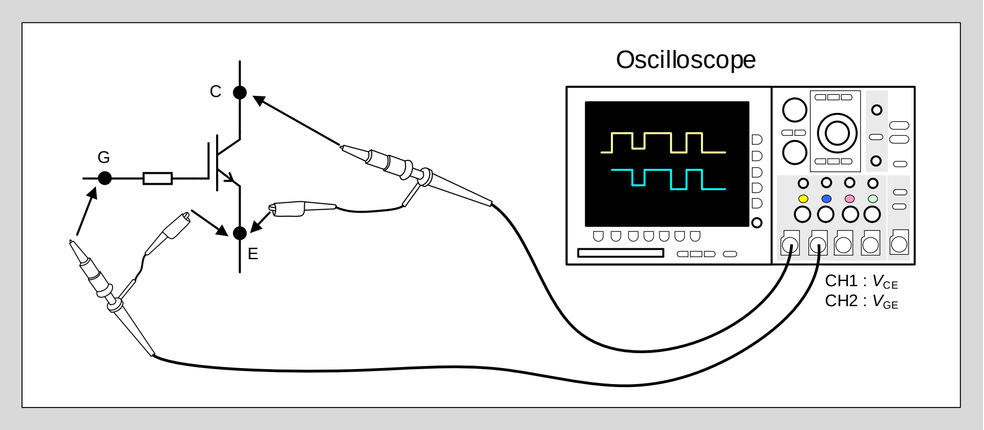


Fig. 9-10 Voltage probes connection

2.6.2 Current probes

The types and outlines of current probes are shown in section 2.3. This section describes the precautions in actual applications.

(1) Current probe selection

As mentioned before, there are two types of current probes: DC current probes and AC current probes. AC current probes, due to their excellent noise immunity, are recommended for measuring current waveforms during high-speed switching operation.

If a DC or low-frequency AC current is measured with an AC current probe, the core inside the probe will saturate and output will not be obtained. Therefore, to measure the switching operation of IGBTs used in circuits that operates with DC or low-frequency AC, some techniques are necessary, such as fabricating and using a timing control circuit to simulate the actual operation.

(2) Precautions

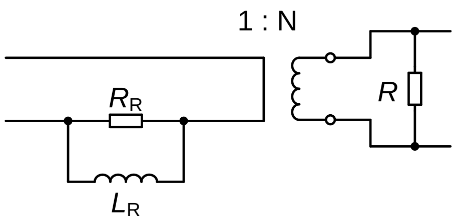
a. The tip of the current probe contains a ferrite core, which is extremely vulnerable to impact and must be handled with care.

b. Be careful not to exceed the ratings.
   - Withstand voltage: If the circuit voltage is high, cover the measuring point with a voltage resistant tube.
   - A-S (product of current): Pulse current rating. Excessive current may damage the probe.
   - Maximum RMS current resistance: Limited by the power capacity of the secondary circuit in the probe transformer. Exceeding this maybe burn out the probe.

c. In the case of clip type, perform measurement with the probe being securely clipped.

d. Do not leave the secondary side open with the current probe clipped to the circuit. (Especially if there is no terminator, high voltage will be generated on the secondary side)

e. Inserting the probe generates an insertion impedance on the primary side of the circuit. It is important to ensure that the insertion impedance does not affect the measurement target. Assuming that the probe is an ideal transformer, the insertion impedance can be expressed as shown in Fig. 9-11.



$$L_R = \frac{Secondary\ inductance(L)}{N^2}$$

$$R_R = \frac{Secondary\ load\ resistance(R)}{N^2}$$

Fig. 9-11 Probe insertion impedance

2.7 Using current transformer

A current transformer is used to ease the constraint on the application range of a current probe and to minimize the effect of modifications made for measurement purposes may have upon circuit performance. Refer to section 2.3 for information on the current transformer insert locations and current measurement method.

Assuming that the number of turns (secondary) of the transformer is N, the primary current is I_1, and the secondary current is I_2, an ideal transformer would meet the relationship I_2 = I_1/N. Considering the excitation current I_0, the relationship can be rewritten as follows.

$$I_o = I_1 - N \cdot I_2$$

The excitation current must be a small value because it might cause measurement error. Check the current transformer N value, measure I_1 and I_2, and calculate I_0 from the above equation to make sure that the measurement accuracy is acceptable. Also, be careful not to drop the ferrite core of the current transformer, which is extremely vulnerable to impact.