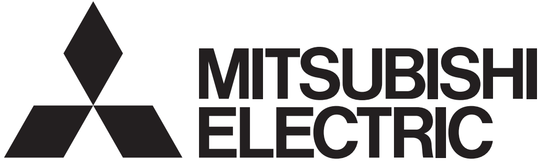

IGBT Modules Application Note

The 5th Generation [*CSTBT*™] IGBT Chip use

12NF/24NF/24A series

Mar. 2014

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I n d e x

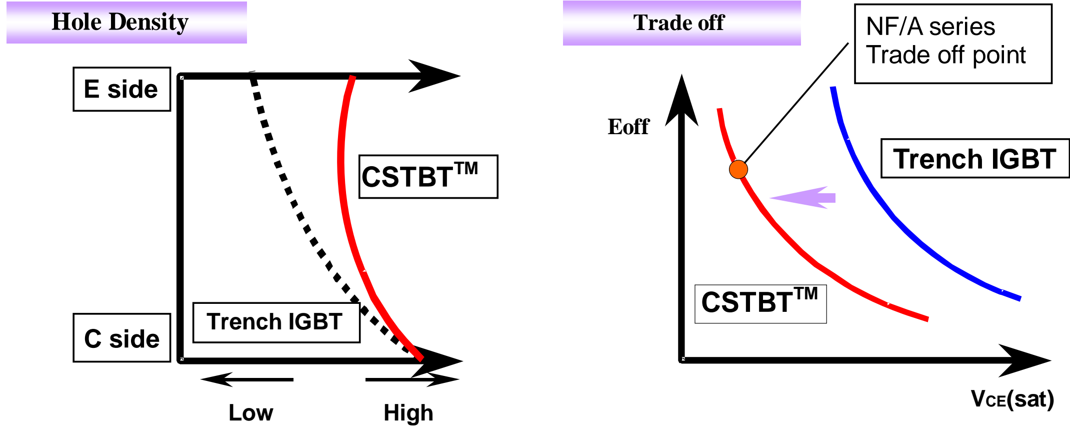
- ☐ NF/A series IGBT Module Features 4
- ☐ Product Line-up 5
- ☐ Term Explanation 6
- ☐ Numbering System 8
- ☐ Example Applications of IGBT Modules to AC Motor Controls (General purpose Inverter) 9
- ☐ Structure 10
- ☐ Safety Standard (UL) 11
- ☐ Correct and Safety Use of Power Module 13
- ☐ Installation of Power Module 15
  - 1. Installing Capacitor
  - 2. Installation Hints
  - 3. Thermal Impedance Considerations 18
  - Chip Location 19
- ☐ Reliabilitiy 38
  - 1. Introduction
  - 2. Basic Concepts of Semiconductor Device Reliability
  - 2.1 Semiconductor Device Failure Rate Varied with The Lapse of Time
  - 2.2 Power Module Failure Reason 39
  - 2.3 Thermal Fatigue of Power Module 40
  - 3. Mitsubishi's Quality-Assurance Program 43
  - 4. Reliability Testing 45
  - 5. Failure Analysis 46
  - 6. Derating and Reliability Projections
  - 7. Conclusion
- ☐ Using IGBT Module 47
  - 1. IGBT Module Characteristics
  - 2. Static Electricity Precaution
  - 3. Derating Consideration
  - 4. Precautions in Using IGBT Modules 48
  - 5. Switching Loss 55
  - 6. Parallel Operation 65
  - 7. Safe Operation Area 67
  - 8. Power Loss and Junction Temperature 7 1
- ☐ Average Power Loss Simplified Calculation 7 5

NF/A series IGBT Module Features

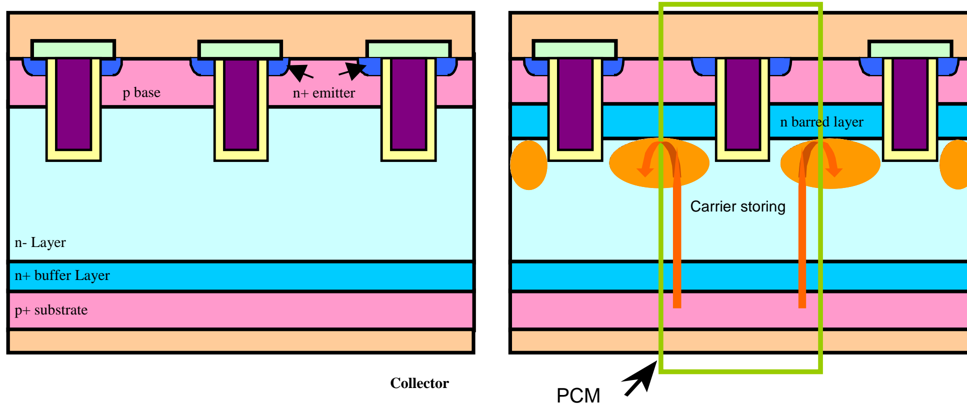
1. The 5th generation IGBT chip

■ A newly developed IGBT chip, the novel Carrier Stored Trench Gate Bipolar Transistor (CSTBT™), meets all requirements for low on-state voltage $V_{CE(sat)}$ and low on-state losses.

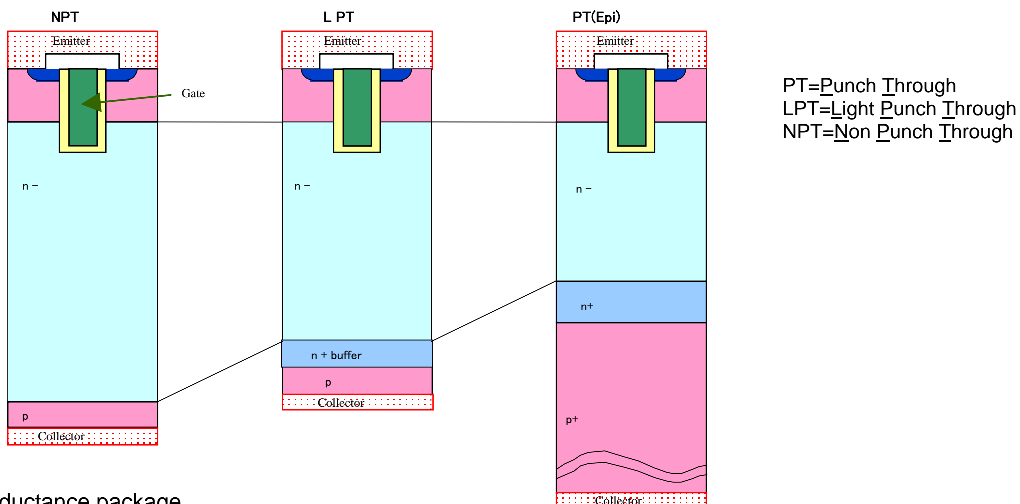
CSTBT™: Carrier Stored Trench Gate Bipolar Transistor



■ A significant performance with an excellent natural short circuit capability (SCSOA) and reduced gate capacitance was obtained by employing the novel Plugged Cell Merged (PCM) surface pattern.



■ 1200V chips are using Light Punch Through (LPT) structure, and 600V chips are using Punch Through (PT) structure.



PT=Punch Through
LPT=Light Punch Through
NPT=Non Punch Through

2. Low inductance package

■ Full package compatibility with Mitsubishi Electric's 3rd generation H series IGBTs allows easy drop-in replacement without needing changes to either the bus bar or the heat sink. In addition, the same low inductance as F series has been achieved by the low inductance package.

Product Line-up

■IGBT Modules

Dual

600V
CM150DY-12NF
CM200DY-12NF
CM300DY-12NF
CM400DY-12NF
CM600DY-12NF

1200V
CM100DY-24NF
CM150DY-24NF
CM200DY-24NF
CM300DY-24NF
CM400DY-24NF
CM600DU-24NF

MPD

1200V
CM900DU-24NF
CM1400DU-24NF

6pack

600V
CM 75TL-12NF
CM100TL-12NF
CM150TL-12NF
CM200TL-12NF

1200V
CM 50TL-24NF
CM 75TL-24NF
CM100TL-24NF
CM150TL-24NF
CM200TL-24NF

7pack

600V
CM 75RL-12NF
CM100RL-12NF
CM150RL-12NF
CM200RL-12NF

1200V
CM 50RL-24NF
CM 75RL-24NF
CM100RL-24NF
CM150RL-24NF
CM200RL-24NF

Dual (A series)

1200V
CM100DY-24A
CM150DY-24A
CM200DY-24A
CM300DY-24A
CM400DY-24A
CM600DY-24A

Single (A series)

1200V
CM400HA-24A
CM600HA-24A
CM600HB-24A

※MPD (Mega Power Dual) : "Mega Power Dual" IGBT module sizes available are 900A and 1400A at 1200V.

Related Products

■Rectifier Diode Modules

RM20TPM-H
RM30TPM-H
RM20TPM-2H
RM75TPM-M, H, 24,2H

■Fast Recovery Diode Modules (for CRDi snubber circuit)

RM50HG-12S
RM25HG-24S

■Hybrid ICs (ISAHAYA Electronics Corporation : for more information please refer to : http://www.idc-com.co.jp/)

VLA500-01
VLA502-01
M57159L-01
M57959AL-01
M57962AL-01
M57962CL-01

Term Explanation

General 1

Symbol		Definition
IGBT	Insulated Gate Bipolar Transistor	
FWDi	Free Wheeling Diode	anti-parallel to the IGBT
IPM	Intelligent Power Module	
tdead	Dead Time	Low side turn-off to high Side turn-on & High Side turn-off to low side turn-on
IPM Motor	Interior Permanent Magnet Motor	
(PC)	Opto-coupler	
PC	Programmable Controller	
CMR	Common Mode Noise Reduction	The maximum rise ratio of common mode voltage
CM_H		The maximum rise ratio of common mode voltage at the specific high level
CM_L		The maximum rise ratio of common mode voltage at the specific low level
CTR	Current Transfer Ratio	the ratio of the output current to the input current

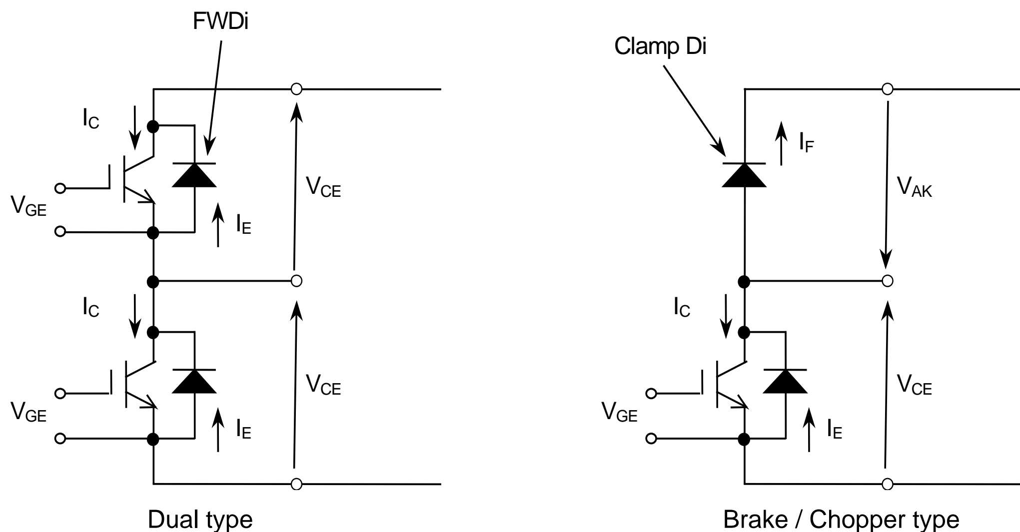
General 2

Symbol	Parameter	Definition
T_a	Ambient Temperature	Atmosphere temperature without being subject to thermal source
T_c	Case Temperature	Case temperature measured at specified point
T_c'	Case Temperature	Case temperature measured at specified point different from the Tc measured point

Absolute maximum Ratings

Symbol	Parameter	Definition
V_{CES}	Collector-Emitter Blocking Voltage	Maximum Off-state collector-emitter voltage with gate-emitter shorted
V_{GES}	Gate-Emitter Voltage	Maximum gate-emitter voltage with collector-emitter shorted
I_C	Continuous Collector Current	Maximum collector current – DC
I_{CM}	Peak Collector Current Repetitive	Peak collector current, Tj≤150°C
I_E	Continuous FWDi Current	Maximum diode current – DC
I_{EM}	Peak FWDi Current Repetitive	Diode peak current, Tj≤150°C
P_C	Power Dissipation	Maximum power dissipation, per device, T_C=25°C
T_j	Junction Temperature	Allowable range of IGBT junction temperature during operation
T_{stg}	Storage Temperature	Allowable range of temperature within which the module may be stored or transported without being subject to electrical load.
V_{iso}	Isolation Voltage	Minimum RMS isolation voltage capability applied all shorted electric terminal to base plate, 1 minute duration
-	Mounting Torque	Allowable tightening torque for terminal and mounting screws

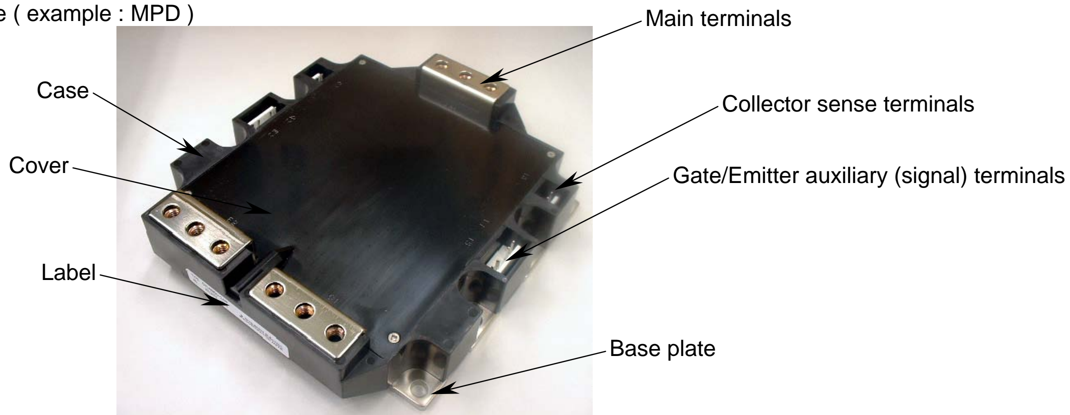
※I_E and I_F are using by the difference of the connection and so on like the following figure.



Electrical and Thermal Characteristics

Symbol	Parameter	Definition
I_{CES}	Collector-Emitter Leakage Current	I_C at V_{CE} = V_{CES}, V_{GE} = 0V
$V_{GE(th)}$	Gate-Emitter Threshold Voltage	V_{GE} at I_C = specified mA, V_{CE} = 10V
I_{GES}	Gate-Emitter Leakage Current	I_G at V_{GE} = V_{GES}, V_{CE} = 0V
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	V_{CE} at I_C = rated I_C and V_{GE} = 15V
C_{ies}	Input Capacitance	Gate-Emitter capacitance with V_{CE}=10V
C_{oes}	Output Capacitance	Collector-Emitter capacitance with the gate shorted to the emitter
C_{res}	Reverse Transfer Capacitance	Gate-Collector capacitance with the emitter connected to the guard terminal of the impedance analyzer
$t_{d(on)}$	Turn-on Delay Time	Time from V_{GE}=0V to I_C=10% of final value
t_r	Rise Time	Time from I_C=10% of final value to I_C=90% of final value
$t_{d(off)}$	Turn-off Delay Time	Time from V_{GE}=90% of initial value to I_C=90% of initial value
t_f	Fall Time	Time from I_C = 90% of initial value to I_C=10% of initial value
E_{on}	Turn-on Switching loss	Energy dissipated inside the IGBT during the turn-on of a single collector current pulse. Integral time starts from the 10% rise point of the collector current and ends at the 10% of the collector-emitter voltage point.
E_{off}	Turn-off Switching loss	Energy dissipated inside the IGBT during the turn-off of a single collector current pulse. Integral time starts from the 10% rise point of the collector-emitter voltage and ends at the specified low collector current point, x% of Ic. x%:2% (NF/A series) , 10% (F series)
Err	Recovery loss	
t_{rr}	Diode Reverse Recovery Time	Time from I_C=0A to projection of zero I_C from Irr and 0.5×Irr points with I_E = rated I_C.
Q_{rr}	Diode Reverse Recovery Charge	Area under Irr curve from I_C=0A to projection of zero I_C from Irr and 0.5×Irr points with I_E=rated I_C and at specified di/dt.
V_{EC}	Forward Voltage Drop of Diode	V_{EC} at -I_C = rated Ic
R_{th}	Thermal Resistance	The rise of junction temperature per unit of power applied for a given time period
$R_{th(j-c)}$	Thermal Resistance, Junction to Case	I_C conducting to establish thermal equilibrium
$R_{th(c-f)}$	Thermal Resistance, Case to Fin	I_C conducting to establish thermal equilibrium lubricated
R_G	Gate Resistance	Allowable range of gate resistance

Parts name (example : MPD)



Numbering System

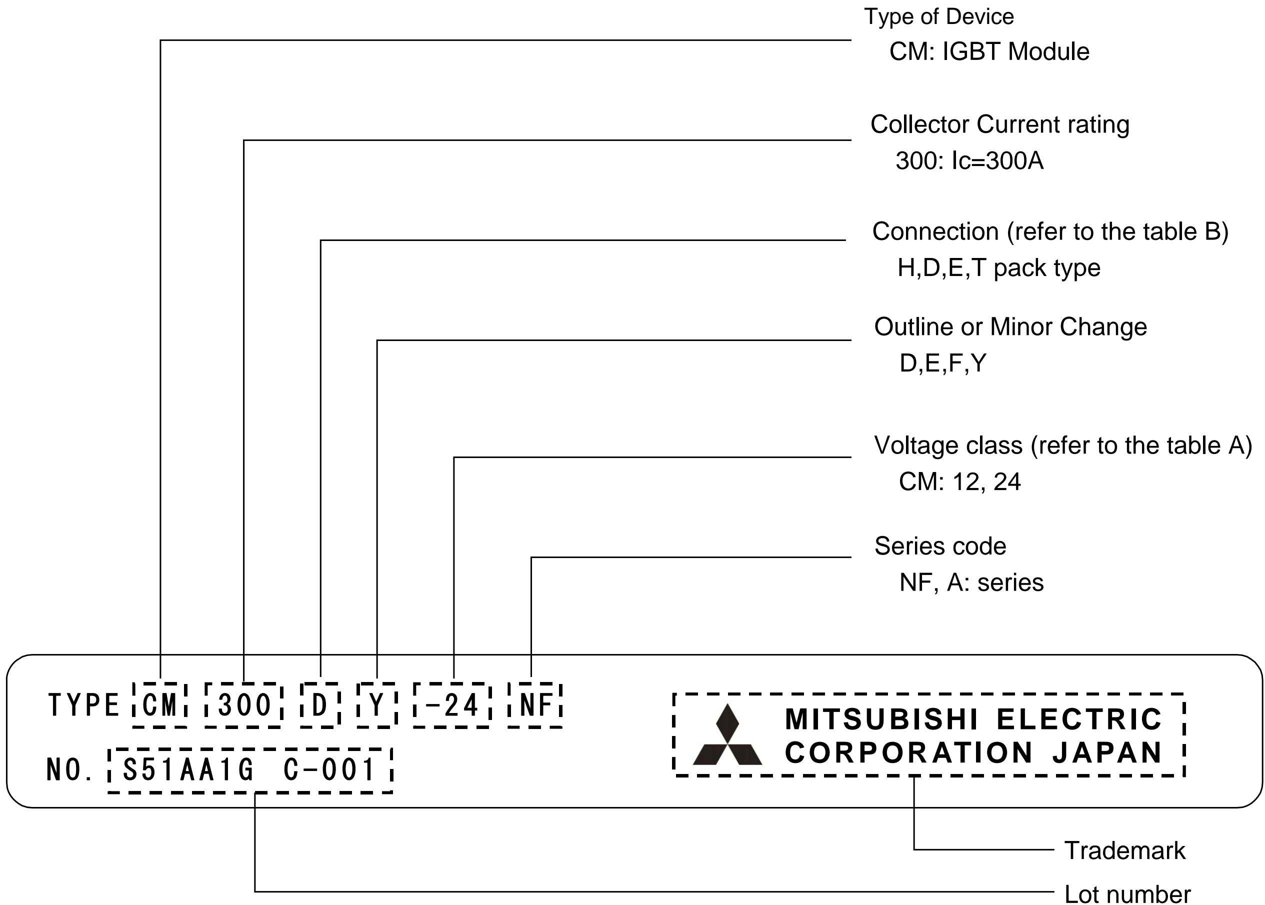
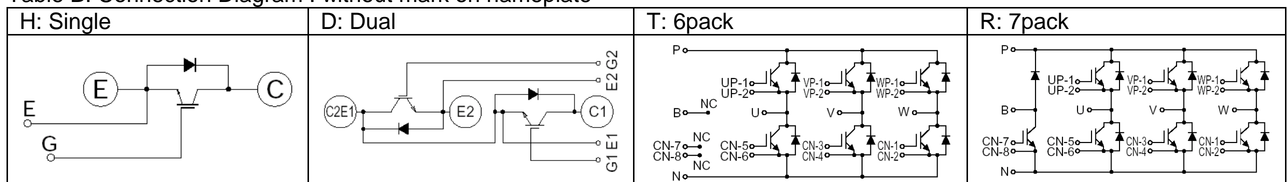


Table A. Voltage Class

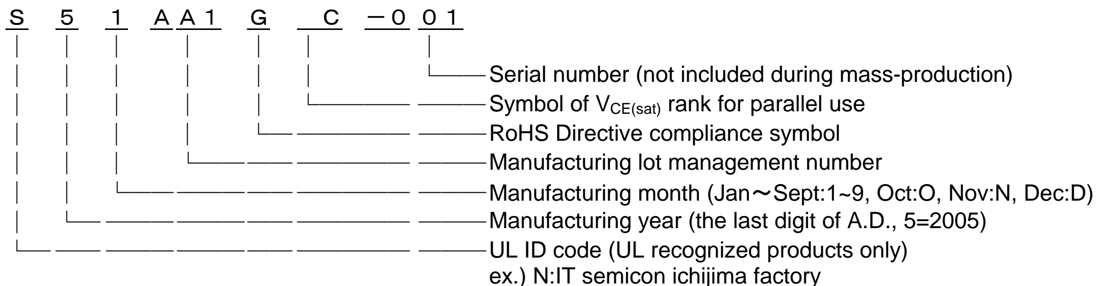
	IGBT modules		Rectifier Diode modules	
AC Input Voltage (V)	Voltage Class	V_{CES} (V)	Voltage Class	V_{RRM} (V)
220 ~ 240	12	600	H	800
440 ~ 480	24	1200	2H	1600
575 ~ 600	34	1700	40	2000
~ 690			-	-

Table B. Connection Diagram : without mark on nameplate

H: Single	D: Dual	T: 6pack	R: 7pack



Lot number



Example Applications of IGBT Modules to AC Motor Controls(General purpose Inverter)

■AC220V Line

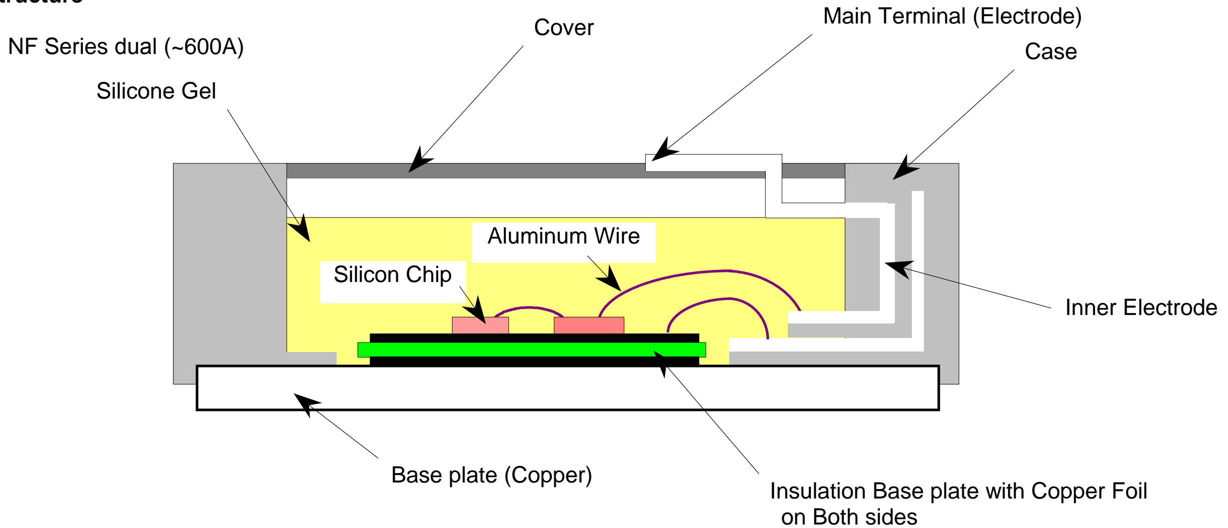
Motor Ratings (kW)	For Inverter IGBT Module			For Converter Diode
	NF Series	F Series	U Series	
5.5	CM75TL/RL-12NF	CM75TU-12F	CM75TU-12H CM75DU-12H × 3	RM30TB-H
7.5	CM75TL/RL-12NF	CM75TU-12F	CM100TU-12H CM100DU-12H × 3	RM30TA-H
11	CM100TL/RL-12NF	CM100TU-12F	CM100TU-12H CM100DU-12H × 3	RM50TC-H RM60DZ-H × 3
15	CM150DY-12NF × 3 CM150TL/RL-12NF	CM150TU-12F	CM150TU-12H CM150DU-12H × 3	RM75TC-H RM60DZ-H × 3
18.5	CM200DY-12NF × 3 CM200TL/RL-12NF	CM200TU-12F	CM200TU-12H CM200DU-12H × 3	RM60DZ-H × 3
22	CM200DY-12NF × 3 CM200TL/RL-12NF	CM300DU-12F × 3	CM300DU-12H × 3	RM100DZ-H × 3
30	CM300DY-12NF × 3	CM300DU-12F × 3	CM300DU-12H × 3	RM100DZ-H × 3
37	CM400DY-12NF × 3	CM400DU-12F × 3	CM400DU-12H × 3	RM150DZ-H × 3
45	CM400DY-12NF × 3	CM400DU-12F × 3	CM600HU-12H × 6	RM150DZ-H × 3
55	CM600DY-12NF × 3	CM600DU-12F × 3 CM600HU-12F × 6	CM600HU-12H × 6	RM150DZ-H × 3

■AC440V Line

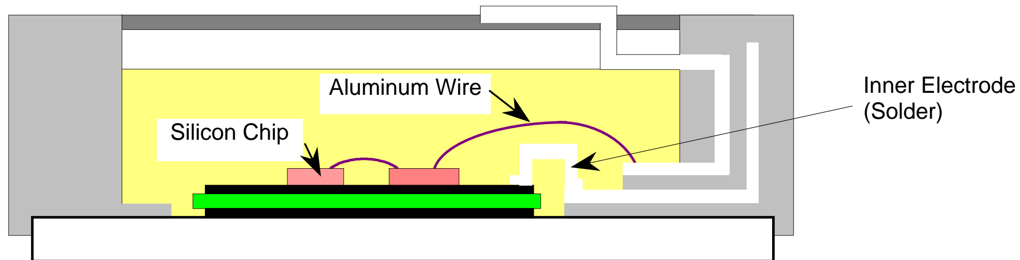
Motor Ratings (kW)	For Inverter IGBT Module			For Converter Diode
	NF Series	F Series	U Series	
5.5	CM50TL/RL-24NF	CM50TU-24F	CM50TU-24H CM50DU-24H × 3	RM15TA-2H
7.5	CM50TL/RL-24NF	CM50TU-24F	CM50TU-24H CM50DU-24H × 3	RM20TA-2H
11	CM75TL/RL-24NF	CM75TU-24F	CM75TU-24H CM75DU-24H × 3	RM50TC-2H
15	CM75TL/RL-24NF	CM100TU-24F	CM100TU-24H CM100DU-24H × 3	RM30DZ-2H × 3
18.5	CM100DY-24NF × 3 CM100DY-24A × 3 CM100TL/RL-24NF	CM150DU-24F × 3	CM150DU-24H × 3	RM60DZ-2H × 3
22	CM100DY-24NF × 3 CM100DY-24A × 3 CM100TL/RL-24NF	CM150DU-24F × 3	CM150DU-24H × 3	RM60DZ-2H × 3 RM50TC-2H
30	CM150DY-24NF × 3 CM150DY-24A × 3 CM150TL/RL-24NF	CM200DU-24F × 3	CM200DU-24H × 3	RM60DZ-2H × 3
37	CM200DY-24NF × 3 CM200DY-24A × 3 CM200TL/RL-24NF	CM200DU-24F × 3	CM200DU-24H × 3	RM60DZ-2H × 3
45	CM200DY-24NF × 3 CM200DY-24A × 3 CM200TL/RL-24NF	CM300DU-24F × 3	CM300DU-24H × 3	RM100DZ-2H × 3
55	CM300DY-24NF × 3 CM300DY-24A × 3	CM300DU-24F × 3	CM300DU-24H × 3	RM150DZ-2H × 3
75-90	CM400DY-24NF × 3 CM400DY-24A × 3 CM400HA-24A × 6	CM400HU-24F × 6	CM400HU-24H × 6	RM150DZ-2H × 3
110	CM600DY-24NF × 3 CM600DY-24A × 3 CM600HA-24A × 6 CM600HB-24A × 6	CM600DU-24F × 3 CM600HU-24F × 6	CM600HU-24H × 6	RM250DZ-2H × 3

Structure

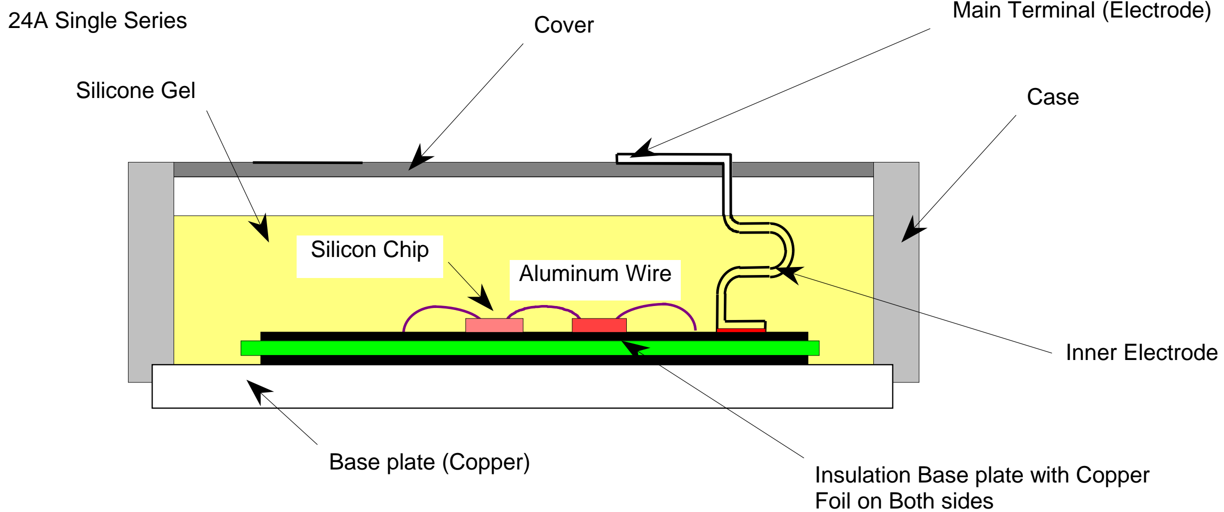
NF Series dual (~600A)



MPD (an image figure for the ~600A comparison. The actual structure is different.)



24A Single Series



About the flammable

The epoxy to be using for IGBT module has the fireproof of the UL 94V-0 fitness, but the silicone gel is combustible and does not base plate in with UL 94V-0.

* The breakdown strength after the hardening is using the product of the characteristic above 10kV/mm at the 340°C flash point, the 450°C ignition point.
Because there is not self extinguish-ability, too, in case of the fire, a fire must be extinguished using the dry chemicals, the carbon dioxide extinguishing agent and the bubble extinguishing agent and so on.
Because epoxy has self extinguish-ability, if a burning source is cut off, there is not live danger.
There is not a fireproof standard of UL which corresponds to the other silicon chip, the copper base board and so on.

Safety Standard (UL)

Compliance with international standard UL1557 has already been certified (File No. E80271).
Please refer the certified modules to UL homepage.

1. Certified modules can be searched through the following website (2007/12), click the Certifications button, and input the card number E80276 in frame of UL File No, then hit the SEARCH button.
http://database.ul.com/cgi-bin/XYV/template/LISEXT/1FRAME/index.htm

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Number of hits: 1

Previous Page

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Company Name	Category Name	Link to File
MITSUBISHI ELECTRIC CORP SEMICONDUCTOR DIV	Power Switching Semiconductors - Component	*QQQX2.E80276*

Previous Page

Notice of Disclaimer · Questions?

Model number information is not published for all product categories. If you require information about a specific model number, please contact Customer Service for further assistance.

3. Certified Modules

Power Switching Semiconductors - Component

Guide Information

MITSUBISHI ELECTRIC CORP E80276
SEMICONDUCTOR DIV
MITSUBISHI DENKI BLDG
MARUNOUCHI
TOKYO 100-8310, JAPAN

Diodes, Type RM or SR followed by 10, 15, 20, 30, 40, 50, 60, 75, 100, 150, 200, 250, 300, 400 or 500, followed by C, C1A, C1F, C1Z, C2Z, CA, CF, CZ, D2F, DA, DF, DZ, HA, HC, TA, TB, TC, TPM or UZ, followed by 2H, 5H, 6S, 10F, 12, 12F, 12S, 16, 16F, 20, 20F, 20S, 24, 24F, 24S, 40, H or M.

Types RM10TB-H, -TB-M, RM15TB-H, -TB-M, -TPM-2H, RM20TPM-2H, -TPM-24, -TPM-H, -TPM-M, RM30TB-H, -TB-M, -TPM-H, -TPM-M.

Power switching semi-conductors, Cat. Nos. BCR30GM; Types A, B, C.

Type CM followed by 10, 15, 20, 25, 30, 50, 75, 100, 150, 200, 300, 400, 600, 800, or 1000, followed by AD00 thru AD63 , DY, E3Y, HA, LD, LDL, MD, MDL, MD1, MD1L, MD3 or MDC, followed by -12H, -24H, -28H or -28K.

Type CM followed by 15, 20, 25, 30, 50, 75, 100, 150, 200, 300, 400 600, 800, or 1000, 1200, followed by DK, DY, DY1, E3Y, HA, HA1, HB , HK, TF or TX, followed by -12, -12E, -12G, -12H, -12HE, -20, -24, -24E, -24G, -24H, -24J, -28 or -28H.

4. Naming Approach

CM150DY-12NF as an example, from the line 7th to the 10th of Power Switching Semi-conductors table(In square frame)
Type CM followed by -10,15,20….or 24H, the module is named by combination of CM, 150, DY, -12NF.

Power switching semi-conductors, Cat. Nos. BCR30GM; Types A, B, C.

Type CM followed by 10, 15, 20, 25, 30, 50, 75, 100, 150, 200, 300, 400, 600, 800, or 1000, followed by AD00 thru AD63 , DY, E3Y, HA, LD, LDL, MD, MDL, MD1, MD1L, MD3 or MDC, followed by -12H, -24H, -28H or -28K.

Type CM followed by 15, 20, 25, 30, 50, 75, 100, 150, 200, 300, 400 600, 800, or 1000, 1200, followed by DK, DY, DY1, E3Y, HA, HA1, HB , HK, TF or TX, followed by -12, -12E, -12G, -12H, -12HE, -20, -24, -24E, -24G, -24H, -24J, -28 or -28H.

Type CM followed by -10, 15, 25, 40, 50, 75, 100, 110, 150, 165, 200, 300, 400, 450, 600, 800, 900 or 1400, followed by BU, BU1, DU, DUM, DUR, DUS, DY, E2U, EU2A, EC2U, E3U, E3UA, EC3U, HU, HUA, HUE, HUS, RU , TJ, TJA, TU, YE4, YE2N, YE2P, YE4 or YE13, followed by -5F, -12, -12F, -12H, -12NF, -12NFA, -12NFH, -24, -24A, -24F, -24NF, -24NFH or -24H.

Type FM followed by 15, 20 or 30, followed by BF or TF, followed by -5, -6, -9, -9S, -10 or -10S.

Type FM followed by 30, 50, 75 or 100, followed by DW, DY, E2Y, E3Y, HA or HY, followed by -1, -9, -9S, -10 or -10S.

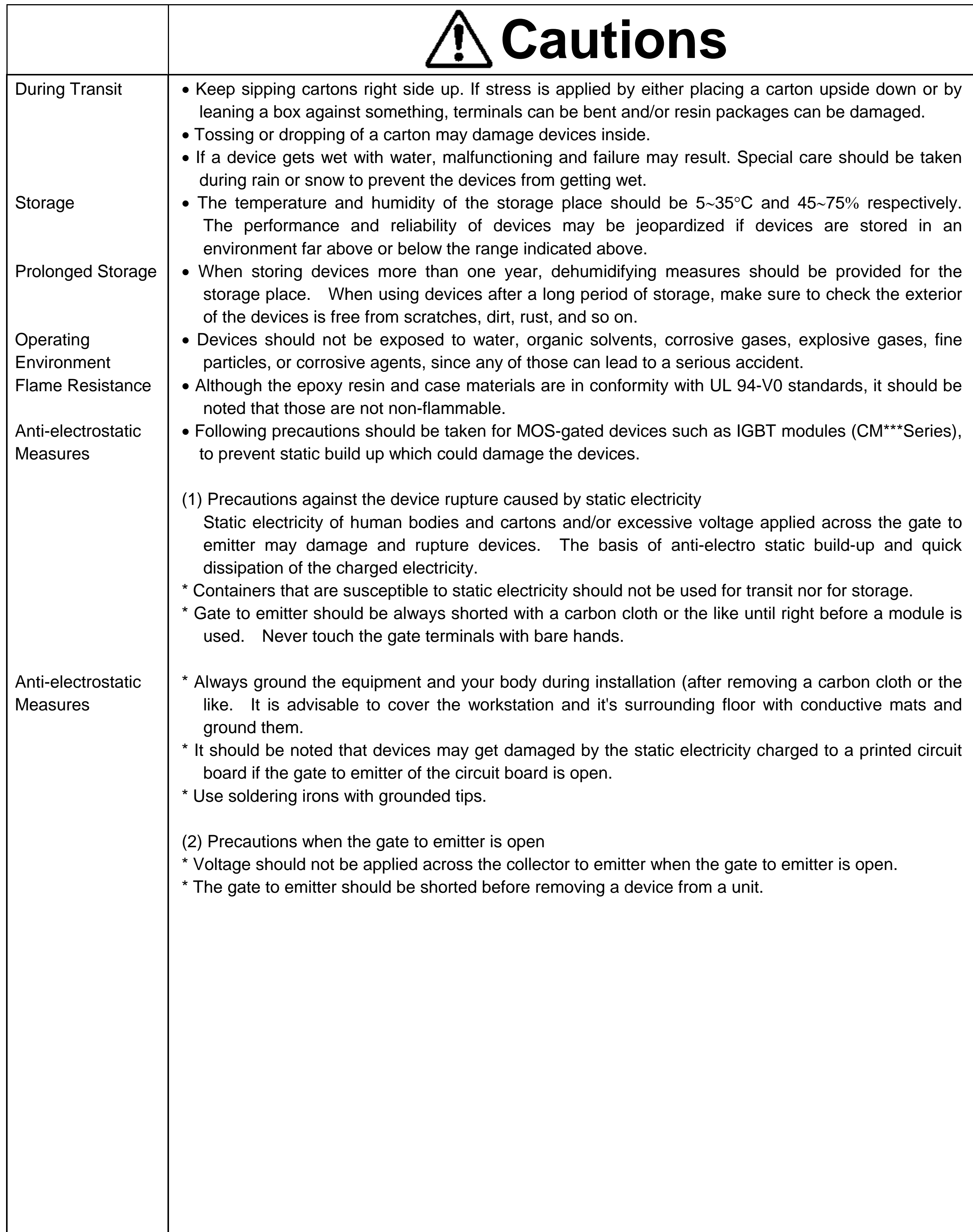
Type CM followed by 40, 50, 75, 100, 150 or 200, followed by RL, TL or YE13, followed by -12F, -12H, -12NF, -12NFB or -24NF.

Type PM followed by 10, 15, 20, 25, 30, 50, 75, 100, 150, 200, 300, 400, 600 or 800, followed by B, C, D, E, H, R or V, followed by AN, BS, EA, FE, HA, HB, HC, HS, KA, KF, KK, LA, LB, LG, MA, MC, NA, NC, NE, NJ, RA, RB, RS, SA, SB, SC, SD, SE, SEA, SF, SH, SJ, SK, TJ, TK, TM, VA, VD or ZF, followed by 060, 060-1, 060-3, 060-4, 060-5, 060-8, 060-9, 060-10, 060-12, 060-13, 060-16, 060-17, 060-21, 060-22, 060-39, 120, 120-1 or 120-2 or 120-18 .

* Not the product that the form name which derives in the combination has authorized (and, are producibility) all UL.
* There is a case of the omission of the update delay and the authorization article according to the convenience of the update of HomePage.
* When a corresponding article isn't found out, please contact us..
* At present, we don't publish yellow card "E80276".

Correct and Safety Use of Power Module

Unsuitable operation (such as electrical, mechanical stress and so on) may lead to damage of power modules.
Please pay attention to the following descriptions and use Mitsubishi Electric's IGBT modules according to the guidance.

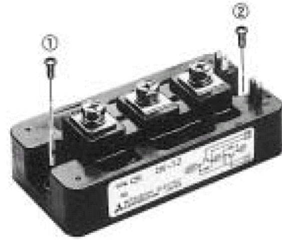


	⚠ Cautions
During Transit	• Keep sipping cartons right side up. If stress is applied by either placing a carton upside down or by leaning a box against something, terminals can be bent and/or resin packages can be damaged. • Tossing or dropping of a carton may damage devices inside. • If a device gets wet with water, malfunctioning and failure may result. Special care should be taken during rain or snow to prevent the devices from getting wet.
Storage	• The temperature and humidity of the storage place should be 5~35°C and 45~75% respectively. The performance and reliability of devices may be jeopardized if devices are stored in an environment far above or below the range indicated above.
Prolonged Storage	• When storing devices more than one year, dehumidifying measures should be provided for the storage place. When using devices after a long period of storage, make sure to check the exterior of the devices is free from scratches, dirt, rust, and so on.
Operating Environment	• Devices should not be exposed to water, organic solvents, corrosive gases, explosive gases, fine particles, or corrosive agents, since any of those can lead to a serious accident.
Flame Resistance	• Although the epoxy resin and case materials are in conformity with UL 94-V0 standards, it should be noted that those are not non-flammable.
Anti-electrostatic Measures	• Following precautions should be taken for MOS-gated devices such as IGBT modules (CM***Series), to prevent static build up which could damage the devices. (1) Precautions against the device rupture caused by static electricity Static electricity of human bodies and cartons and/or excessive voltage applied across the gate to emitter may damage and rupture devices. The basis of anti-electro static build-up and quick dissipation of the charged electricity. * Containers that are susceptible to static electricity should not be used for transit nor for storage. * Gate to emitter should be always shorted with a carbon cloth or the like until right before a module is used. Never touch the gate terminals with bare hands.
Anti-electrostatic Measures	* Always ground the equipment and your body during installation (after removing a carbon cloth or the like. It is advisable to cover the workstation and it's surrounding floor with conductive mats and ground them. * It should be noted that devices may get damaged by the static electricity charged to a printed circuit board if the gate to emitter of the circuit board is open. * Use soldering irons with grounded tips. (2) Precautions when the gate to emitter is open * Voltage should not be applied across the collector to emitter when the gate to emitter is open. * The gate to emitter should be shorted before removing a device from a unit.

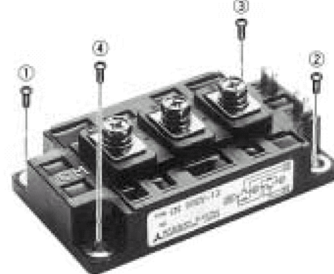
⚠ Cautions

Mounting

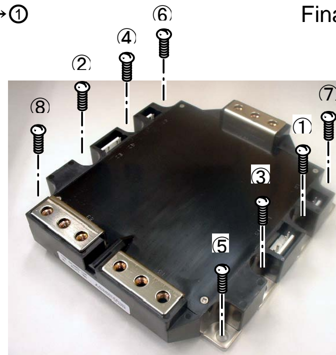
When mounting a module on a heat sink, a device could get damage or degrade if a sudden torque ("one side tightening ") is applied at only one mounting terminal, since stress is applied on a ceramic plate and silicon chips inside the module. Shown in Fig.1 is the recommended torquing order for mounting screws.



(a) Two-Point Mounting Type
Temporary tightening ①→②
Final tightening ②→①



(b) Four-Point Mounting Type
Temporary tightening ①→②→③→④
Final tightening ④→③→②→①



(c) Eight-Point Mounting Type
Temporary tightening ①→②→③→④→⑤→⑥→⑦→⑧
Final tightening ①→②→③→④→⑤→⑥→⑦→⑧

Fig.1 Recommended Torquing Order for Mounting Screws

*:<u>Temporary tightening torque should be set at 20~30% of maximum rating.</u>

Also, care must be taken to achieve maximum contact (i.e. minimum contact thermal resistance) for the best heat dissipation.)

The flatness of a heat sink where a module (except 24A series IGBT) is mounted (ref. Fig.2) should be as follows. Also, the surface finish should be less than Rz12.

Copper base plate module:−100μm~+100μm

Thermal compound with good thermal conductivity should be applied evenly about Aluminum base plate modules:−100μm~+200μm on the contact surface of a module and a heat sink.

*24A series IGBT Module (CMxxHA/HB-24A)

Heat sink flatness: Less than ± 20μm on a length of 100mm
/Less than 10μm of roughness

Thermal grease thickness: +50~+100μm

Grease on the contact surface prevents the corrosion of the contact surface. However, use the kind of grease that has a stable characteristic over the whole operating temperature range and does not change its properties for several years.

A torque wrench shall be used in tightening mounting screws and tighten screws to the specified torque. Excessive torquing may result in damage or degradation of a device.

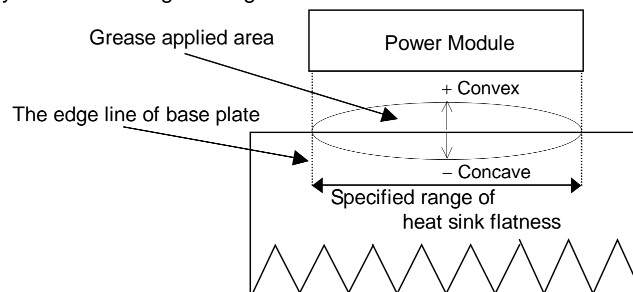


Fig.2 Heat Sink Flatness

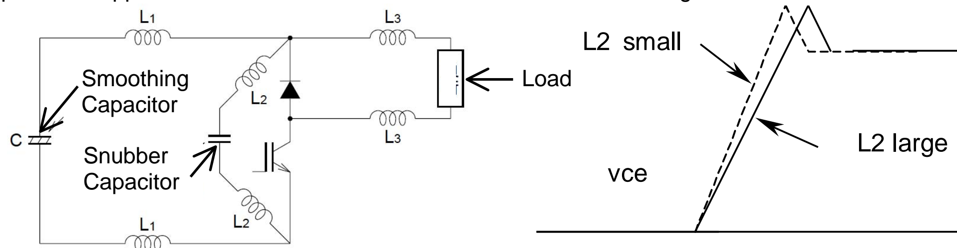
Installation of Power Module

1. Installing Capacitor

During switching, voltage is induced in power circuit stray inductance by the high di/dt of the main current. This voltage can appear on the IGBT module and cause damage. In order to avoid this problem, guidelines that should be followed in designing the circuit layout are:

① Located the smoothing capacitor as close as possible to the IGBT module
② Use ceramic capacitor near the IGBT module to bypass high frequency current
③ Adopt low impedance electrolytic capacitor as smoothing capacitor
④ Use snubber circuit to absorb surge voltage
⑤ Decrease switching speed in order to lower di/dt.

② and ⑤ are the most effective to reduce surge voltage. The stray inductance of snubber circuit generally is not considered to avoid complicating the circuit. In addition, combination of ②, ④, ⑤ is needed since there is a limit on the length of wiring. The bypass capacitor of approach ② act as a snubber when oscillation is occurring.



L1 : Stray inductance between the smoothing (electrolytic) capacitor and the IGBT module.
L2 : Stray inductance between the snubber (filter) capacitor and the IGBT module.
L3 : Stray inductance between the load and the power circuit's output stage

2. Installation Hints

When mounting IGBT modules on a heat sink, uneven mounting can cause the modules ceramic isolation to crack.

To achieve the best thermal radiation effect, the bigger the contact area is, the smaller the thermal resistance is. Heat sink should have a surface finish in range of Rz6 ~ Rz12, curvature within 100μm (for 24A series products, heat sink should have a surface roughness within 10μm, curvature within 20μm corresponding to 100mm length).

Uniform coating of thermal grease between the module and heat sink can prevent corrosion of contact parts. Select a compound, which has stable characteristics over the whole operating temperature range and does not change its properties over the life of the equipment.(See Table1 for suggested type).

Use a uniform coating of thermal interface compound.

The thickness of thermal grease should be ranked in 100~200μm (24A series 50~100μm) according to the surface finish.

Mounting screws should be tightened by using a torque wrench to the prescribed torque in progressive stages in a cross pattern. As mentioned before, over torque terminal or mounting screws may result in damage of IGBT modules. When an electric driver is used, thermal grease with low viscosity is recommended and extra grease must be extruded before final tightening screws.

* For the recommended torque order for mounting screws referring to "Inistallation Method" in the section of "Correct and Safety Use of Power Module"

Note) Maximum torque specifications are provided in device data sheets. The type and quantity of thermal compounds having an effect on the thermal resistance are determined by consideration of both thermal grease and heat sink. Typical value given in datasheet is measured by using thermal grease producted by Shin-Etsu Chemical Co.,Ltd.
(G-746, which has not issued in Shin-Etsu's publications, is almost the same as G-747.)

Note : Usually the mounting screws are prepared for users as accessories with module. But for some reasons, this service is stopped for NF series products.
The mounting screws for《H Series》modules can be referred according to Table 1.

Table.1

Size	Type	Manufacturer	(2004/09/30 to present)
M4×8/10	Cross recess nuts and screws	Toyo Bussan Co. Ltd.	http://www.tobutsu.co.jp/
M5×12	Cross recess nuts and Hexagon head bolts	FC tech Company	+81-52-991-7311
M6×12	Cross recess nuts and Hexagon head bolts		
M8×16	Cross recess nuts and Hexagon head bolts		

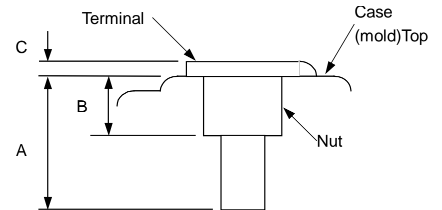
M5~M8 Hexagon head bolt : JIS B 1187

Table.2 The terminal screw attached products

Module type	Size	Screw type
CM150DY-12NF, CM200DY-12NF, CM300DY-12NF CM100DY-24NF, CM150DY-24NF CM100DY-24A, CM150DY-24A, CM200DY-24A	M5×12 (main)	Cross-recessed hexagon screws with washer
CM400DY-12NF, CM600DY-12NF CM200DY-24NF, CM300DY-24NF, CM400DY-24NF CM300DY-24A, CM400DY-24A, CM600DY-24A	M6×12 (main)	Cross-recessed hexagon screws with washer
CM400HA-24A, CM600HA-24A	M6×12 (main)	Cross-recessed hexagon screws with washer
	M4×10 (auxiliary)	Cross-recessed pan head screws with washer
CM600HB-24A	M8×16 (main)	Cross-recessed hexagon screws with washer
	M4×10 (auxiliary)	Cross-recessed pan head screws with washer
CM600DU-24NF	M8×16 (main)	Cross-recessed hexagon screws with washer
	M4×8 (auxiliary)	Cross-recessed pan head screws with washer

Installation of Power Module

Note: when used the screw except the attached screw, be careful of the screw length. If use the screw which is long more than necessary, the bursting screw head reaches gel and an aluminum wire in the module and causes the device destruction in the resin of the terminal area. Use a screw with the length which is the optimal for the top to refer to the thickness and the following size of the terminal for the connection.



Terminal screwing hole depth and thickness(Unit in mm tolerance:±0.3mm)

V_{CES} (V)	Part number	Screw size		A	B	C	depth
600	CM150DY-12NF, CM200DY-12NF, CM300DY-12NF	main	M5	12.5	4.2	1	13.2
1200	CM100DY-24NF, CM150DY-24NF CM100DY-24A, CM150DY-24A, CM200DY-24A						
600	CM400DY-12NF	main	M6	13.7	5.2	1	14.4
1200	CM200DY-24NF, CM300DY-24A						
600	CM600DY-12NF	main	M6	12	5.3	1	12.7
1200	CM300DY-24NF,CM400DY-24NF, CM400DY-24A						
1200	CM600DU-24NF	main	M8	11	7.3	1.6	12.3
		auxiliary	M4	6.2	3.2	0.5	6.4
600	CM75TL/RL-12NF, CM100TL/RL-12NF, CM150TL/RL-12NF	main	M5	12	4.2	1	12.7
1200	CM50TL/RL-24NF, CM75TL/RL-24NF, CM100TL/RL-24NF						
600	CM200TL/RL-12NF	main	M5	15	4.2	1	15.7
1200	CM150TL/RL-24NF, CM200TL/RL-24NF						
1200	CM400HA-24A, CM600HA-24A	main	M6	11.5	5	1	12.2
		auxiliary	M4	8.2	3.2	0.8	8.7
1200	CM600HB-24A	main	M8	12.4	7	1	13.1
		auxiliary	M4	8.2	3.5	0.8	8.7
1200	CM900DU-24NF, CM1400DU-24NF	main	M6	15	5.2	1.2	16.3

※ Not include the float of the terminal in size C.

<u>The expression with minimum valid depth</u>

The formula with minimum valid depth in CM600DU-24NF is as the following.

The main terminal A - tolerance + C=11-0.3+1.6=12.3 mm

The auxiliary terminal A - tolerance + C=6.2-0.3+0.5=6.4 mm

3. Thermal Impedance Considerations

The junction to case thermal resistance $R_{th(j-c)}$ and the case to heat sink thermal resistance $R_{th(c-f)}$ are given in datasheet.

The case temperature has been measured at the side of base. However, the European standards indicate that the temperature measurement point is just under the chip.

The case temperature measurement point of various products is shown in Table 3-1, 3-2, 3-3, 3-4, 3-5 and Table 3-6. It is measured by uniform 100μm~200μm (50~100μm for 24A single series) coating of thermal grease with thermal conductivity of 0.92W/m・°C between the module and heat sink. A Thermo-couple is used to measure the temperature of case and heat sink at the same point shown in the following tables. (0.8φ 3mm depth, 0.3φ thermo-couple)

・Note

*The thermal impedance depends on the material, area and thickness of heat sink. The smaller the area and the thinner the heat sink is, the lower the impedance is for the same material.

※The type and quantity of thermal compounds can affect the thermal resistance.

The thermal impedance just under the chips for Dual types (unit : °C/W)

Part number	$R_{th(j-c)}$ maximum		Contact (typical)	Part number	$R_{th(j-c)}$ maximum		Contact (typical)
	IGBT	FWDi			IGBT	FWDi	
CM150DY-12NF	0.16	0.29	0.022	CM100DY-24NF	0.13	0.23	0.022
CM200DY-12NF	0.13	0.22	0.022	CM150DY-24NF	0.093	0.17	0.022
CM300DY-12NF	0.093	0.16	0.022	CM200DY-24NF	0.066	0.12	0.02
CM400DY-12NF	0.066	0.11	0.020	CM300DY-24NF	0.046	0.085	0.02
CM600DY-12NF	0.046	0.078	0.018	CM400DY-24NF	0.034	0.062	0.018
—	—	—	—	CM600DU-24NF	0.023	0.042	0.015

※The notice

* With the thickness of the heat sink to use, the thermal resistance $R_{th(f-a)}$ of the heat sink sometimes changes with the area of it with the material of it.
  The smaller the area is in the heat sink with the identical material, the thinner the thickness becomes, the bigger the thermal resistance becomes.
* With the amount of coating of grease, contact thermal resistance $R_{th(c-f)}$ sometimes changes with the kind of it.
* As for water-cooled, the: general industrial power module presupposes use by the cooling system, which used an auto cooling, and an air-cooled heat sink.
  When using a water-cooled heat sink, the qualitatively of the expanse of the heat, thermal resistance $R_{th(j-c)}$ sometimes change substantially.
* Because the package of the: general industrial power module is not secret structure in the basic of it about the liquid cooling, it is possible for liquid to invade easily inside the module.
  We assume and we aren't designing long-range contact with the one except the package material, the semiconductor chips, the silicone gel to be using.
  Therefore, when making IGBT module silicone oil and so on in the immersion as for oil cooling, therefore, the characteristic and the reliability cannot be guaranteed.

Table 3-1 Chip location - 600V class Dual (Unit : mm)

CM150DY-12NF (Tr : IGBT, Di : FWDi)

CM200DY-12NF (Tr : IGBT, Di : FWDi)

CM300DY-12NF (Tr : IGBT, Di : FWDi)

Table 3-1 Chip location - 600V class Dual (Unit : mm)

CM400DY-12NF (Tr : IGBT, Di : FWDi)

CM600DY-12NF (Tr : IGBT, Di : FWDi)

Table 3-2 Chip location - 600V class 6pack (Unit : mm)

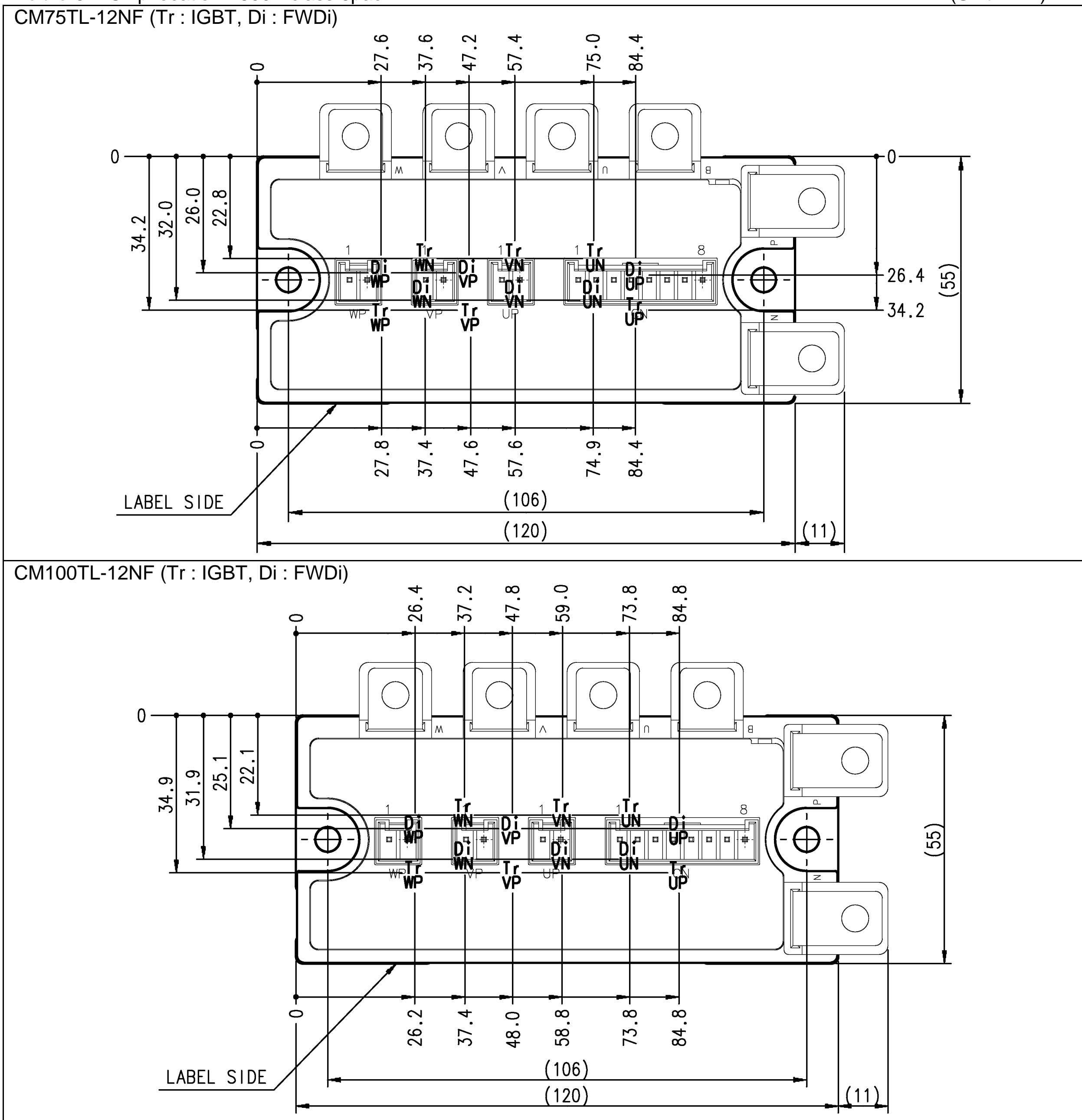
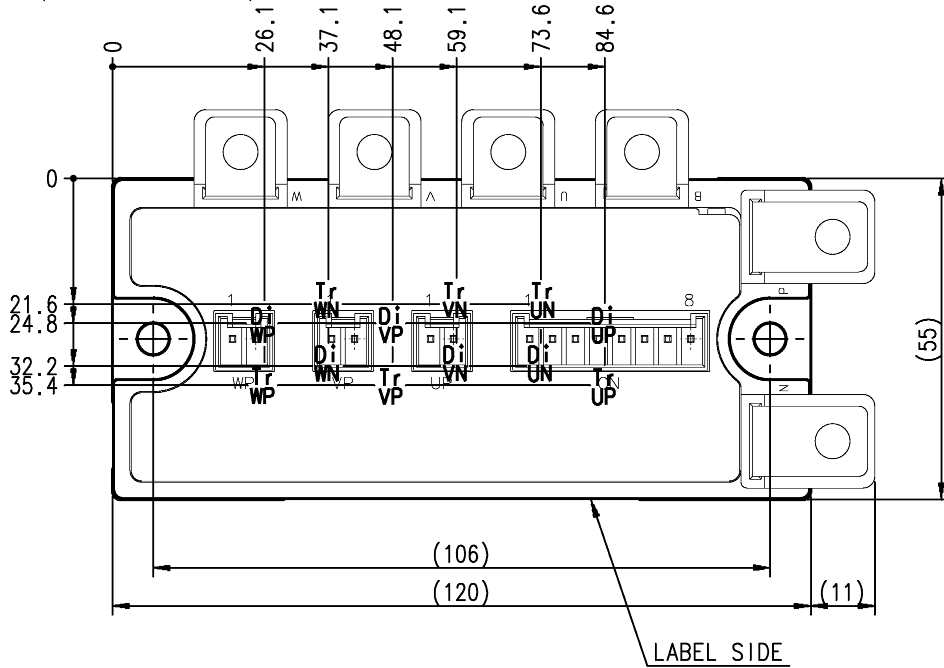


Table 3-2 Chip location - 600V class 6pack (Unit : mm)

CM150TL-12NF (Tr : IGBT, Di : FWDi)



CM200TL-12NF (Tr : IGBT, Di : FWDi)

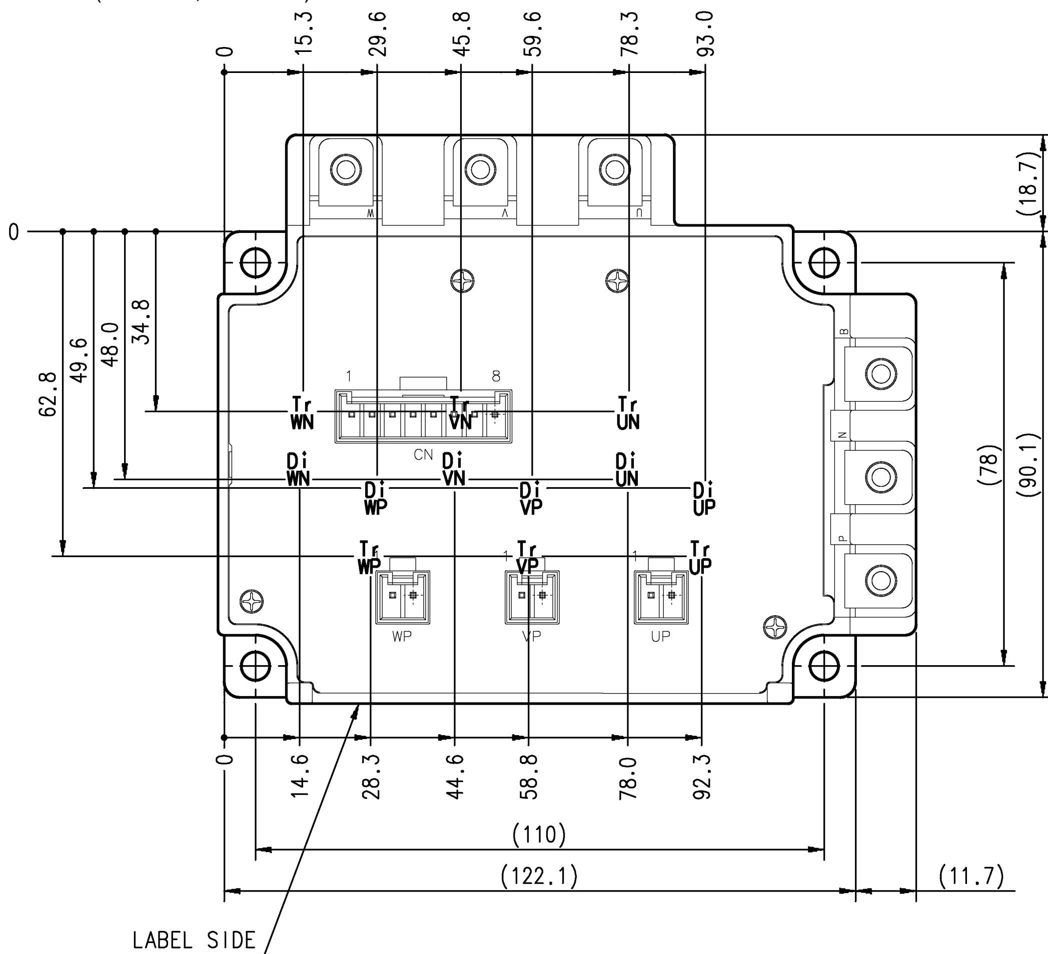


Table 3-2 Chip location - 600V class 7pack (Unit : mm)

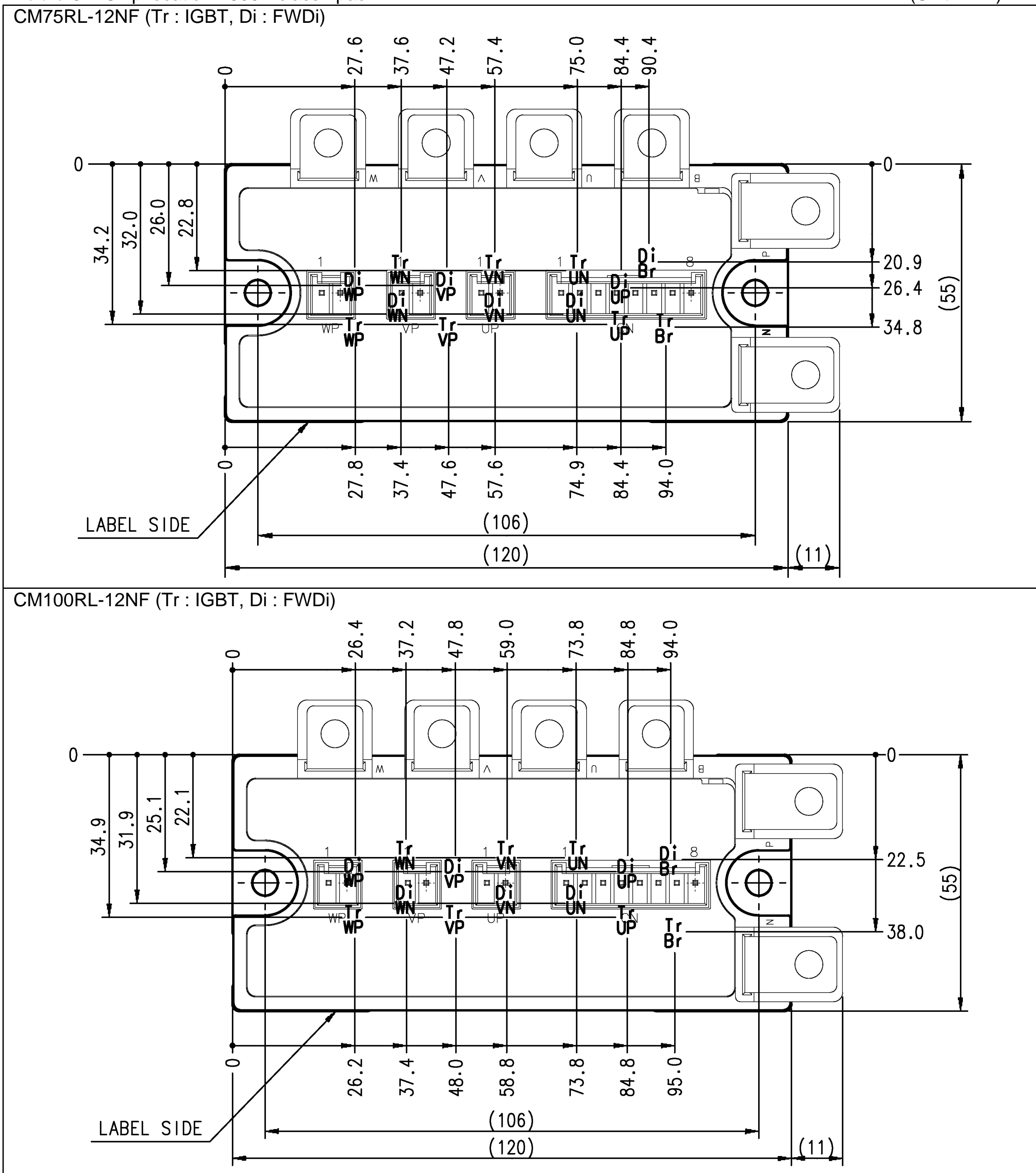
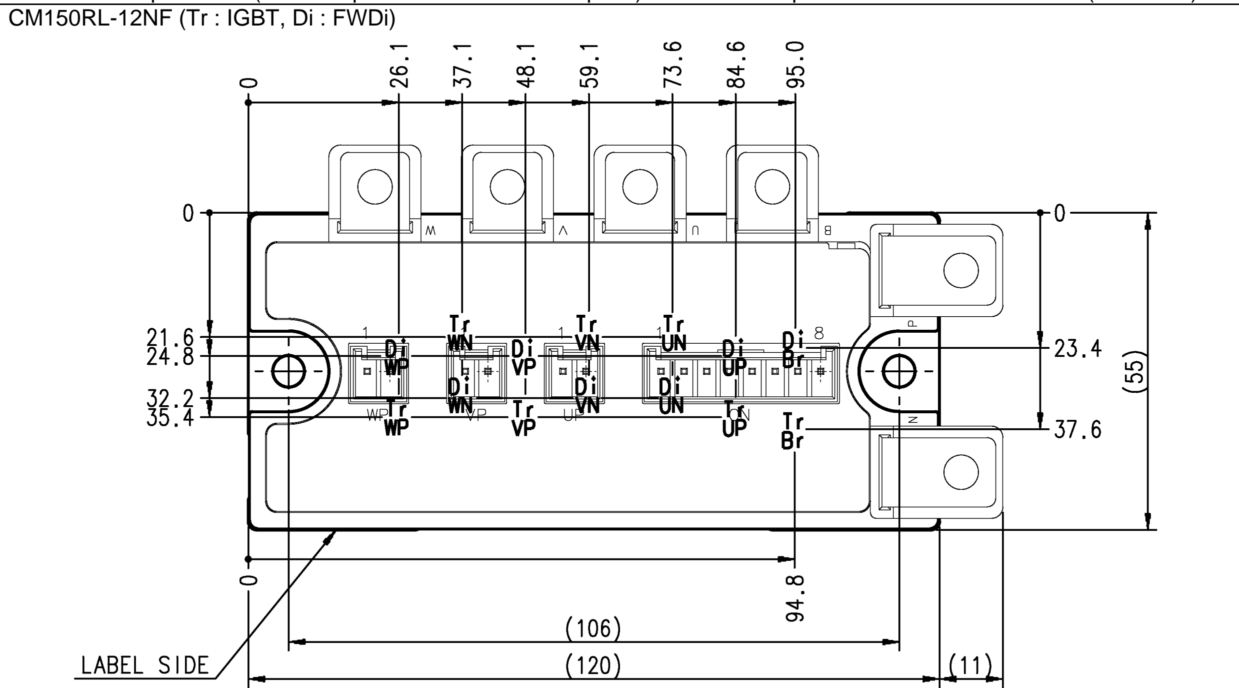


Table 3-2 Chip location (case temperature measurement point) - 600V class 7pack (Unit : mm)

CM150RL-12NF (Tr : IGBT, Di : FWDi)



CM200RL-12NF (Tr : IGBT, Di : FWDi)

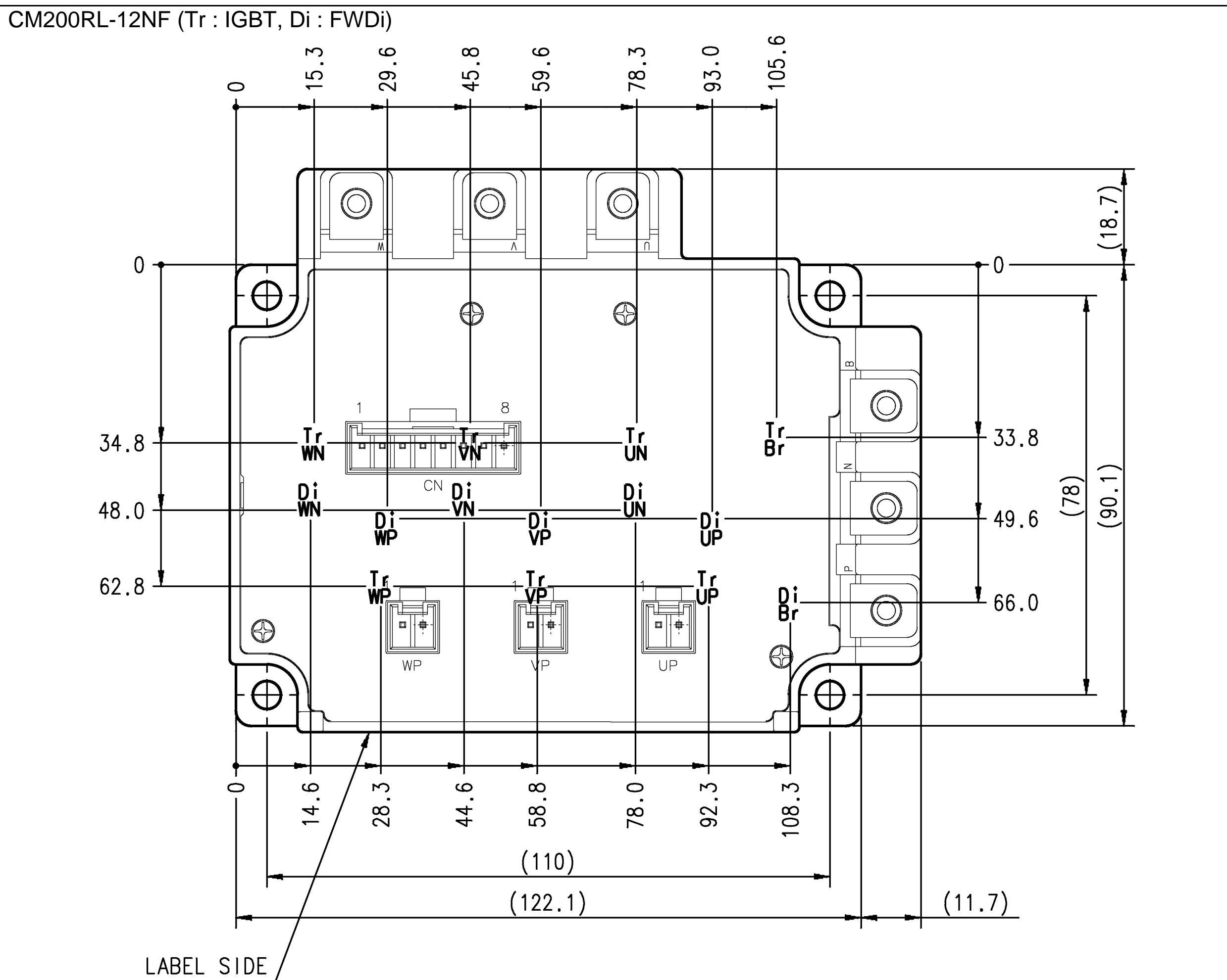
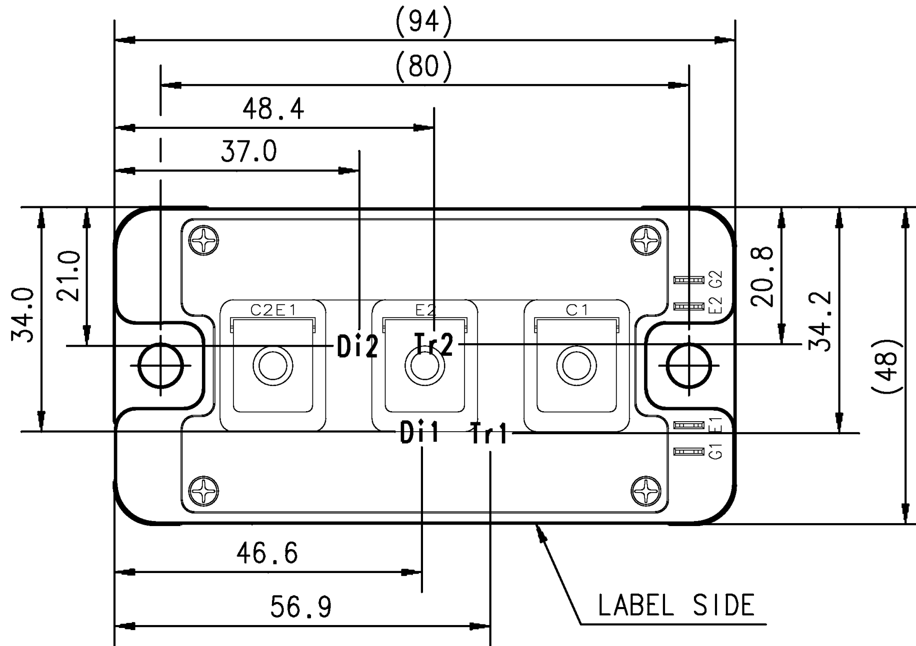


Table 3-3. Chip location - 1200V class Dual (Unit : mm)

CM100DY-24A (Tr : IGBT, Di : FWDi)



CM100DY-24NF, CM150DY-24A (Tr : IGBT, Di : FWDi)

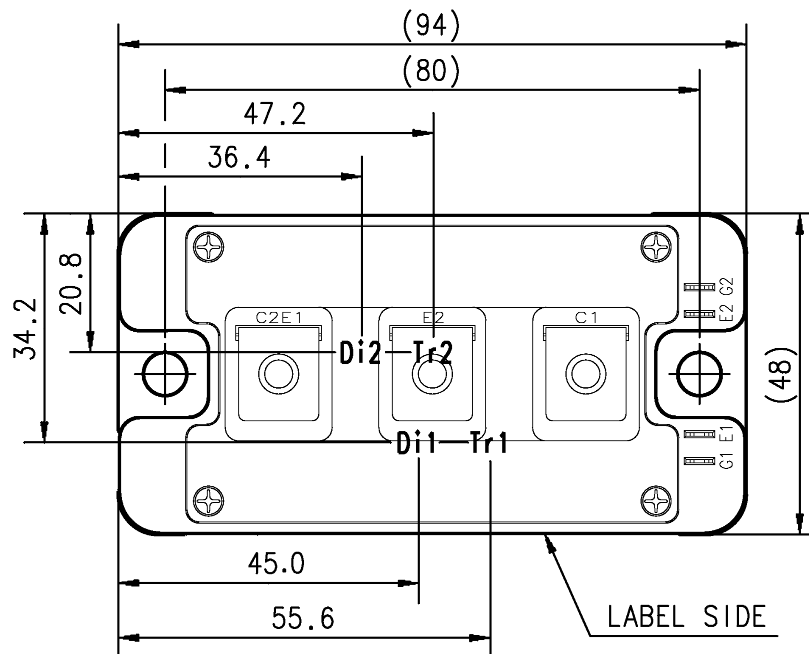
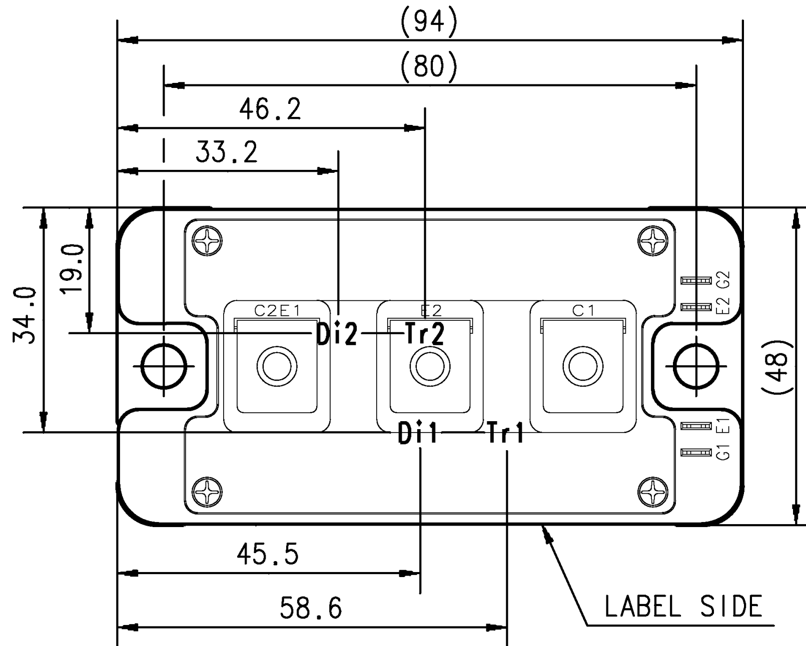


Table 3-3 Chip location - 1200V class Dual (Unit : mm)

CM150DY-24NF, CM200DY-24A (Tr : IGBT, Di : FWDi)



CM200DY-24NF, CM300DY-24A (Tr : IGBT, Di : FWDi)

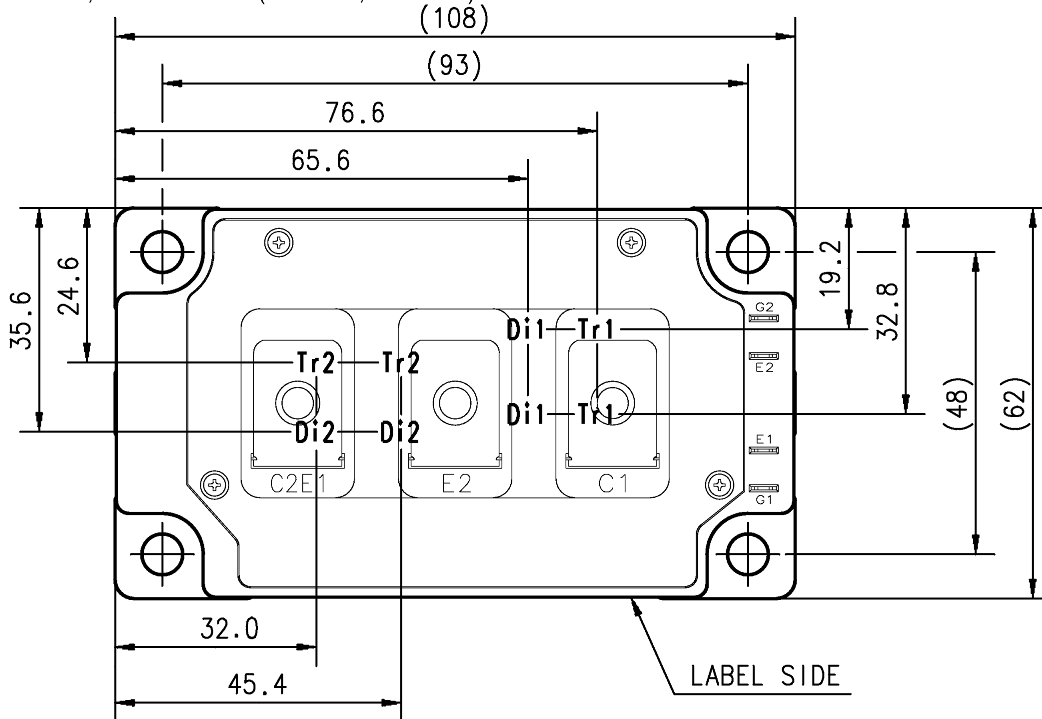


Table 3-3 Chip location - 1200V class Dual (Unit : mm)

CM300DY-24NF, CM400DY-24A (Tr : IGBT, Di : FWDi)
(110), (93), 78.6, 66.4, 44.2, 32.0, 21.6, 35.0, 48.2, (62), (80), 20.6, 33.6, 46.6, Di1, Tr1, Tr2, Di2, C2E1, E2, C1, G2, E2, E1, G1, LABEL SIDE
CM400DY-24NF, CM600DY-24A (Tr : IGBT, Di : FWDi)
(110), (93), 78.8, 65.8, 44.7, 31.4, 21.6, 35.0, 48.2, (62), (80), 20.6, 33.6, 46.6, Di1, Tr1, Tr2, Di2, C2E1, E2, C1, G2, E2, E1, G1, LABEL SIDE

Table 3-3 Chip location - 1200V class Dual (Unit : mm)

CM600DU-24NF (Tr: IGBT, Di : FWDi)

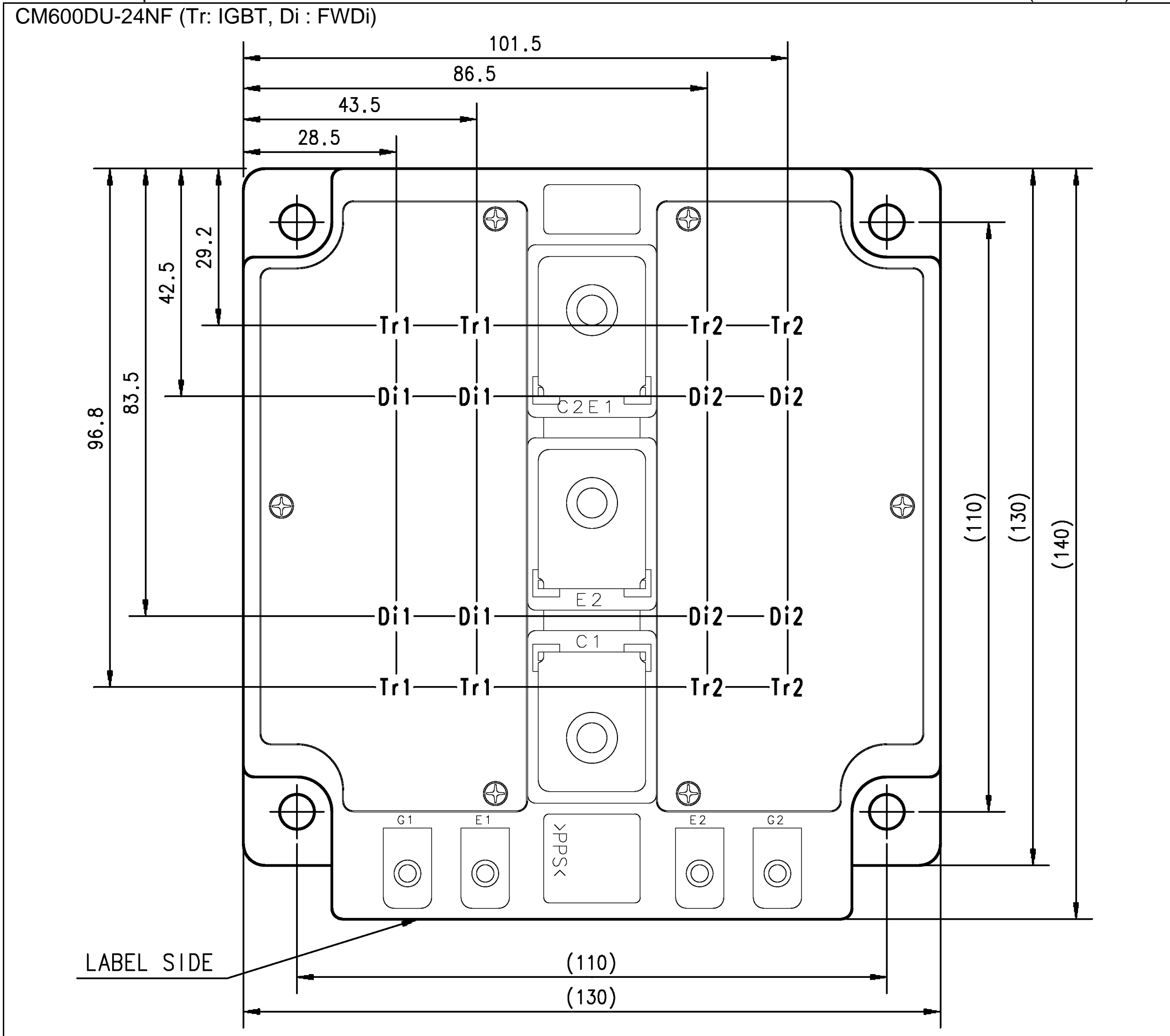
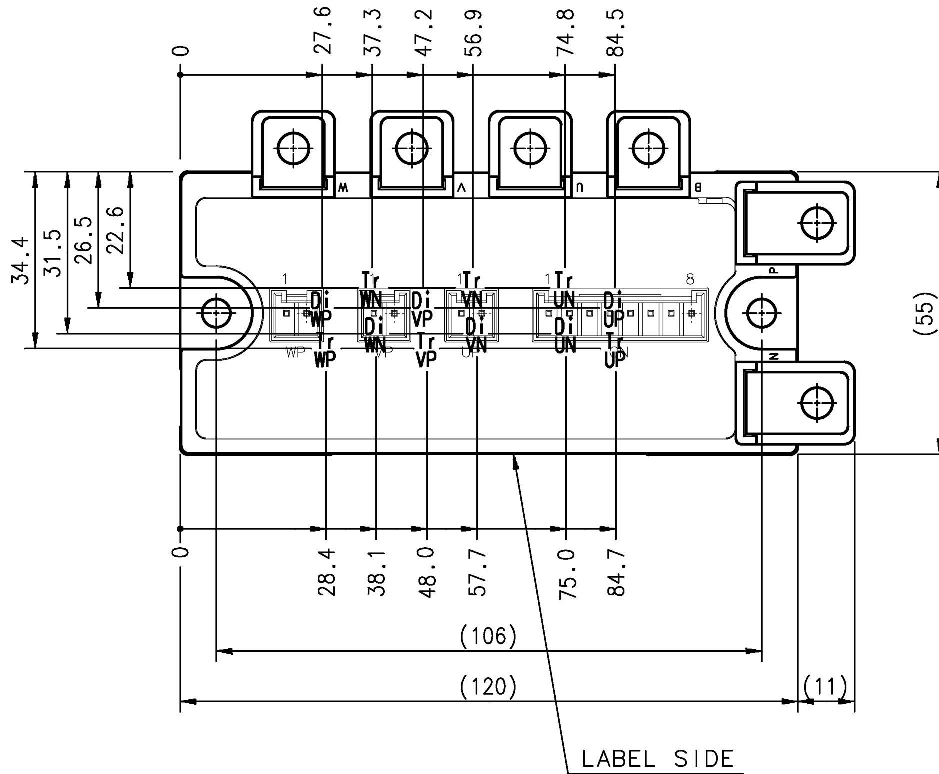


Table 3-4 Chip location - 1200V class 6pack (Unit : mm)

CM50TL-24NF (Tr : IGBT, Di : FWDi)



CM75TL-24NF (Tr : IGBT, Di : FWDi)

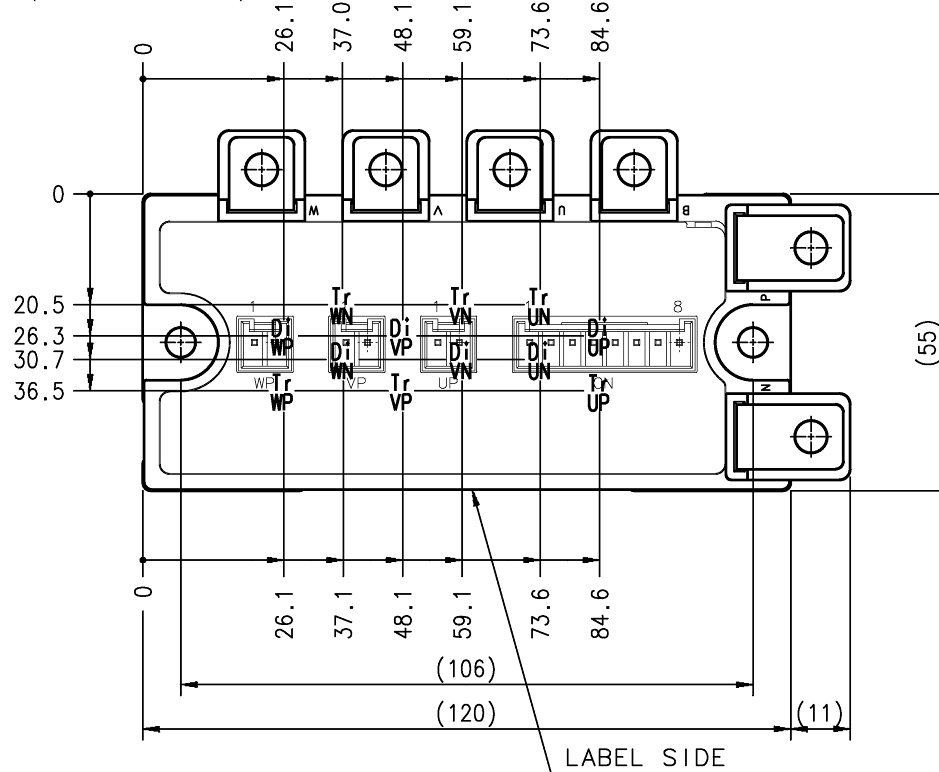
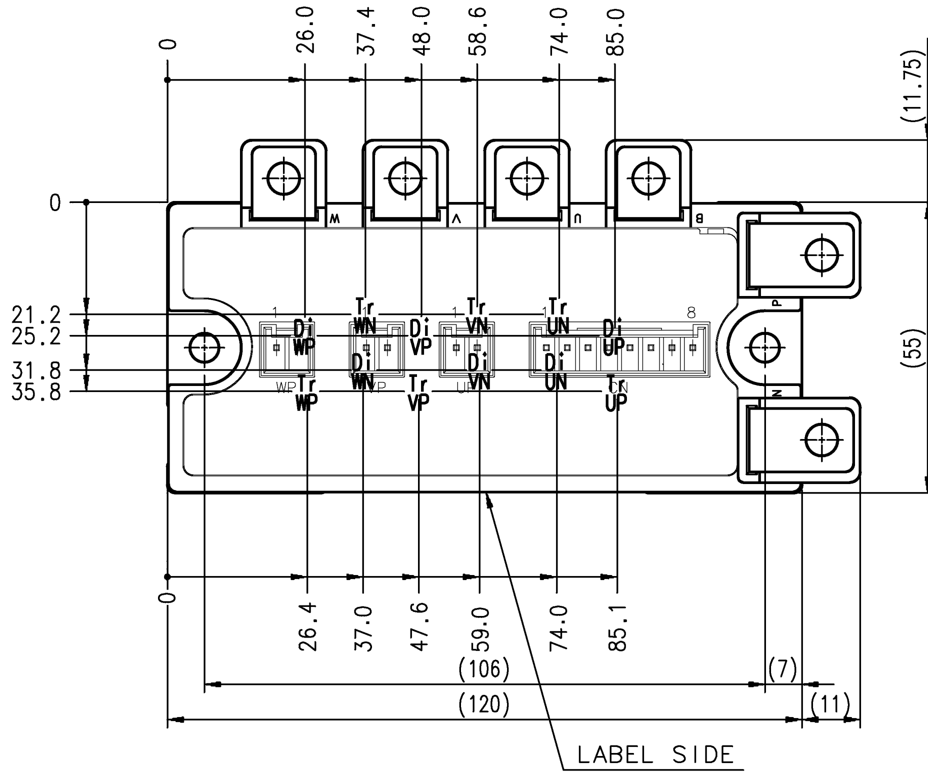


Table 3-4 Chip location - 1200V class 6pack (Unit : mm)

CM100TL-24NF (Tr : IGBT, Di : FWDi)



CM150TL-24NF (Tr : IGBT, Di : FWDi)

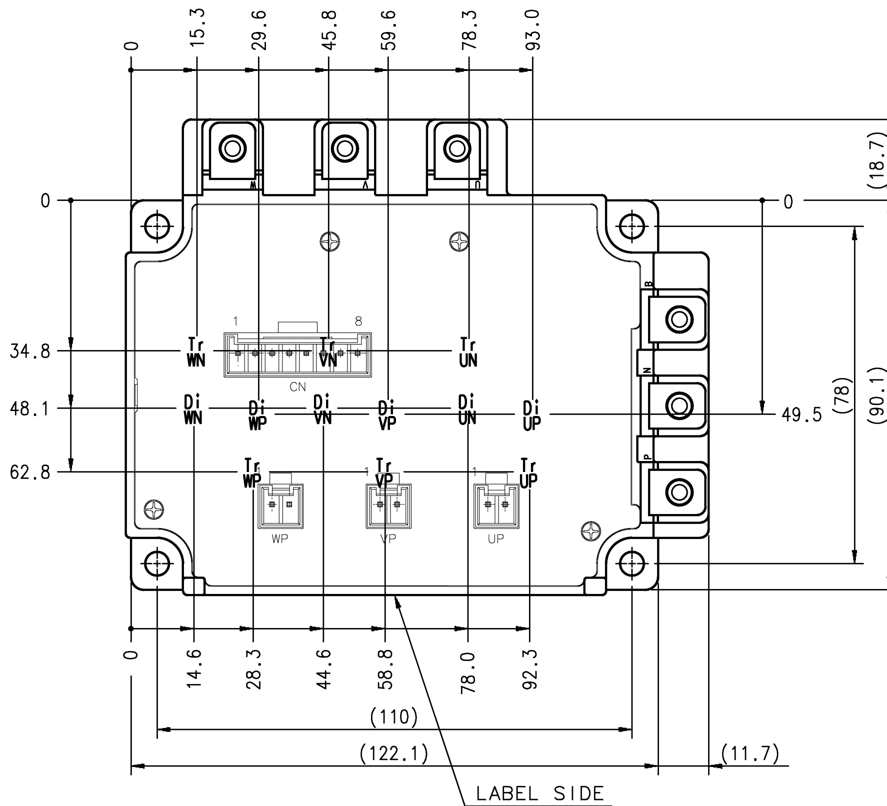


Table 3-4 Chip location - 1200V class 6pack (Unit : mm)

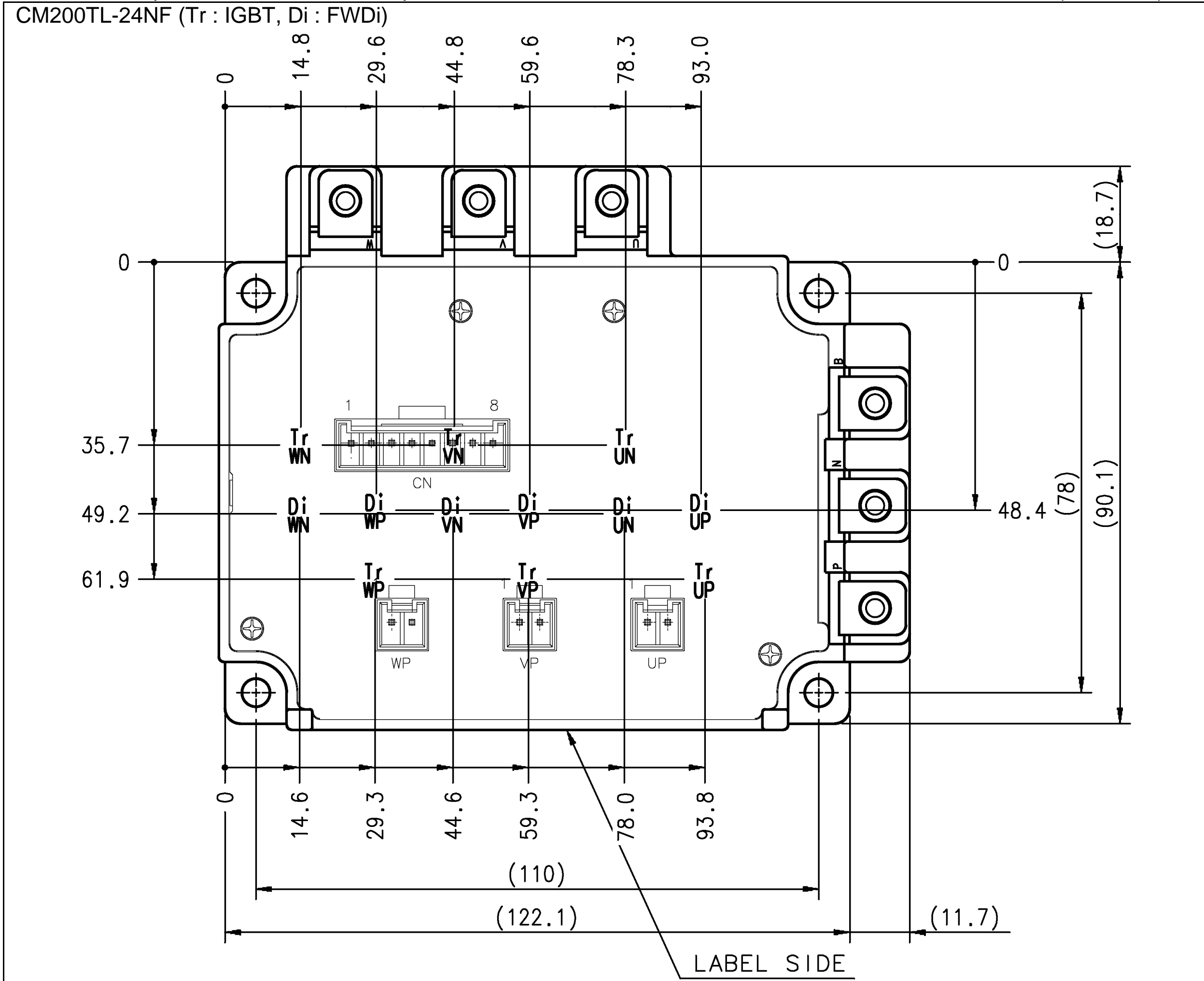
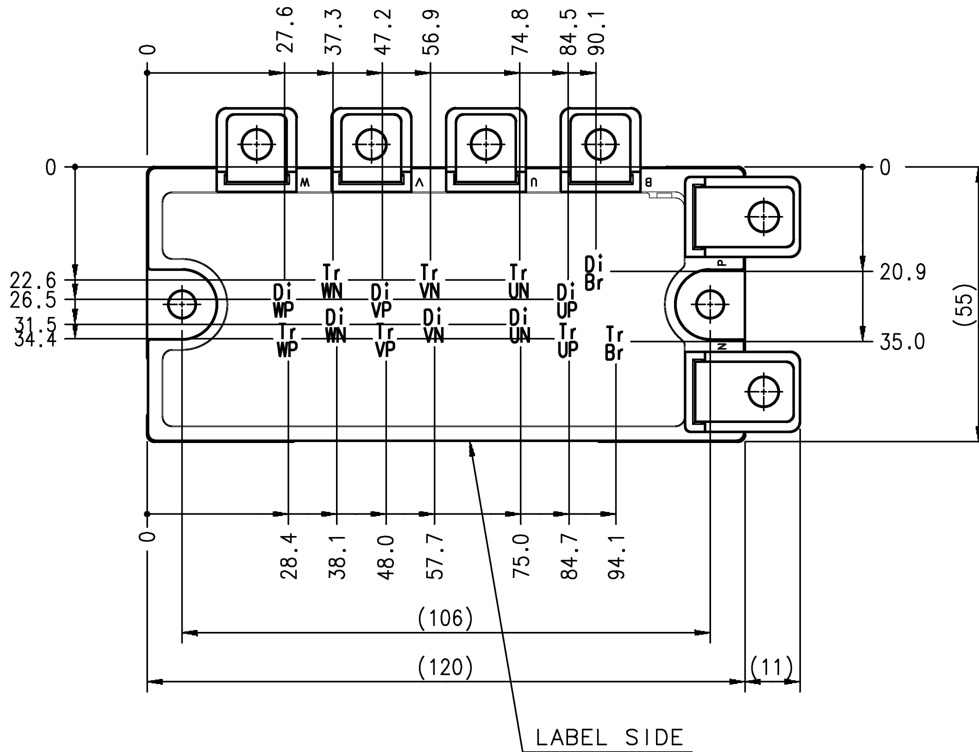


Table 3-4 Chip location - 1200V class 7pack (Unit : mm)

CM50RL-24NF (Tr : IGBT, Di : FWDi)



CM75RL-24NF (Tr : IGBT, Di : FWDi)

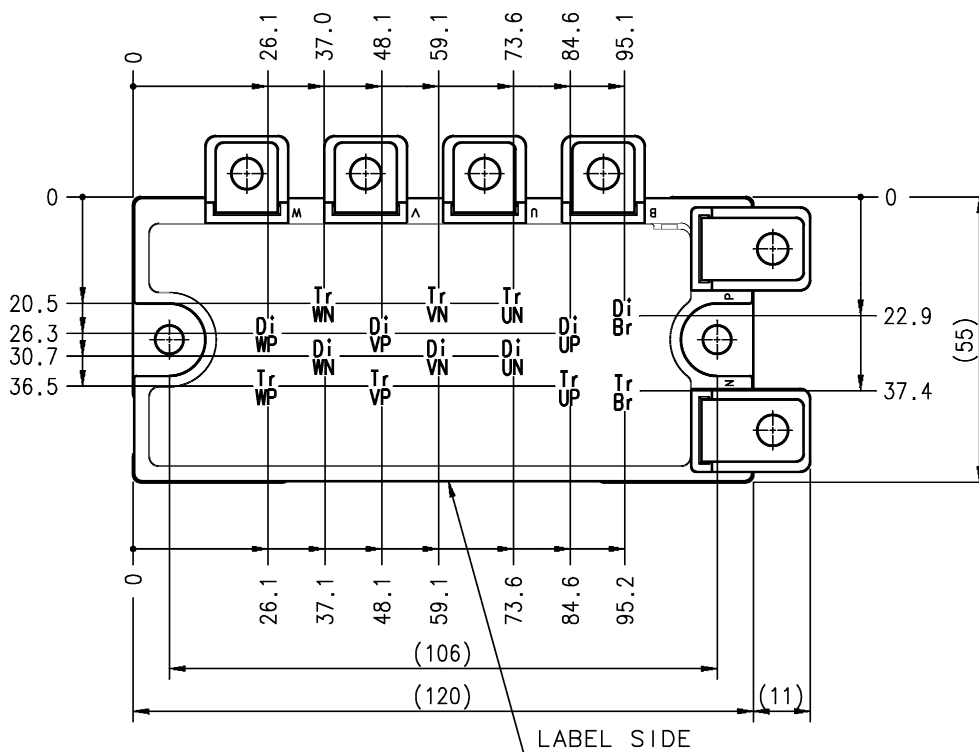
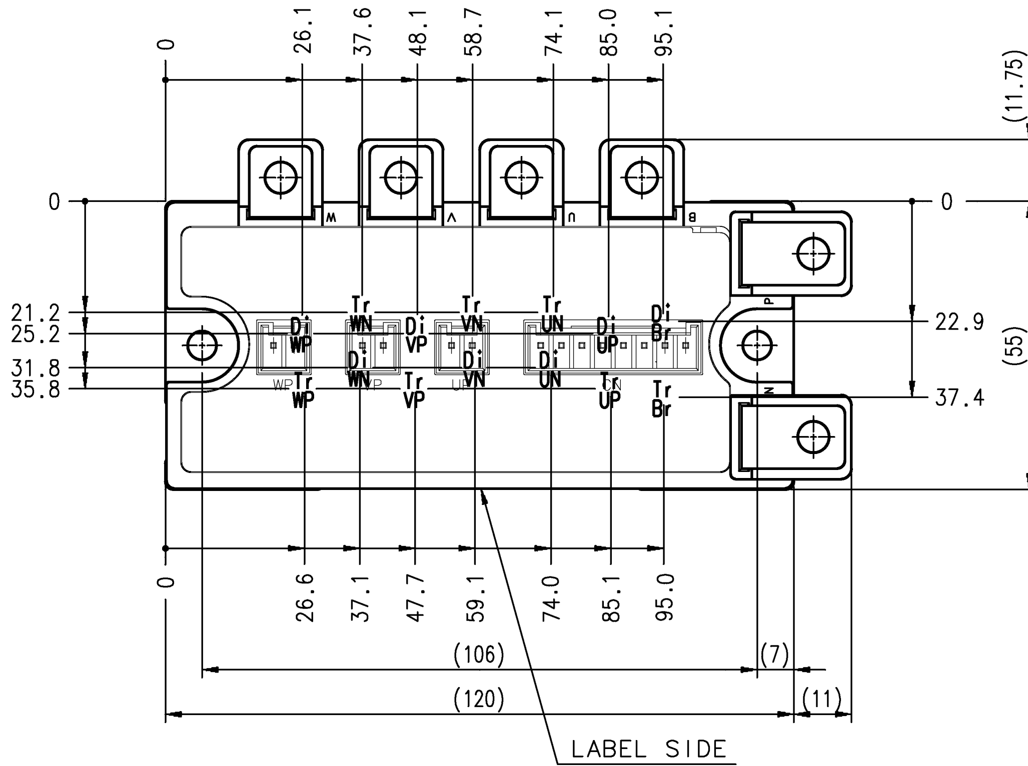


Table 3-4 Chip location - 1200V class 7pack (Unit : mm)

CM100RL-24NF (Tr : IGBT, Di : FWDi)



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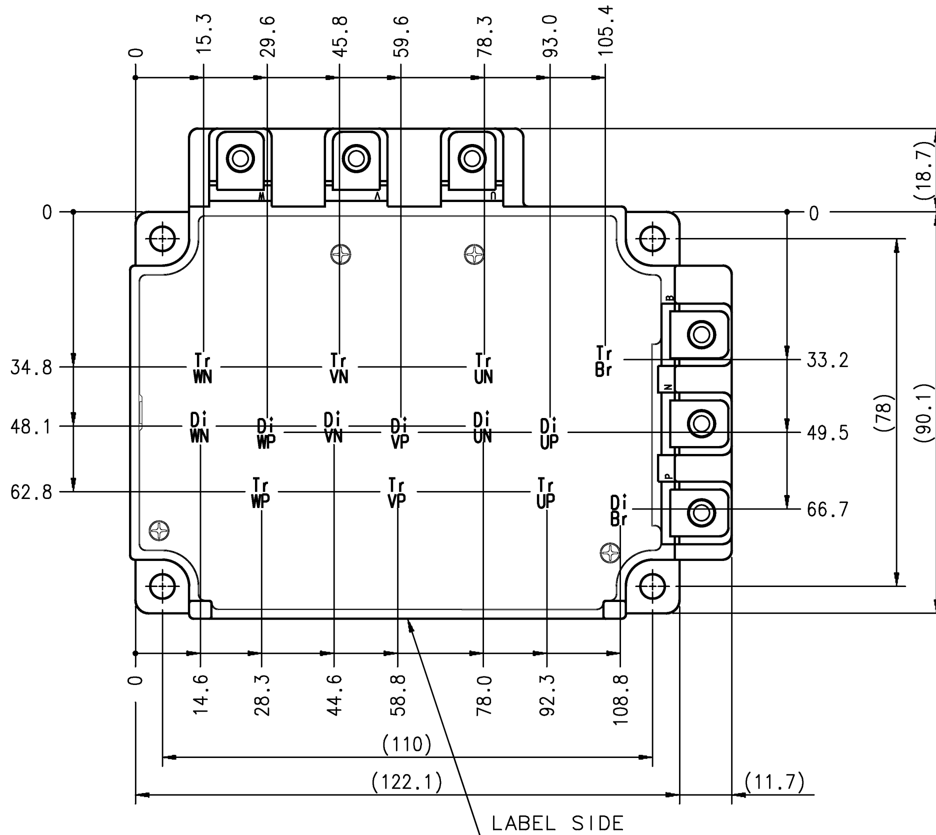


Table 3-4 Chip location - 1200V Class 7pack (Unit : mm)

CM200RL-24NF (Tr : IGBT, Di : FWDi)

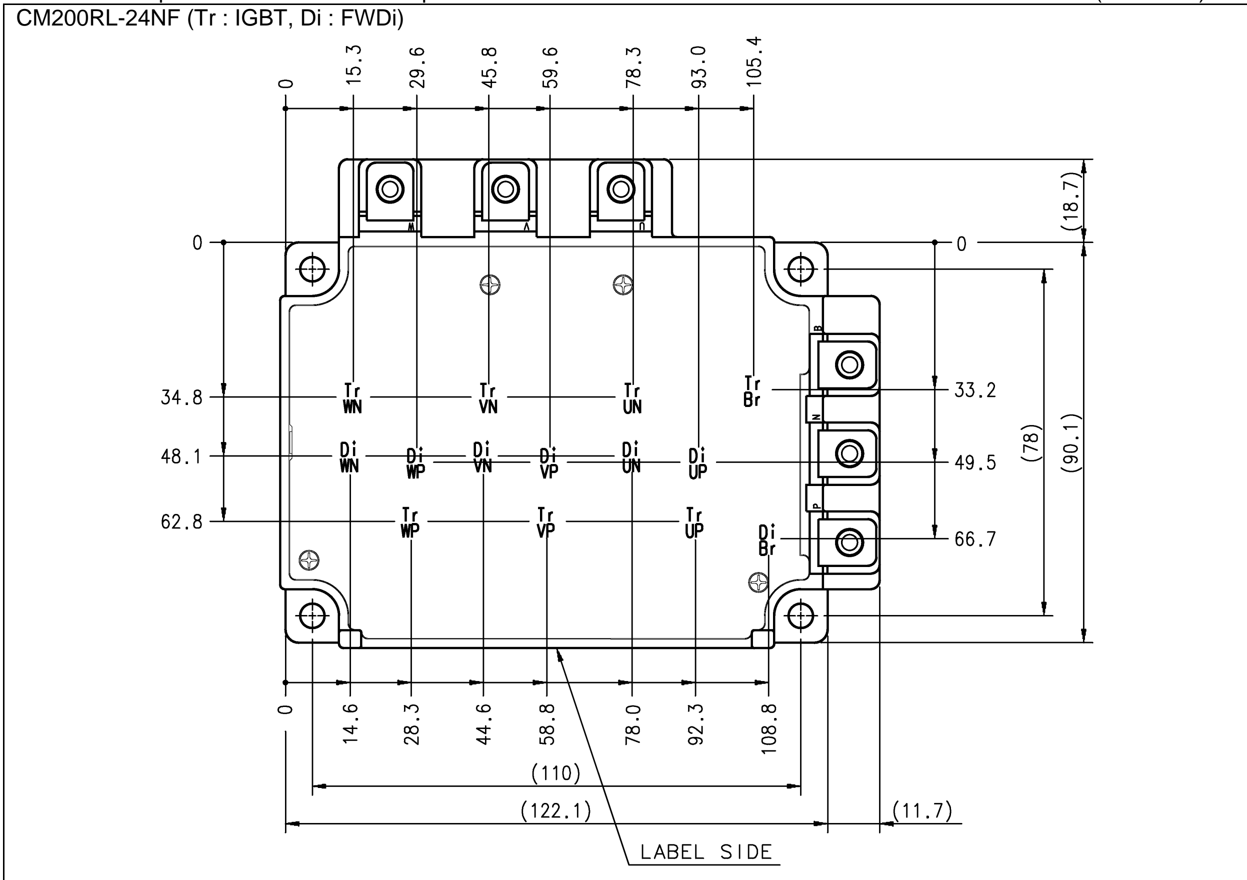
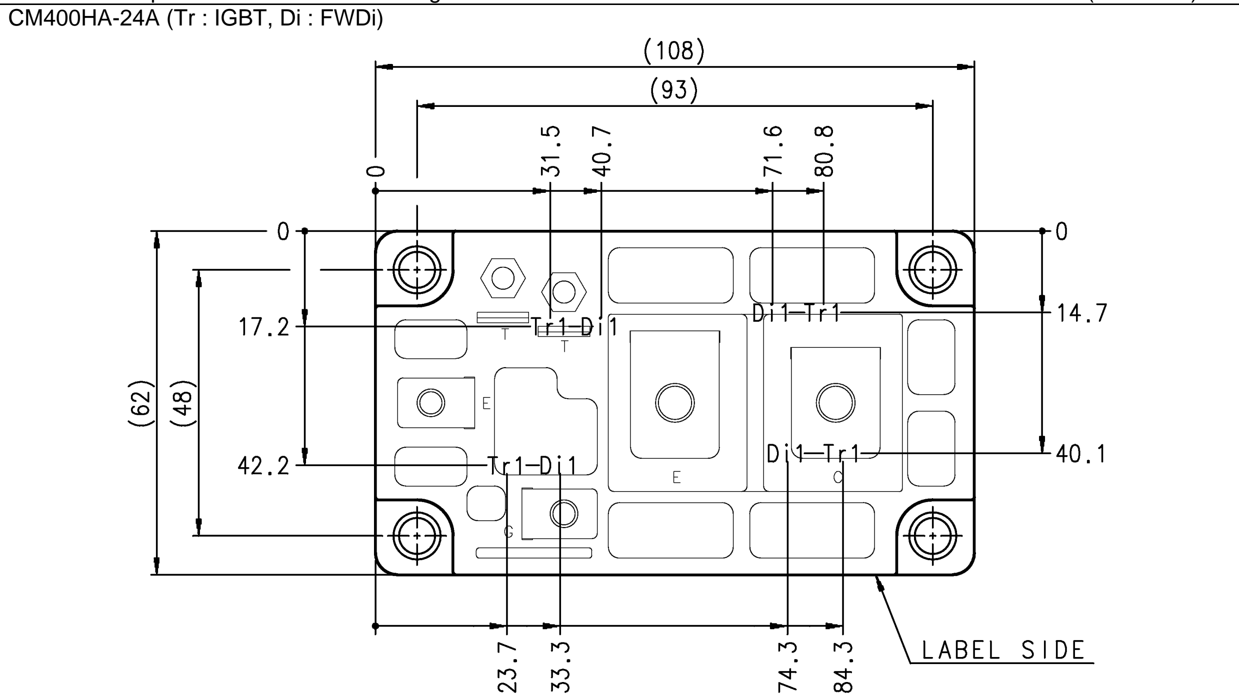


Table 3-5 Chip location - 1200V class Single (Unit : mm)

CM400HA-24A (Tr : IGBT, Di : FWDi)



CM600HA-24A (Tr : IGBT, Di : FWDi)

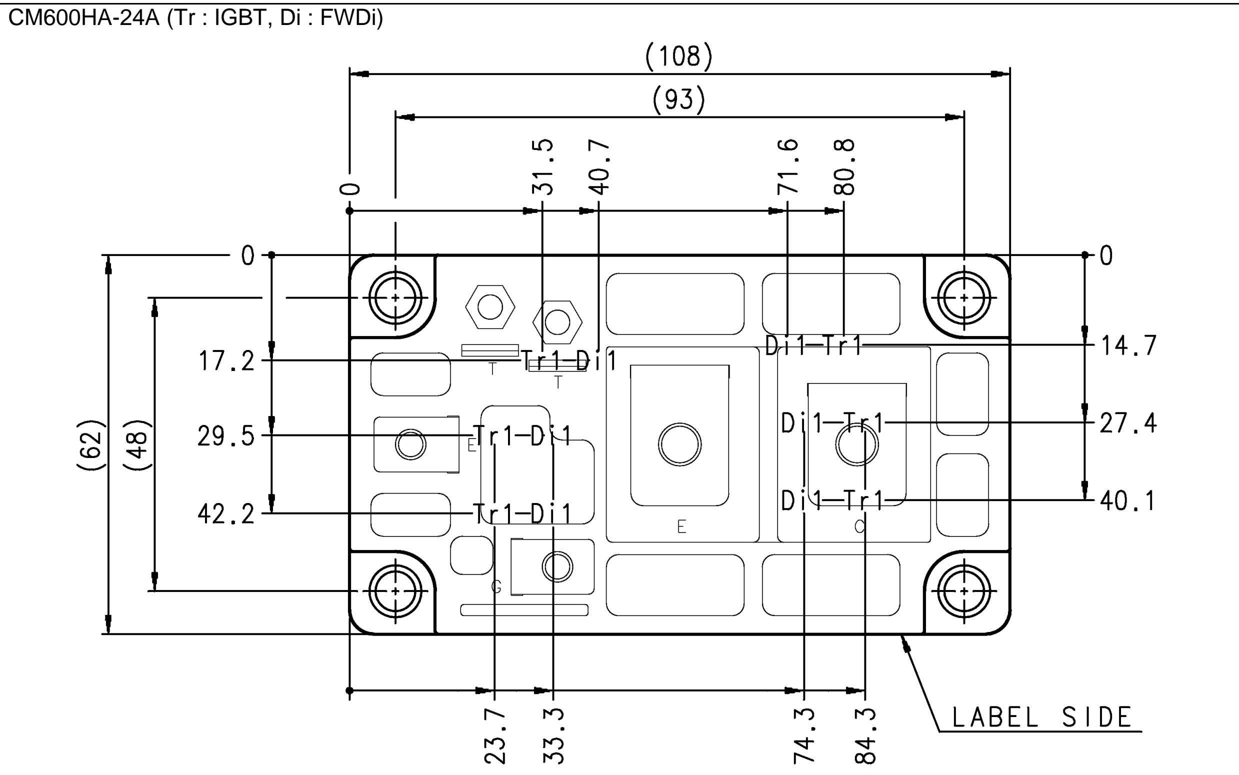


Table 3-5 Chip location - 1200V class Single (Unit : mm)

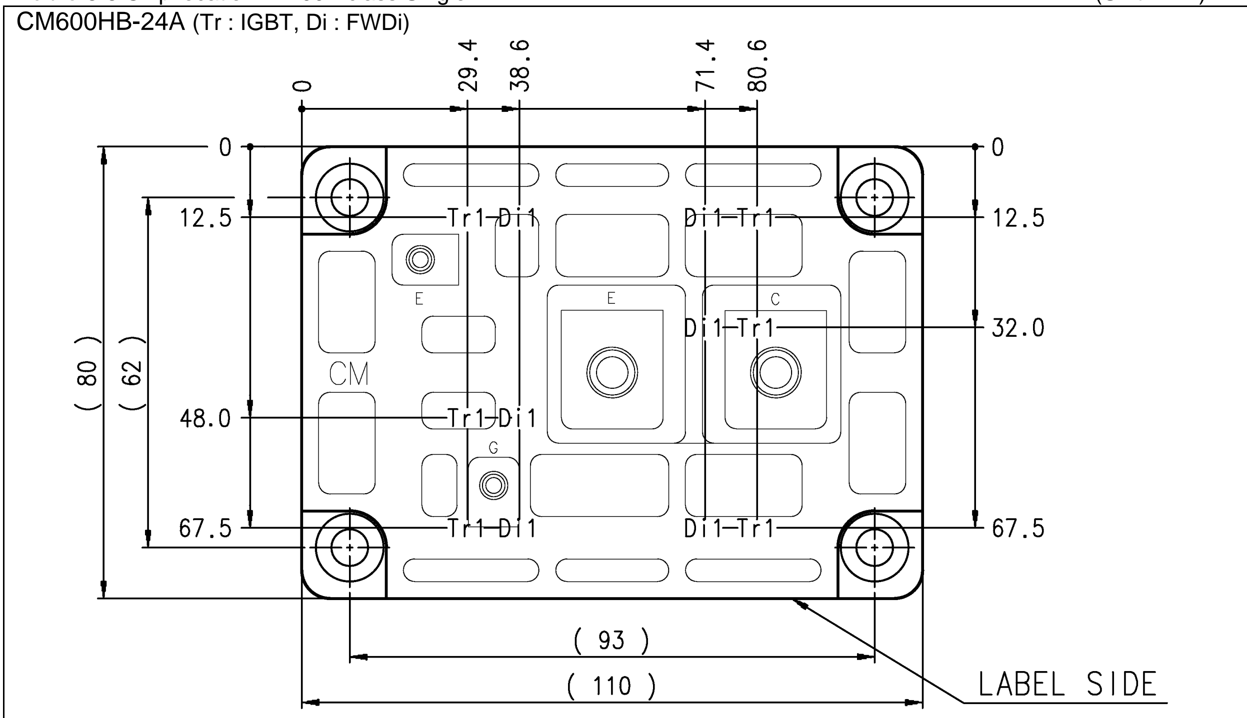
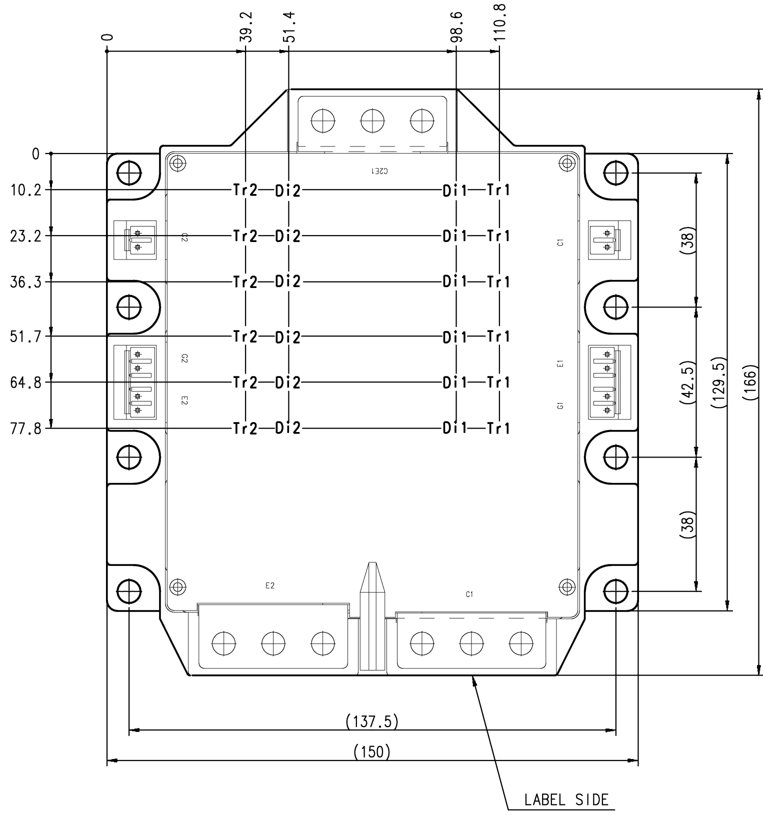
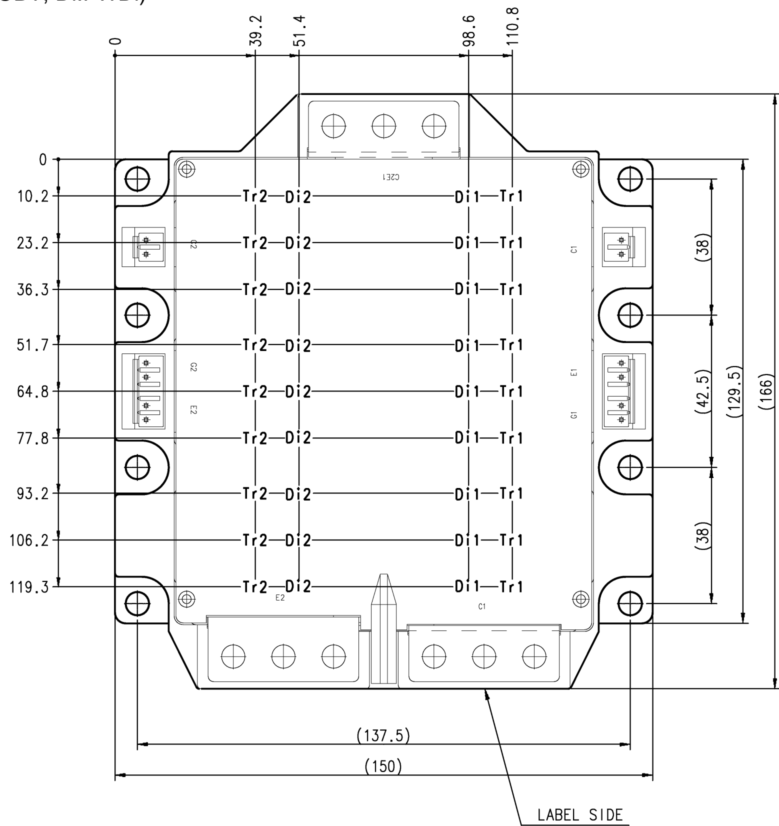


Table 3-6 Chip location - 1200V class MPD (Unit : mm)

CM900DU-24NF (Tr:IGBT, Di:FWDi)



CM1400DU-24NF (Tr:IGBT, Di:FWDi)



Reliability

1. Introduction

It has only been somewhat over 30 years since semiconductor devices such as rectifier diodes, thyristors, and transistors gained widespread acceptance for use in industrial machinery and consumer appliances, but during that period the reliability standards for these devices have made rapid advances.

In equipment where high reliability is a must, failure rate of the semiconductor devices must range from 10 to 100 FIT (1 FIT=10^{-9}/hours). Of course, to achieve such reliability in the equipment itself, not only must each individual device be reliable, but also it is also extremely important to match the specific characteristics of the device with its application within the piece of equipment. In fact, information obtained in field studies show that for semiconductor devices manufactured using identical procedures, failure rates in the field could vary by a factor of 10 depending simply on how the device was used.

The following information covers device reliability with regards to how a device is used. An introductory discussion is also presented on quality-control procedures, and some examples of reliability testing data are given.

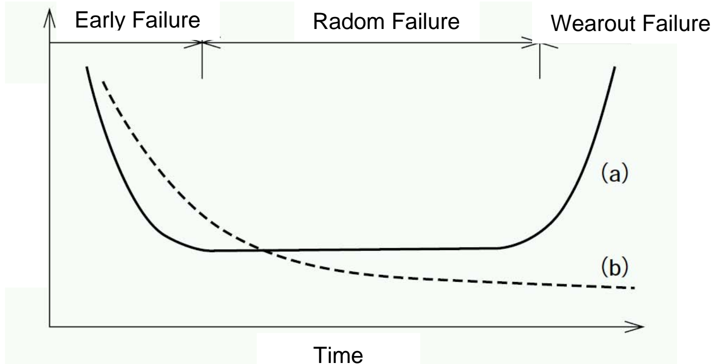


Fig.1 Failure Rate Versus Time

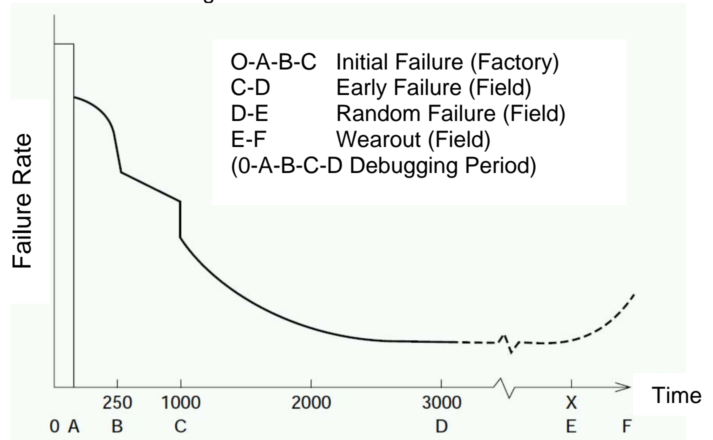


Fig.2 Semiconductor Device Failure Rate Versus Time

2. Basic Concepts of Semiconductor Device Reliability

2.1 Semiconductor Device Failure Rate Varied with The Lapse of Time

The failure rate of devices used in an average piece of equipment can be expressed by using the bathtub curve shown in Fig.1, line (a). Taken from the standpoint of time, device failures can be classified as an early failure, random failure and wear out failure period.

Three points must be considered regarding the service life of a device; early and random failures rate, and lifetime before wear out.

But the failure rate of semiconductors is illustrated by line (b) in the graph, where failure rate is shown to gradually diminish as a factor of time. In other words, a notable feature of semiconductor devices is that the longer a particular device has been used, the more stable it will be. Viewed from a different perspective, even though random failure rate has been reduced to virtual stability, the failure distribution pattern shows early failures to still be prevalent. As shown by Fig.2 where failure rate versus time is given for an actual device, the highest failure rate occurs immediately after manufacture, but the process of ageing and debugging gradually lowers this failure rate.

The next step is with the user, who assembles, adjusts, and takes the device aging. Failure rates continue to decline during this period also. Generally, the rate for major defect during this period drops to less than 0.1%, and if this rate is exceeded by a substantial margin, one must look for a fault in the circuit design, assembly procedure, or the device itself. Unless the problem is found and corrected, frequent field failures will be the likely result. In most cases, the field failure rate can be correlated to major defect during this period, so this is an important aspect of device reliability.

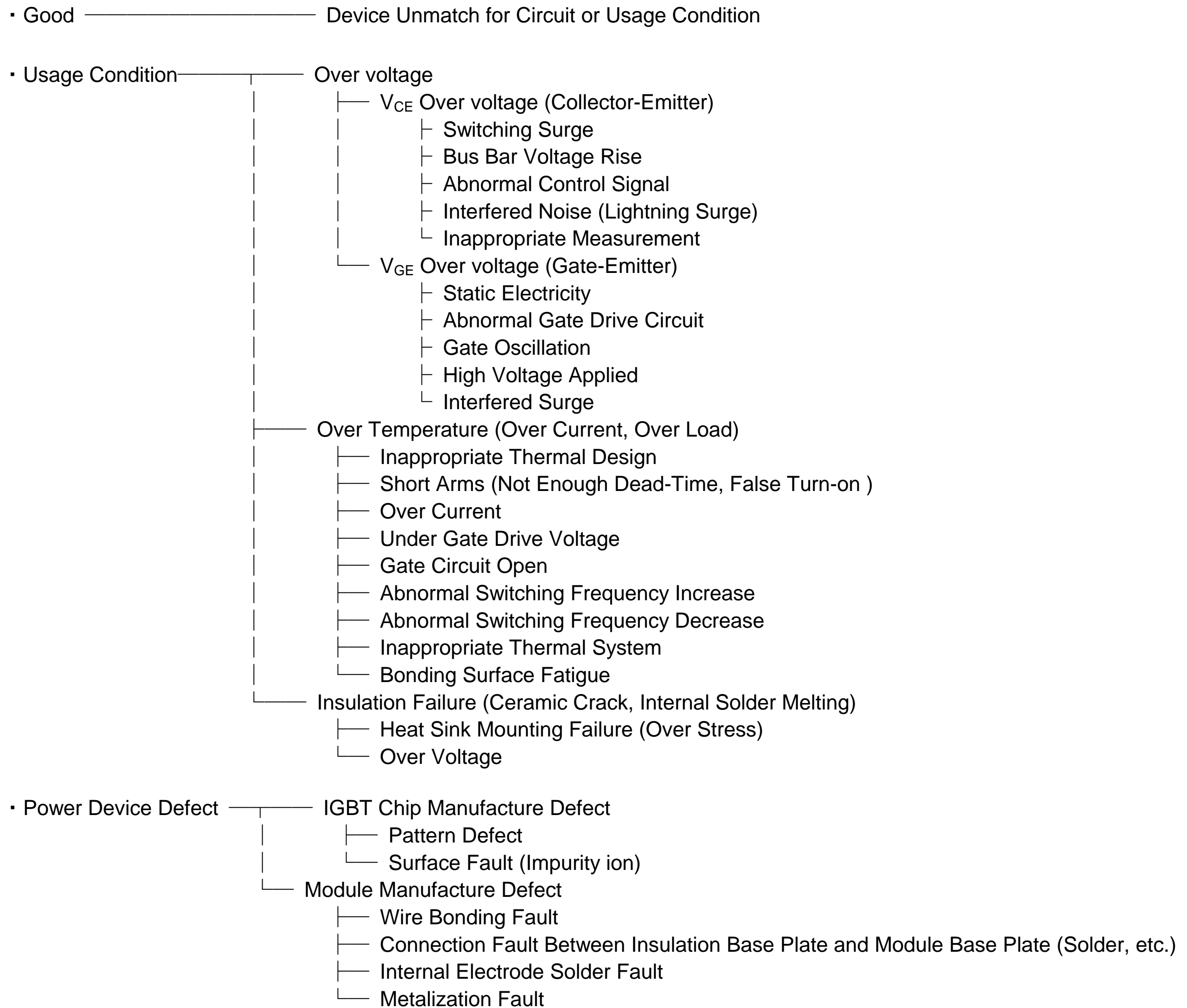
Upon transferring the equipment to field service, the stress level is reduced further, with a corresponding drop in failure rates. Failure rates normally range from several FIT to several hundred FIT during this period.

On the other hand, the user must design greater margins. For example, diodes and thyristors should be operated at 50 ~ 60% of their maximum voltage ratings or lesser, and junction temperatures should not exceed 70 ~ 80% of maximum rating. It is also important to remember that a device must be in working harmony with other components in the circuit for maximum reliability standards can be assured.

When designing a piece of equipment for reliable service, device selection must be considered from a standpoint of performance, reliability, and economy. Since it is not easy to achieve high performance/reliability and economy at the same time, a balance must be struck on the side of practical value. In other words, device selection should be based on the user's expectations for the machine he is designing.

2.2 Power Module Failure Reason

After a piece of equipment has been assembled and adjusted, or has been placed in field service, failed devices that are returned to the factory are analyzed to determine the cause of failure. This procedure is intended to determine whether the problem lays with the device itself, or the manner in which it was used. This section will list potential reasons of failure.



Operation life is dependent on the internal wire bonding, thermal fatigue between insulation base plate and module base plate. The thermal fatigue will be described in the next page.

2.3 Thermal Fatigue of Power Module

2.3.1 Operating Temperature Pattern

The operating temperature pattern of power module is displayed in Fig.3. It is important to consider two patterns that are independent each other in thermal fatigue life of power module.

■Operation Mode 1

Power cycle life is called when change of case temperature is small, but frequent change of junction temperature occurs.

■Operation Mode 2

The other one is thermal cycle life when comparatively slow change of temperature occurs by start and stop of the system.

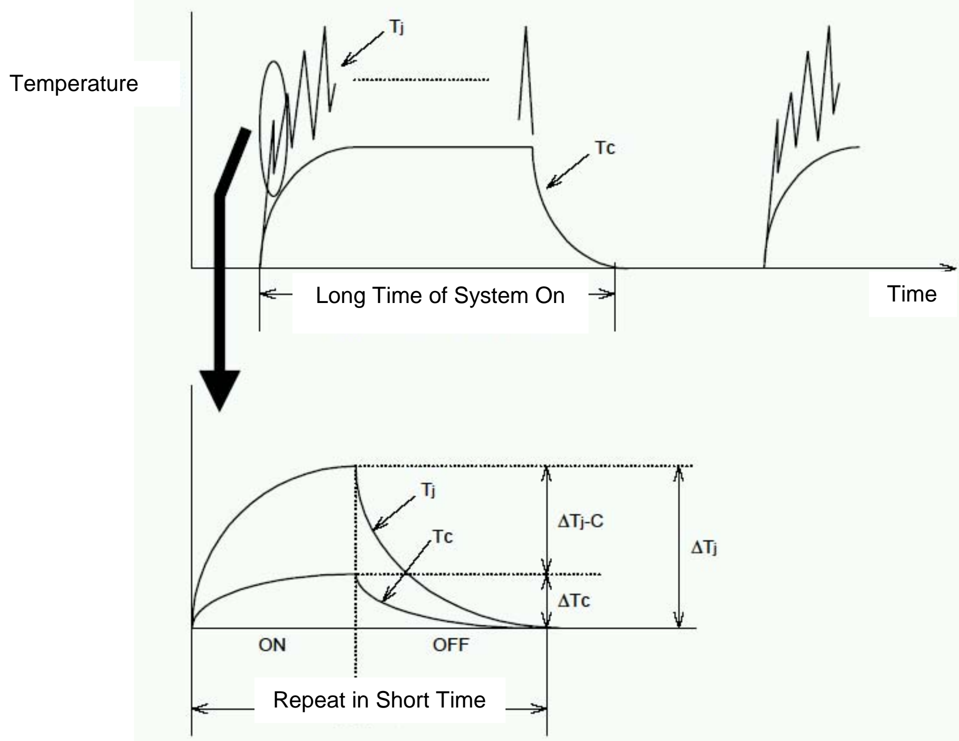


Fig.3 Operating Temperature Pattern

2.3.2 Power Cycle Failure Mechanism

Fig.4 shows the typical construction of power module. When junction temperature of power module is changed, stress strain between aluminum wire and silicon chip, and between silicon chip and insulation substrate occurs due to the difference of coefficient of linear expansion. If this stress is supplied repetitively, thermal fatigue for the junction becomes failure.

For inverter use, power cycle life is a necessary concern, which should be given during designing system. An example is given in Fig.5. The failure mode is that the crack of bonding surface makes progress by stress due to the difference of linear expansion between aluminum wire and silicon chip and finally lead to the peel failure mode.

A power cycle testing result of Mitsubishi Electric's module is shown in Fig.6.

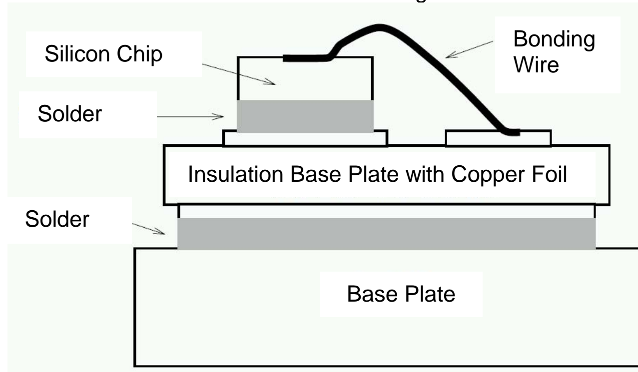


Fig.4 Module Structure

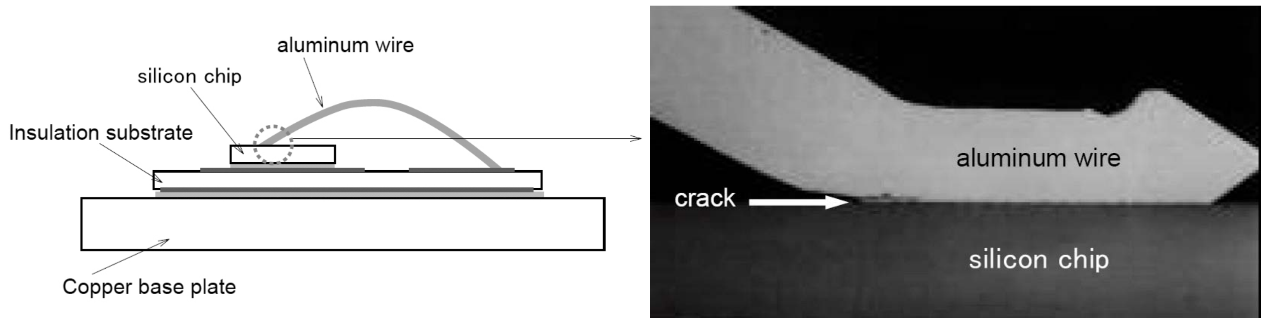


Fig.5 Bonding Surface Fatigue Caused by Power Cycle Testing

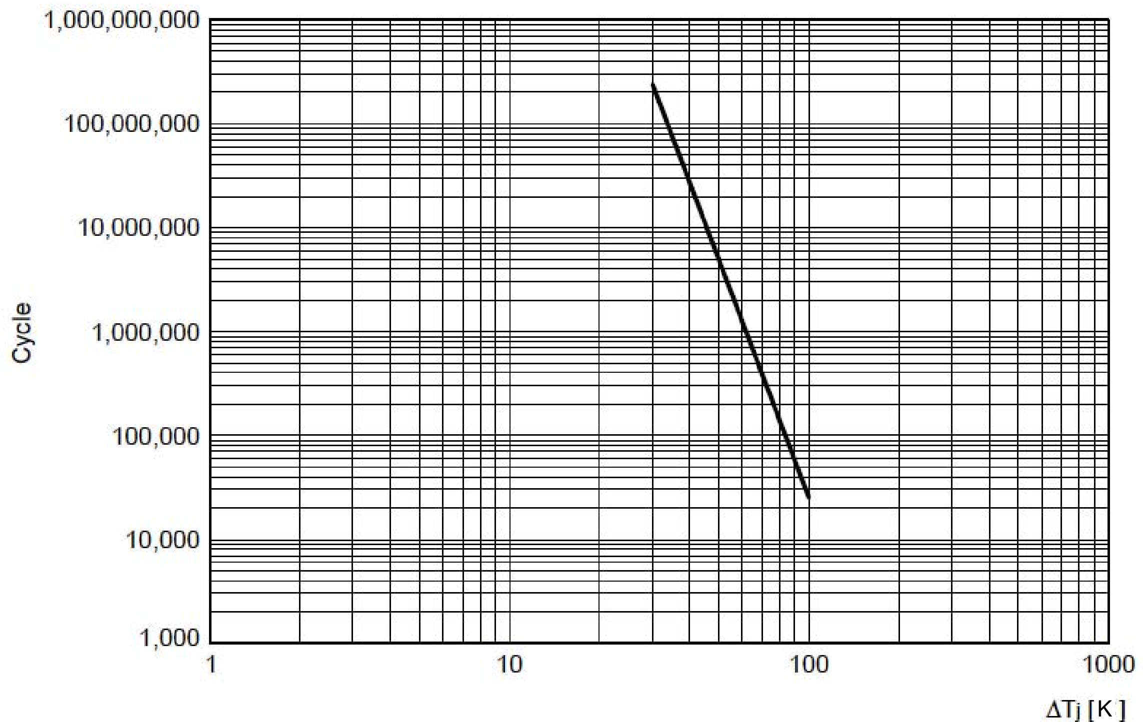


Fig.6 Power Cycle Curve

2.3.3 Thermal Cycle Failure Mechanism

In case of operation pattern at which case temperature (Tc) of power module become comparatively slowly and big change, the stress strain in the solder layer between insulation substrate and cupper base plate occur due to the different coefficient of expansion between the insulation substrate and the cupper base plate.

The crack in the solder occurs due to the accumulation of these stress cycles. And if this crack reaches to the part of the solder under the chip, thermal resistance increases and leads to the thermal runaway. Or ΔTj become increased by rise of thermal resistance and power cycling capability become decreased and finally lead to the wire peeling failure as shown in Fig.7.

A thermal cycle testing result of Mitsubishi Electric's module is shown in Fig.8.

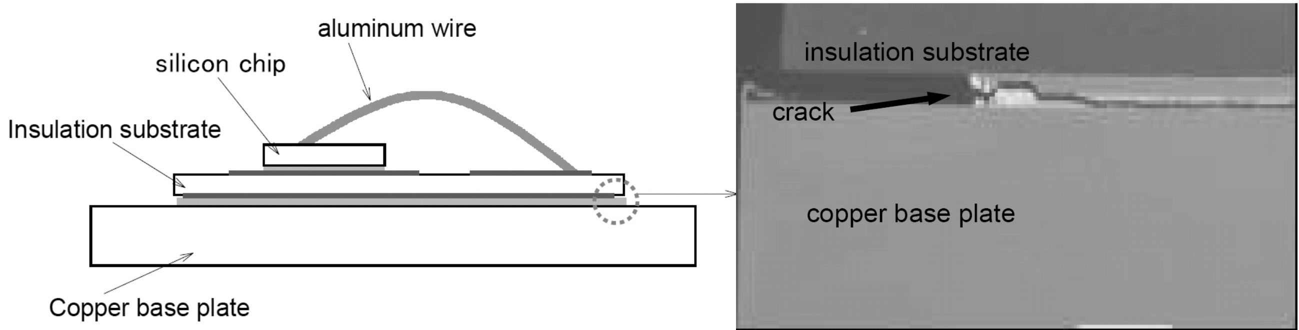


Fig.7 Solder Fatigue Caused by Thermal Cycle Testing

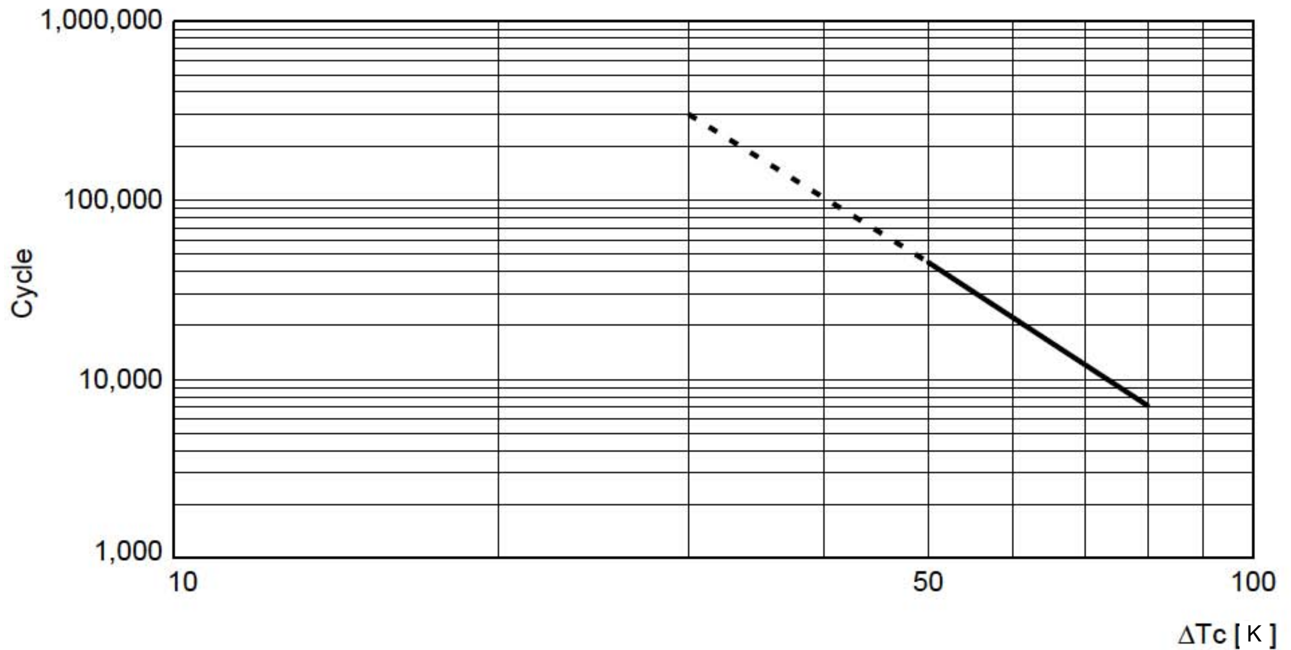


Fig.8 Thermal Cycle Curve

3. Mitsubishi's Quality-Assurance Program

One of the basic goals of Mitsubishi Electric is to offer our customers quality products. As a consequence, product quality, price, timely delivery, and service are equally important aspects deserving an equal amount of attention. Still, product quality must stand above all others from a standpoint of customer confidence.

Quality standards in the semiconductor industry are extremely high; production of wafers is a carefully controlled, precision process, and assembly processes are done under microscopes to assure that there are no sacrifices made in technology, or in quality.

The following subsections outline the quality-assurance programs Mitsubishi Electric uses in its mass-production.

3.1 The Path to a Mass-Production Device

From research prototype, through mass-production, a serial type tests are run at each stage to assure performance and reliability of the ultimate product. At the same time, the design drawings are also closely checked. The path from the research stage to mass-production is shown in the flow chart of Fig.3. The subsections that follow briefly describe the reliability tests used to check for device reliability.

3.2 Environmental Controls

The semiconductor industry as a whole recognizes the affect environmental factors have on product quality, and rigorous standards have been established regarding the control of dust, humidity, and temperature in manufacturing facilities. The same level of standards is also used for the various gases, and the water used in the manufacturing process.

3.3 Periodic Inspection and Maintenance of Manufacturing Equipment and Instrumentation

The various equipment and measuring instruments used in semiconductor production are an extremely important element of the total process. It is therefore imperative that a periodic program be implemented to inspect and adjust these components so that optimum precision standards are maintained, and to forestall any interruptions in the production process.

3.4 Quality-Control of Materials Purchases

Materials are subjected to rigorous acceptance tests using equipment such as spectrometers, helium leak detectors, etc. Before placing full orders, thorough sample testing is done, and all problem areas are worked out before making an official decision. Quality-control procedures at the supplier’s plant are also considered in any procurement decision.

3.5 Control of the Manufacturing Process

Various measures have been taken to control the elements that have a decisive influence on the quality of the product. Measuring instruments are used to monitor water purity, atmospheric conditions, furnace temperatures, gas flow, and other factors. Check-sheet inspections are made, and recorders keep automatic records. These records are carefully correlated with the records kept on matters such as diffusion depth and surface density to establish proper working conditions.

3.6 In-Process and Final Inspections

The goals of the in-process and final inspections are twofold: the first is to assure product quality from the standpoint of outer appearance, dimensions, structural integrity, and mechanical and electrical characteristics. The second is to feed this information back upline to improve quality, and to reduce variations in future batches.

In-process inspections are intended to check the wafer and assembly processes, and serve two purposes; one being self-imposed checks on the production process, the other for use as a quality-control tool. As its name implies, production personnel to correct deficiencies they clearly recognize use the self-imposed check, and emphasis is placed on points that are difficult to detect in completed devices. After the device is completed, it is subjected to the final inspection and the quality-assurance inspection. The final inspection is run on all devices, and consists of testing electrical characteristics and outer appearance. Quality-assurance personnel assume the role of the end user, and inspect samples for correct electrical characteristics, outer appearance, and reliability before devices are packed in storage.

The flow chart for the quality-assurance program covered in the above is noted in Fig.9.

3.7 Quality Information

Mainly the quality assurance division compiles various kinds of quality information such as inspection results and customer-supplied information. They are quickly fed back to related divisions including the production division for maintenance and improvement of quality.

In addition, we employ computer-based, streamlined, and effective quality control systems in order to modernize the information management.

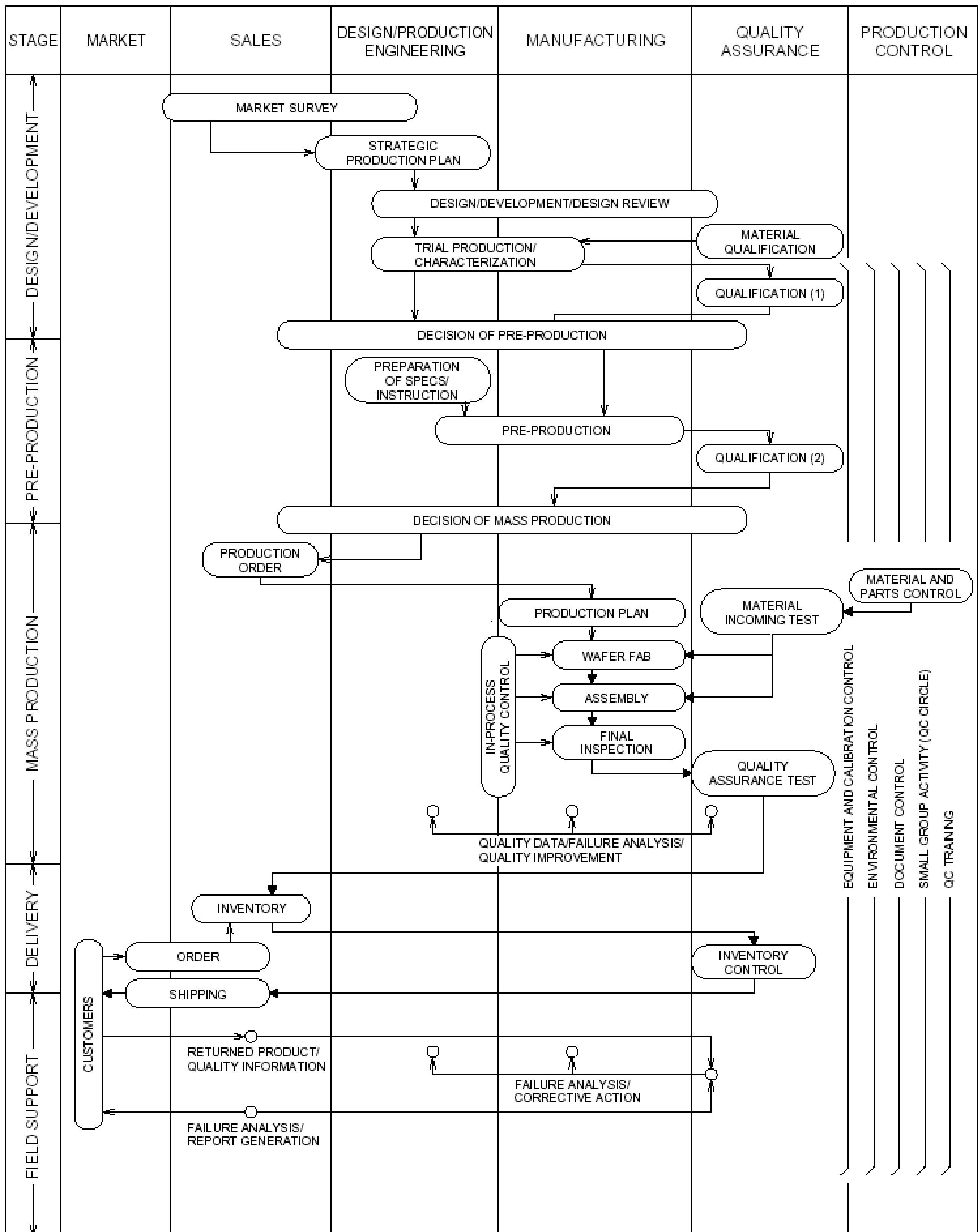


Fig.9 Flow Chart of Quality Assurance Program

4. Reliability Testing

4.1 Reliability Testing Procedures

High reliability standards are assured with Mitsubishi semiconductor devices through the rigorous quality-control inspections, which the devices are subjected to in the design and manufacturing stages, and through the quality-assurance inspections run on each production lot. Numerous reliability tests have been implemented in order to maintain this standard of reliability.

This section provides an overview of the reliability testing of thyristor devices. Test parameters are shown in Table 1, and as noted, conform to the procedures specified by the Japan Electronics and Information Technology Association (JEITA) handbook. (Related standards: International Electrotechnical Commission (IEC))

4.2 Results of Reliability Test of IGBT Module

Table 2 lists the results of the reliability tests performed on IGBT module CM300DY-24NF, a resin sealed type with current rating up to 300A to date. Failure criterion information is noted in Table 3.

Table1. Mitsubishi Power Module Reliability Testing

	Test Parameter	Test Method		Test Conditions
Environmental Test	Thermal Shock	ED-4701	B-141	[Condition A] 100°C : 5 minutes, 0°C: 5 minutes, 10 cycles
	Temperature Cycling	〃	B-131	Tstg min 60 minutes～Tstg max 60 minutes, 10 cycles
	Vibration	〃	A-121	[Condition B] 10～500Hz/15 minutes, 98.1m/s^2, 6h
	Robustness of Termination	〃	A-111-Ⅰ	9.8~40N, 10±1s
	Solder Heat Resistance	〃	A-132	[Condition A] 260±5°C, 10±1s, Rosin flux used
	Solderability	〃	A-131	[Condition A] 235±5°C, 5±0.5s, Rosin flux used
	Mounting Torque	〃	A-112-Ⅱ	M8:8.83~10.8N･m, 10±1s M6:2.94~4.5N･m, 10±1s M5:1.96~3.5N･m, 10±1s M4:1.47~1.7N･m, 10±1s M3:0.98N･m, 10±1s
Endurance Test	High Temperature Storage	〃	B-111	Ta=Tstg max, 1000 h
	Low Temperature Storage	〃	B-112	Ta=Tstg min, 1000 h
	Wetproof	〃	B-121	[Condition B] Ta=60°C, RH=90%, 1000h
	Intermittent Current Flow	〃	―	ΔTc=50°C(ΔTc=100°C), 5000 cycles
	High Temperature Reverse Bias	〃	―	Ta=Tstg max, VCE=85%VCES, VGE=0V, 1000h
	High Temperature Gate Bias	〃	―	Ta=Tstg max, VCE=20V, VGE=0V, 1000h

*:Environmental and resistance testing conforms to standards specified in EIAJ E4-4701 for discrete semiconductor devices.

Table2. CM300DY-24NF Reliability Test Results

	Test Parameter	Test Method		Test Conditions	No of Samples	No of Failures
Environmental Test	Thermal Shock	ED-4701	B-141	[Condition A] 100°C(5 minutes), 0°C(5 minutes), 10 cycles	5	0
	Temperature Cycling		B-131	-40°C(60 minutes)~125°C(60 minutes), 10 cycles	5	0
	Vibration		A-121	[Condition B] 10~500Hz / 15 minutes, 98.1m/s^2, 6h	5	0
	Robustness of Termination		A-111-Ⅰ	40N, 10±1 s	5	0
	Solder Heat Resistance		A-132	[Condition A] 260°C±5°C, 10±1 s, Rosin flux used	5	0
	Mounting Torque		A-112-Ⅱ	Mounting Screws:M6, 4.5N･m, 10±1 s Main Terminal Screws:M6, 4.5N･m, 10±1 s	5	0
Endurance Test	High Temperature Storage		B-111	Ta=125°C, 1000h	5	0
	Low Temperature Storage		B-112	Ta=-40°C, 1000h	5	0
	Wetproof		B-121	Ta=60°C, RH=90%, 1000 h	5	0
	Intermittent Current Flow	―		Ta=125°C, VCES=1020V, VGE=0V, 1000h	5	0
	High Temperature Reverse Bias	―		Ta=125°C, VCE=20V, VGE=0V, 1000h	5	0
	High Temperature Gate Bias	―		Tc=50°C~100°C, 5000cycles	5	0

Talbe3. CM300DY-24NF Failure Criterion

Test Parameter	Test Conditions	Failure Criterion		Note
		Lower Limit	Upper Limit	
ICES	VCE=1200V, VGE=0V	―	U.S.L×2.0	
IGES	VGE=±20V, VCE=0V	―	U.S.L×2.0	
VGE(th)	IC=30mA, VCE=10V	L.S.L.×0.8	U.S.L×1.2	
VCE(sat)	IC=300A, VGE=15V	―	U.S.L×1.2	
VEC	IE=300A, VGE=0V	―	U.S.L×1.2	
Electrical Stress	AC2500Vrms 1 minute	Insulation breakdown		

Note. U.S.L: Upper Specification Limit / L.S.L: Lower Specification Limit

5. Failure Analysis

Failure analysis is one of the sources of information used in maintaining, and making improvements in standards of quality and reliability. Failure analysis procedures are performed on failed devices at all stages of their life cycle, ranging from the development state to failure while in use.
Failure analysis procedures are generally divided into area of external inspections, electrical testing, internal inspections, and chip analysis. The flow chart for these procedures is shown in Fig.10, while Table 4 lists the nature of the tests.
The results of the various reliability and failure analysis tests reveal the failure mode and mechanism, and this information is fed back to the process technology and manufacturing personnel so that they can take the appropriate measures to improve the final product.

6. Derating and Reliability Projections

The degree of reliability for a semiconductor device varies considerably depending on usage and environmental conditions. Design standards, the method of manufacture, and quality-control procedures also play a role in establishing the intrinsic reliability for semiconductors. Correlating device derating with reliability is also not an easy task.

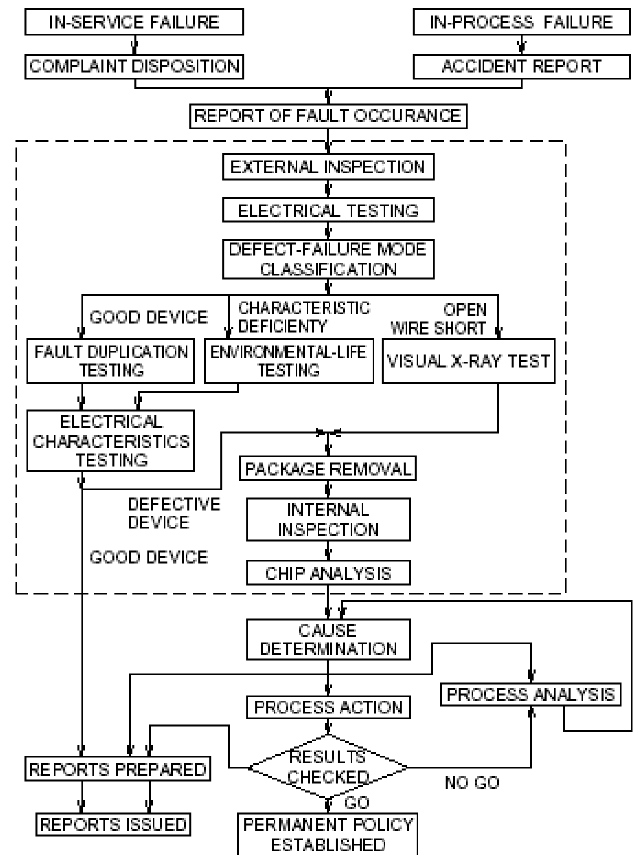


Fig.10 Failure Analysis Procedure

Table4. Failure analysis inspections and equipment used

Category	Inspection Items	Equipment
External Inspection	○ Condition of leads, plating, soldering, and welds ○ Packaging defect ○ Solderability	Stereoscopic microscope Metallurgy microscope
Electrical Characteristics Testing	○ Static electrical characteristics, voltage and temperature margins, checking for broken bond wire, wire ○ Internal wiring	Oscilloscope Curve tracer Characteristics tester X-ray equipment
Internal Inspection	○ Device removed from package and chip surface observed for defects ○ Electrical characteristic check using microprobe ○ Check for hot spots and other abnormalities	Metallurgy microscope microprobe Scanning electron microscope X-ray micro-analyzer Infrared micro-scanner Spectrum analyzer
Chip Analysis	○ Analysis techniques used to supplement chip surface observation in internal inspection ○ Cross-section of chip observed for analyzing oxide film, diffusion and metallizing	

7. Conclusion

The above is a simple introduction to general ideas about reliability, reliability tests, and derating and forcasting of reliability of high power semiconductor, which are semiconductor devices for electric power. As explained above, it is vital for higher reliability in practical use of semiconductor devices to understand their features and select those, which are suitable for equipment and sets. It is also important to design semiconductor devices with some allowance to improve reliability, fully taking their derating into consideration in relation to operating and environmental conditions.
Other essential things to do are to “debug” equipment and sets, and to analyze data obtained in fabrication process and actual operation to feed them back to design and fabrication stages. To improve the reliability by design of high power semiconductor requires considerations on many issues as described above. Utilize the semiconductor devices successfully with the utmost care with comprehensive understanding of their quality, reliability, and economy.

Using IGBT Module

1. IGBT Module Characteristics

It is necessary to comprehend IGBT module characteristics before using it. The main characteristic is described in this section.

(1) Voltage Drive Device
As IGBTs are derived by voltage applied to the gate terminal, it has three characteristic capacitances Cies, Coes, and Cres, shown in Fig.1. The input capacitor (Cies) is charged at turn-on switching and discharged at turn-off switching.

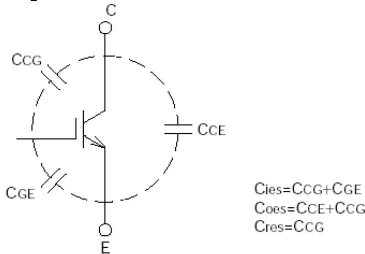


Fig.1

(2) High Speed Device
The IGBT is a high speed switching used under high voltage and high current. High di/dt during switching operation may cause surge voltage.

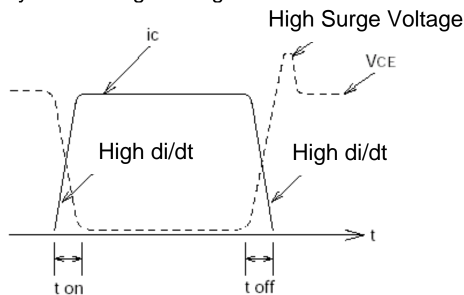


Fig.2

(3) Insulated Gate
Since IGBT gates are insulated from any other conducting region, care should be taken to prevent static build up which could possible damage gate oxides. In no case should a gate drive outside of the range of ±20V. Moreover, no voltage should be applied between collector and emitter while the gate is open. The mechanism to the destruction is the following of the outline.

2. Static Electricity Precaution

(1) IGBT modules are shipped from the factory with conductive foam contacting the gate and emitter control terminals. Never touch the gate terminals during assembly and keep the conducting foam in place until permanent connections are made to the gate and emitter control terminals.

(2) Use grounded work station with grounded floors and grounded wrist straps when handling devices.

3. Derating Consideration

(1) Voltage Rating
The relationship of voltage rating of power device for inverter use and ac line voltage of power supply is

Device Voltage Rating = Input AC Voltage × √2
+ Brake Voltage Increase + Surge Voltage + Allowance

Table1 shows the relationship of AC line voltage and rating voltage of the power device.
Therefore, the busbar line voltage is recommend to be lesser than 50~60% of the device rating voltage. The free-wheeling diode has the same rating as the IGBT device.

Table1.

	Input AC Voltage (V)		
	180~220	380~440	480~575
Rating Voltage (V)	600	1000～1200	1400～1700
Busbar Line Voltage (V)	300～400	600～800	750～900

(2) Collector Current Rating
Proper selection of an IGBT involves two key points. One is that the peak collector current during operation including any required overload current must be within the maximum rating current value. The other one is that the IGBT operating junction temperature must always be kept below maximum rating temperature in all normal operation including expected motor overload.
Usually, the suggested overload rate of an inverter ranges from 150% to 200%. The Stationary current should be about 50~60% of the maximum rating current.
In addition, the peak collector current given in datasheet is including the reverse recovery current (shorter than 1μs) of free-wheeling diode shown in Fig.3.
The free-wheeling diode is designed to flow short pulse. In order to achieve a high efficiency inverter, the duty of free wheeling diode should be designed less than that of IGBT. Therefore, the junction temperature rise due to on-state voltage of the free-wheeling diode can be negligent. However, the on-state power loss of the diode can obviously increase when the diode has almost the same on duty as the IGBT, e.g. converter. In this case, rating values should be derated to half ratings given in the datasheet.

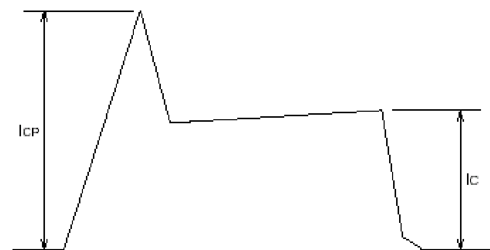


Fig.3

Current rating of device for inverter use is decided according to the following method.
(Inverter = AC 3-phase inductive motor control)

Current rating is dependent on the capacity of inverter.
- ●Inverter Capacity = Motor Capacity ÷ Efficiency (0.75)
- ●Current rating is,
  Peak Current=Inverter Capacity × Overload Rate ÷ AC Voltage(rmsV) ÷ $\sqrt{3}$ × $\sqrt{2}$ × Ripple Rate

<Example>
The current rating of IGBT used in an inverter, which is applied with AC200V to control a 3.7kW motor, is:
- ●Voltage rating can be chosen from 600V class indicated in Table 1.
- ●Current rating is
  3.7(kW) ÷ 0.75=5(kVA)
  5(kVA) × 2 ÷ 200 ÷ $\sqrt{3}$ × $\sqrt{2}$ × 1.2=49 (A)

Therefore the appropriate IGBT module is 600V, 50A.

(3) Junction Temperature
Good design practice with considerations of reliability and the worst-case maximum junction temperature is to limit the steadystate junction temperature to 70% to 80% of the maximum junction temperature or less.

4. Precautions in Using IGBT Modules

(1) Environmental Temperature
In order to avoid disconnection between IGBT chip and bonding wire due to stiffness or crystallization of internal silicon gel, environmental temperature of IGBT modules should be kept in the range from -40°C to 55°C. Never use IGBT modules below -40°C. In addition, rapid temperature change may cause damage of modules.
Keep modules far from dewy environment since water seepage may result in operation fault.

(2) In order to lower surge voltage, the wire length of drive circuit should be as short as possible and snubber capacitor is adopted. The layout must minimize the stray inductance between the driver's output stage and the IGBT. This corresponds to keeping the loop area as small as possible in the indicated section of Fig.4-1.

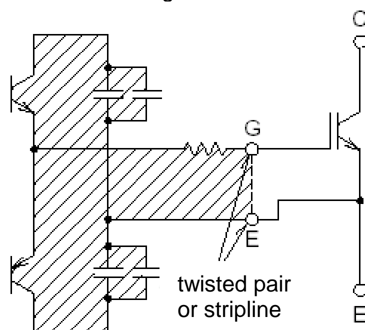


Fig.4-1

Care should be taken to design the layout of drive circuit especially for high speed switching use. An example is shown in Fig.4-2.

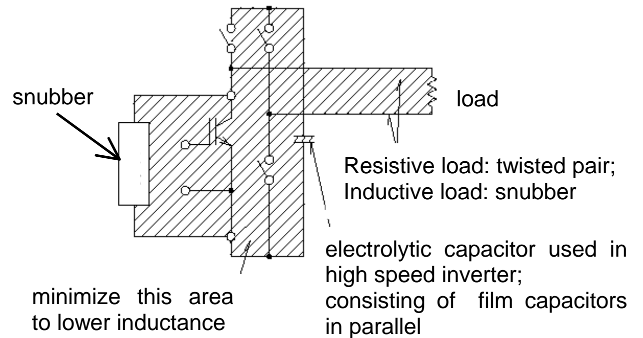
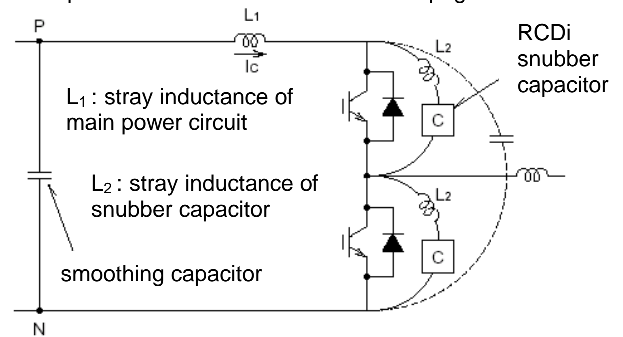


Fig.4-2

(3) Never apply voltage between collector and emitter while the gate is open.
(4) Snubber Circuit Example
The snubber circuit adopted in IGBT module application is shown in Fig.4-3. The recommended stray inductance of main power circuit is indicated in the next page.



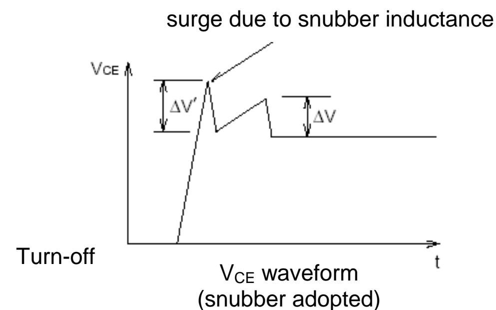


Fig.4-3

(5) Others
Insulation distances of Mitsubishi Electric's modules are in accordance with UL standards. In general, the electric strength to the same space distance falls due to the decrease of atmospheric pressure at high altitude. Moreover, the amount of cosmic rays increases rapidly when the altitude goes up. It has been known that cosmic rays can raise the possibility of faults in semiconductors. There is no data concerning the probability. Practically, it will not become a problem for general industrial use because its voltage is a comparatively low level.

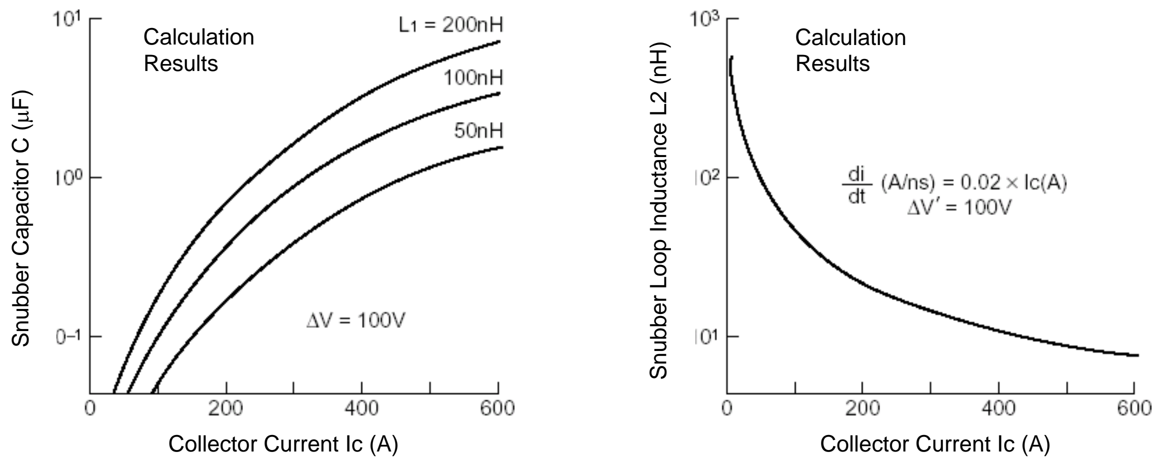


Fig.4.5

Snubber Recommendations

Collector Current Rating	Snubber Capacitor "C"	Main Bus inductance "L1"	Snubber Loop inductance "L2"
15A～75A	0.2μF ≦	＜200nH	＜70nH
100A～200A	0.8μF ≦	＜100nH	＜20n
300A～400A	1.6μF ≦	＜50nH	＜10nH
600A～	3.6μF ≦	＜50nH	＜7nH

4.1 Snubber Design

(1) Snubber Circuit Constant

The voltage spike ΔV′ is caused by a combination of the stray inductance in the snubber circuit and the forward recovery of the snubber diode. The snubber circuit itself cannot absorb it. If a fast IGBT snubber diode is used the majority of this spike will be due to the inductance of the snubber. In this case, the magnitude of ΔV′ can be calculated by using di/dt × L2.

Snubber capacitance can be computed as the following.

$$\frac{1}{2} \bullet L1 \bullet (I_{OFF})^2 = \frac{1}{2} \bullet C_S \bullet (\Delta V)^2$$

$$C_S = \frac{L_1 \bullet (I_{OFF})^2}{(\Delta V)^2}$$

From the computations above, it is clear that high power IGBT circuits will require very low inductance snubbers. Snubbers must be connected as close as possible to the IGBT module and the loop area must be kept as small as possible. It is recommended to use snubbers for each module individually when parallel operation is connected for high current requirement.

In applications using 6pack or 7pack type modules, it is usually possible to use a single low inductance capacitor connected across the P and N terminals as the snubber. In high power designs this single bus decoupling capacitor alone is usually insufficient for control of transient voltages. In these applications a clamp type RCDi circuit like the one shown in Fig.5 is usually used.

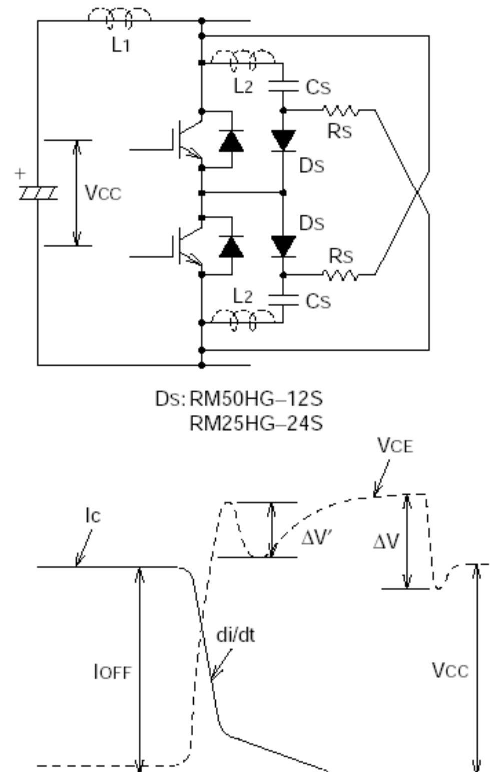


Fig.5

(2) Surge Reduction

① Low stray inductance (L1, L2)

- ●10~200A (6pack module) : printed circuit boards
- ●100A~600A (Dual module) : bus bar or laminated bus plates

② Snubber Circuit

- ●10~150A (6pack module) : snubber circuit a or b
- ●200~600A (Dual module) : snubber circuit c or a (each phase)
- ●400A or more (Single module) : snubber circuit a and c (each phase)

Common IGBT Snubber Circuits

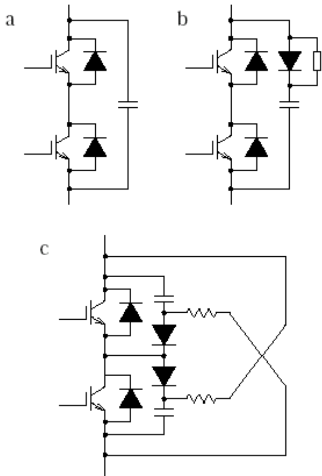


Fig.6

(3) Example Layout with Low Inductance (Single Module)

Laminated busses consisting of alternate copper plates and insulating layers can be designed with very low inductance. The connection sequence has no influence on inductance. The following considerations should be given in laminated bus designs.

① Use copper pipe as a spacer
<more than 2 layers>

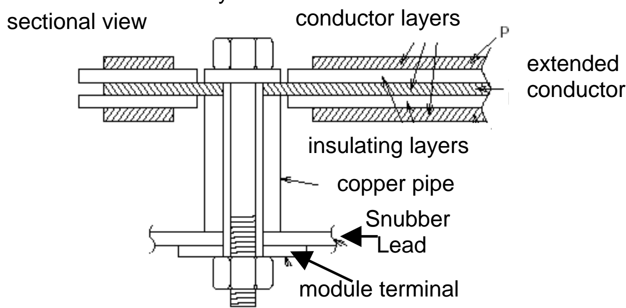


Fig.7

<one unit layout of 3-phase full bridge>

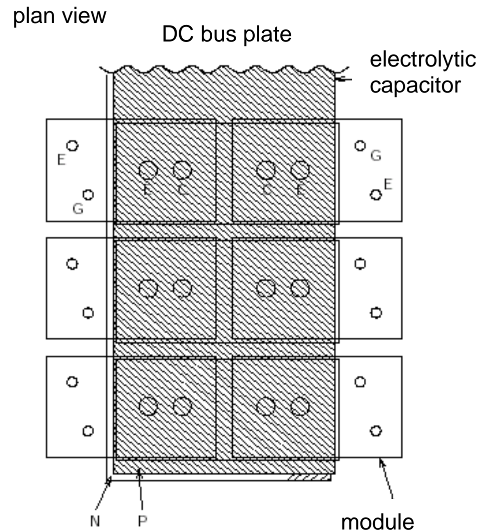


Fig.8

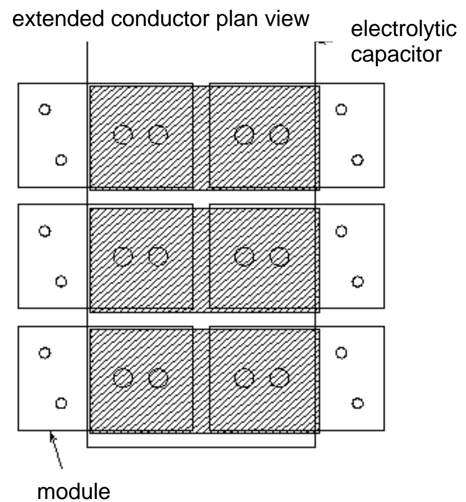


Fig.9

The empirical width of overlapping of conductor is from 40mm to 300mm.
The output leads are connected with module terminals or projections designed on the side of conductors. (Inductance of the output leads can be negligent.)

The Ministry wiring and low inductance wiring (the bus bar) manufacturer example.

Furukawa Electric Works : " The power board "
http://www.furukawa.co.jp/index.htm
ELDRE Inc. : "Bus Bars"
http://www.busbar.com/

② L shape used to reduce thickness of the conductor.
<two layers as an example>

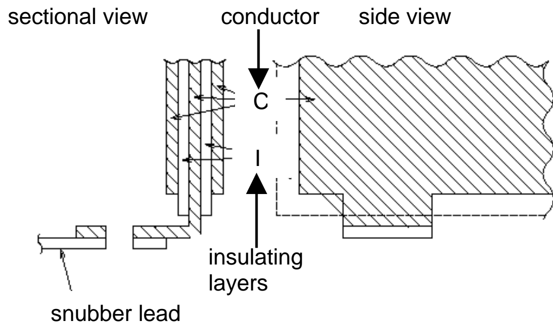


Fig.10

③ Crank shape used to reduce thickness of the conductor
<two layers as an example>

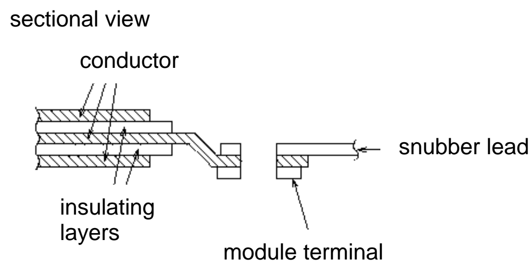
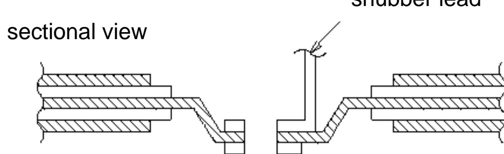


Fig.11

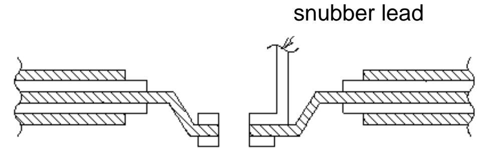
example of horizontal connection



plan view

DC bus plate

Fig.12



extended conductor

Fig.13

<Example of multi-layers>

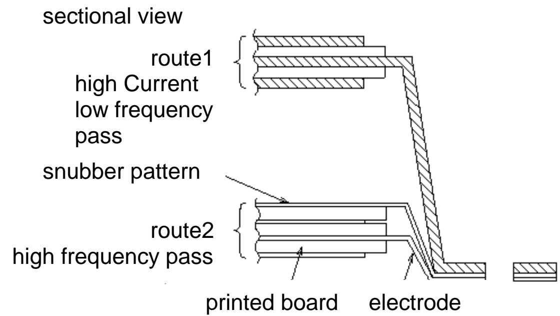
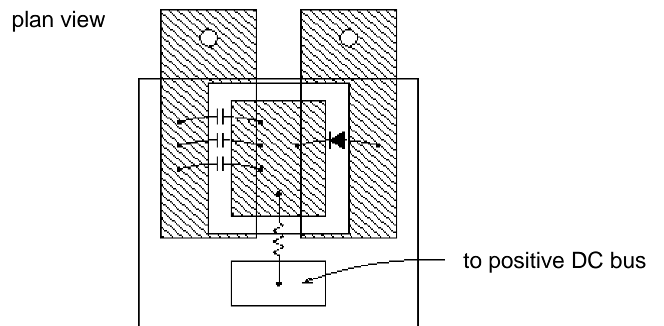


Fig.14

Refer to⋯⋯snubber circuit layout between collector and emitter <N side as an example>



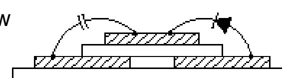


Fig.15

4.2 Gate Drive Recommendation

(1) Gate Drive Design

For turn-on a positive gate voltage of 15V±10% is recommended, and for turn-off a negative gate voltage from -5V to maximum minus voltage is suggested. In order to ensure that the IGBT stays in its off state when dv/dt noise is present in the collector-emitter voltage a reverse bias must be used. A series gate resistor is used to limit current flowing through the gate. The minimum series gate resistance is given in datasheet. In theory, there is no maximum requirement for gate resistance. However, big gate resistor may lead to

・switching loss (time) increase

・oscillation in conjunction with the gate-emitter capacitance and any stray inductance in the gate drive wiring.

Therefore, the recommended maximum gate resistance is 10 times of the minimum value.

Standard resistance given in datasheet is

600V class････････････625 (Ω･A)/current rating (A)

1200V class････････････313 (Ω･A)/current rating (A)

(a part of products excluded)

Key points of IGBT gate drive design are gate drive voltage, series gate resistor and circuit layout. The layout of gate drive circuit is shown in Fig.16.

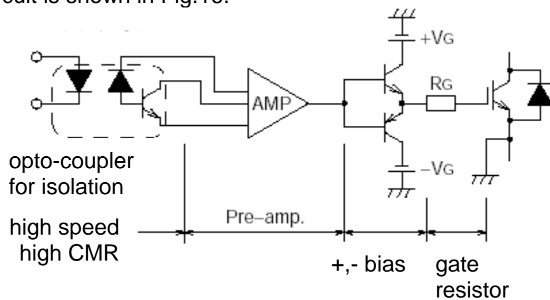


Fig.16

Guidelines that should be followed in designing the gate drive layout are:

(Cies＞10nF, V_{CES} = 600V IGBT Drive)

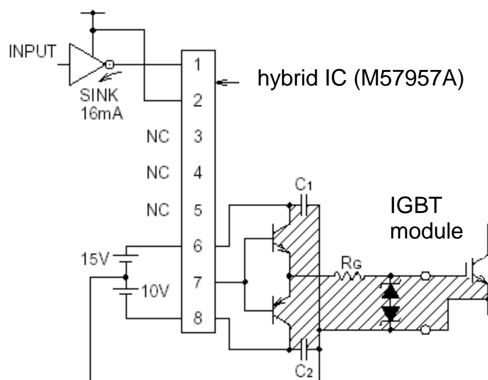


Fig.17-1

Block Diagram（M57958L）

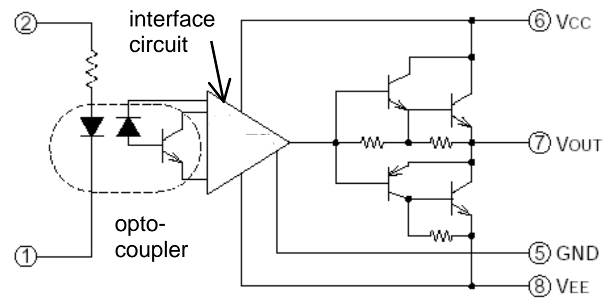


Fig.17-2

M57962AL as an example

For parallel operation of IGBT modules, the snubber circuit shown in Fig.18 must be adopted.

Notes in Application

a. C1 and C2 are low inductance (for switching power supply use) aluminum electrolytic capacitors with value of 220μF or more.

b. Buffer transistor is recommended to use TO-220 series with 5A peak value or more.
(Peak value can be measured or calculated.)
R_G : gate resistor, R_G′:oscillation prevention resistance

c. Over current detection terminal ① is connected with the collector of IGBTs in parallel.

current detection point is in the middle of parallel connection

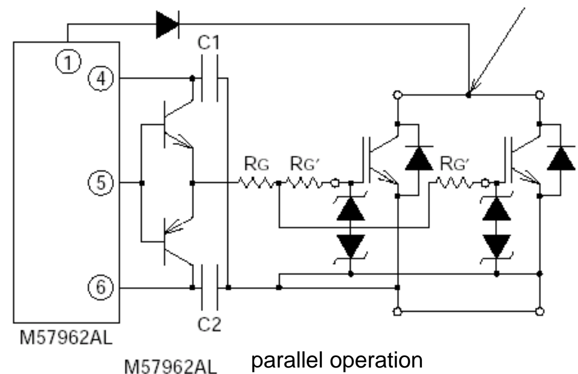


Fig.18

<key points for drive design>

① With consideration of IGBT short circuit capability and power loss, the recommended gate voltage is $+V_{GE}$=15V±10%, $-V_{GE}$=5~10V

② The drive capacity is proportional to current rating of the IGBT and the peak charge/discharge current of high power IGBT may be up to several amperes.

③ Consideration should be given to all of the effects, such as surge voltage (∝di/dt) at FWDi recovery and switching losses, in order to use appropriate gate resistor. Gate resistance value has no effect on $V_{CE(sat)}$.

④ Power supply transformer inter-winding capacitance can be another source of coupled noise. Appropriate measures to reduce these stray capacitances have to be implemented. If opto-couplers are used for isolation of the high side gate drive signals they should have a high common mode transient immunity.

⑤ Keep the loop area of drive circuit as small as possible in the indicated section of Fig.17-1.

(2) Gate Drive Voltage

For turn-on a positive gate voltage of 15V±10% is recommended. In no case should a gate drive beyond the range of 12 to 20V be used for turn-on. In order to limit short circuit current, the gate drive voltage is sufficiently low less than 6.5V. While the gate drive voltage is sufficiently high more than 13.5V to minimize on-state losses. It must be in action to stop IGBT switching when under drive voltage is occurring. In order to ensure that the IGBT stays in its off state when dv/dt noise is present in the collector-emitter voltage a reverse bias must be used. However, the gate voltage increase of trench IGBT during switching off is not that easy because it has smaller reverse transfer capacitance than planar IGBT. The reverse off bias of trench IGBT can be lowered. For F series IGBTs the reverse bias can be as low as -2V. But the NF/A series use plugging cell structure, so reverse bias voltage minimum -5V. Low reverse bias voltage can not only reduce drive circuit power, but also improve switching drive response characteristics. In addition, low reverse bias voltage can speed up switching on time and delay switching off time. Care should be given to dead time design.

① Positive Gate Drive Voltage (+V_{GE})

Fig.19-1 shows the relationship between positive gate drive voltage and on-state voltage. The higher the positive gate drive voltage V_{GE} is, the higher on-state voltage $V_{CE(sat)}$ is and the lower switching power loss during turn on operation. To simplify short circuit protection, the recommended turn-on positive gate drive is +15V±10%.

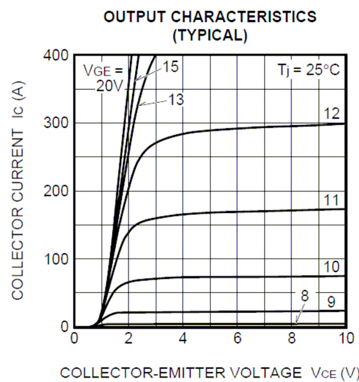


Fig.19-1 Output Characteristics

② Negative Gate Drive Voltage (-V_{GE})

The negative gate drive voltage has small influence on IGBT characteristics. The relationship between switching loss and reverse bias is shown in Fig.19-2. From the Fig.19-2 it can be seen that switching loss E_{Off} is barely influenced by the reverse bias while -V_{GE} is up to 5V or more. Therefore, the recommended minimum negative gate drive voltage is -5V.

In addition, to avoid the gate drive voltage at occurrence of surge exceeding withstand voltage of IGBT gate, optimal reverse bias value is in the range of 5~10V.

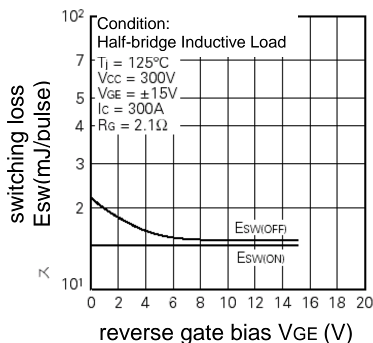


Fig.19-2 Switching Loss vs. Reverse Bias

When a dual module is used for a brake, the gate-emitter short of 600V class module can generally prevent the module from false turn-on. Practically, the voltage between the gate and emitter of the unused IGBT in the brake is monitored to make sure there is no malfunction. For the 1200V class module, because the voltage between the gate and emitter is relatively high and may exceed the threshold voltage, it is necessary to apply reverse bias voltage.

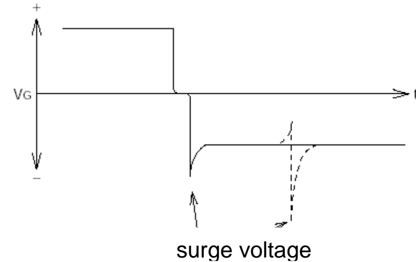


Fig.19-3 and Fig.19-4 show that the value of the gate resistance has a significant impact on the dynamic performance of the IGBT. A smaller gate resistor will reduce the switching times and switching losses. On the other hand, smaller gate resistors allow faster turn-on di/dt of the IGBT. This may cause high surge voltage. Giving consideration to both switching loss and surge voltage, an optimal gate resistance is decided depending on usage conditions. The drive circuit for NF series IGBTs is same as planar IGBTs. It is recommended to choose R_G in the range of standard value given in datasheet to 10 times of standard value.

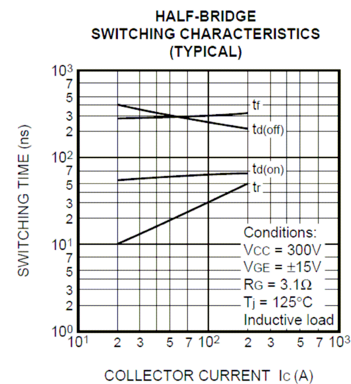


Fig.19-3 Switching Time vs. Gate Resistance

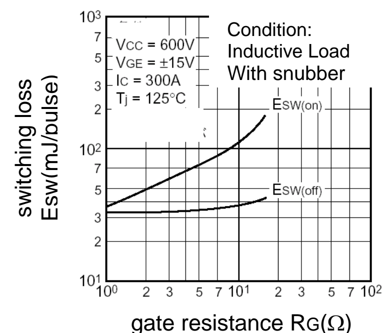


Fig.19-4 Switching Loss vs. Gate Resistance

(3) Example Gate Drive Circuit Design

IGBT switching consumes power from the gate drive power supply as a function of $\pm V_{GE}$, the total gate charge Q_G and the switching frequency fc. It can be calculated as the followings.

① The average current is（not including drive circuit power consumption）

average current (typ.)=$Q_G(-10V \rightarrow +15V) \times fc \fallingdotseq 1.3 \times Q_G \times fc$

Q_G:total gate charge(V_{GE}=0→15V)

fc:switching frequency

Note) Q_G is about 15% increase while V_{CE}=0V.

② The peak current of the supply is

$$I_{Gpeak} = \frac{(+V_{GE}) + (+V_{GE})}{(\text{external } R_G) + (\text{inner module } R_G)}$$

Note）In practical applications, the peak current of the supply is 60 to 80% of calculation value due to delay of I_G caused by drive circuit delay or stray inductance.

The value of the gate resistor has a significant impact on the turn-on speed of IGBTs, while it barely affects the turn-off speed. For some usage with low radiation noise requirement, slowing only the turn-on switching speed is an effective approach. In this case, different gate resistors at turn-on and turn-off are used to adjust switching on/off time. Fig.19-5 shows the connection of gate resistors. Table 1 displays the gate resistance range of the NF series. (For those modules not shown in Table1, please refer to the electrical characteristics) The value given for the minimum series gate resistor is the standard resistor that is used for determining all data sheet parameters and characteristics.

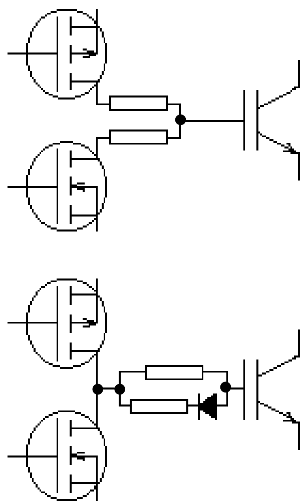


Fig.19-5 Connection of different gate resistors at turn-on and turn-off of IGBT

Linear Operation

Mitsubishi Electric's IGBT modules are not suitable for linear operation. NF series is easy to oscillate when it is operated in linear area for a long time due to the rise of the amplification rate of NF series in linear operation. Gate voltages in the 3 to 11V range should only be applied on the IGBT’s gate during rapid switching transitions. If this long time application of gate voltage is unavoidable, inductance should be carefully chosen to prevent from oscillation. Moreover, the surge voltage appears on the IGBT's gate due to reverse transfer capacitor of IGBT may result in linear operation and destruction of the module. An abnormal emitter loop can raise feedback voltage between gate and emitter and may cause linear operation. It might lead to linear operation when the drive circuit is not connected to the drive emitter but the main terminal.

③ Gate Drive Power

Average Gate Drive Power

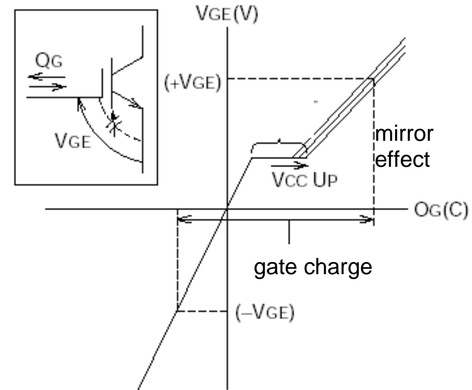


Fig.20. Total Gate Charge in IGBT Switching

The average power is

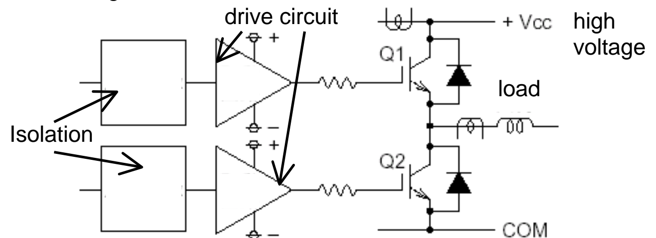
$$= \frac{1}{T}\int V \bullet idt$$

$$= (+V_{GE})\frac{1}{T_1}\int idt + (-V_{GE})\frac{1}{T_2}\int idt$$

$$= (+V_{GE}) \bullet Q_G \bullet fc + (-V_{GE}) \bullet Q_G \bullet fc$$

$$= ((+V_{GE}) + (-V_{GE})) \bullet Q_G \bullet fc$$

④ Bridge Circuit



(a) For the noise malfunction prevention, reverse bias voltage is applied in the off state.

(b) IGBTs used in bridge drive circuit and their insulation parts must not malfunction in the switching range of main circuit. (dV_{CE}/dt=DC~10V/ns).

- ●Care must be taken to avoid coupling of noise between the power circuit and the control circuit. This can be accomplished by proper placement of the gate drive board and/or shielding the gate drive circuit.
- ●If opto-couplers are used for isolation of the high side gate drive signals they should have a high common mode transient immunity. (up to 15kV/μs or more)
- ●Use a bypass capacitor near the control IC to filter out induced noises in order to avoid voltage disturb.

<Example>
gate drive circuit layout in order to prevent turn-on malfunction

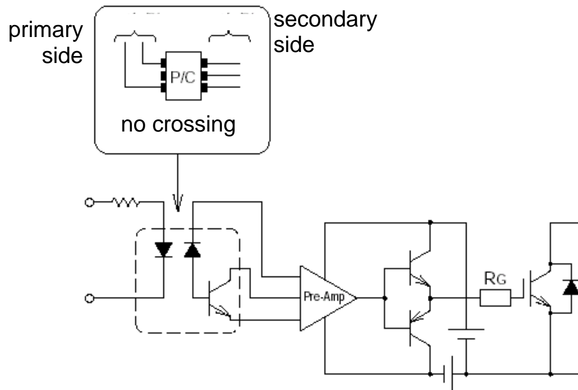


Fig.21.
Problem in gate drive circuit layout
- ●Cause of gate oscillation
- ●Measures to induced noise
- ●Wiring as short as possible
- ●Use twisted pair
- ●Wireless(direct connection of the drive PCB to the IGBT control terminals)
- ●Use the auxiliary emitter terminal

(c) For an arm shoot through prevention, appropriate deadtime (about 5μs) must be considered in designing control signal.
(d) Overcurrent protection cannot react to the recovery current of normal operation. A delay circuit with delay time of 5μs is recommended.
(e) In applications using large IGBT modules (up to 100A or more) high di/dts make it increasingly difficult to avoid ground loop problems. Ground loops are caused when gate drive or control signals share a return current path with the main current. It may cause devices that are supposed to be biased off to turn on. In order to avoid this problem, connection of low side drivers using a single gate drive power supply is recommended.

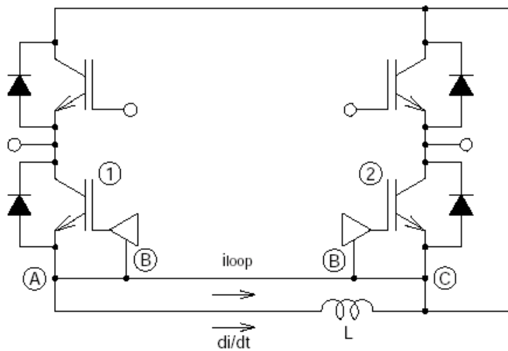
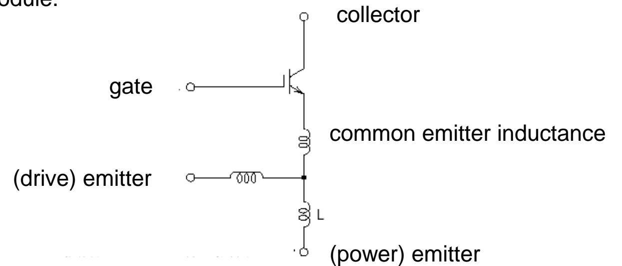


Fig.22. Ground loop

During turning on of IGBT①, voltage is induced in power circuit leakage inductance L by the high di/dt of the main current. (-L･di/dt) When this happens, points in the circuit that should be at “ground” potential may in fact be several volts above ground. Voltages at point A, B and C have the relationship of Ⓐ>Ⓑ>Ⓒ.
Because the gate drive voltage is based on B
Ⓐ>Ⓑ, turn-on of IGBT① is become slowly
Ⓒ<Ⓑ, gate drive voltage of IGBT② is increased
Ⓐ>Ⓒ, current iloop flowing through emitter terminals can cause that bus current increase depends on power circuit leakage inductance L.

(5) Main Circuit (Power Circuit) Layout
It is recommended to use the auxiliary emitter terminal for connecting the gate drive.
Power circuit and gate drive circuit must be located as close as possible to the gate-emitter control terminals of the IGBT module.



5. Switching Loss

Temperature of inductive load at half-bridge operation is raised with current increase. Measured switching losses are shown in Fig.23, 24, 25, 26, 27, 28 and 29 (from next page).

Conditions:
Half-bridge switching mode
Tj=125°C, Vcc=300(12NF)/600(24NF,24A)V, V_{GE}=±15V
R_G:see Table1 SWLOSS

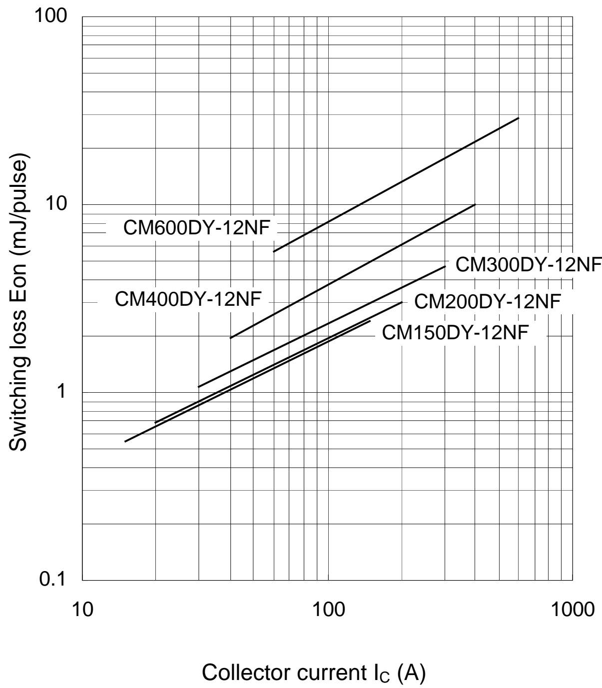


Fig.23.1 Turn-on Switching Loss (12NF)

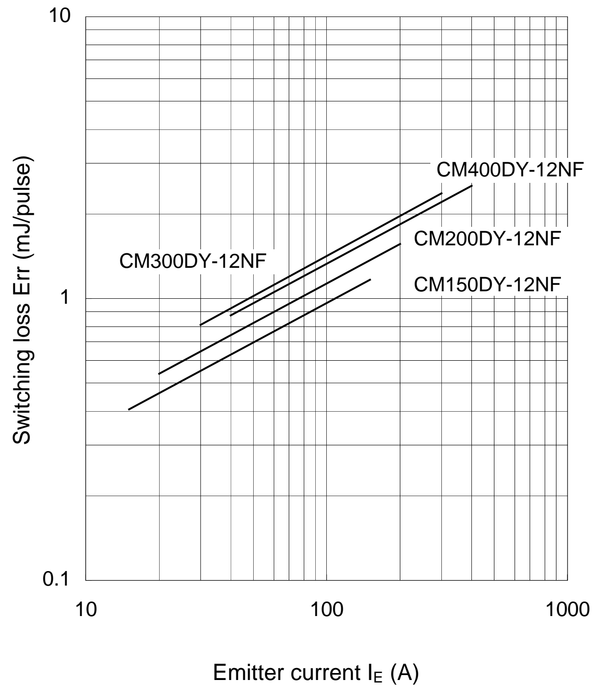


Fig.23.3 Recovery Loss

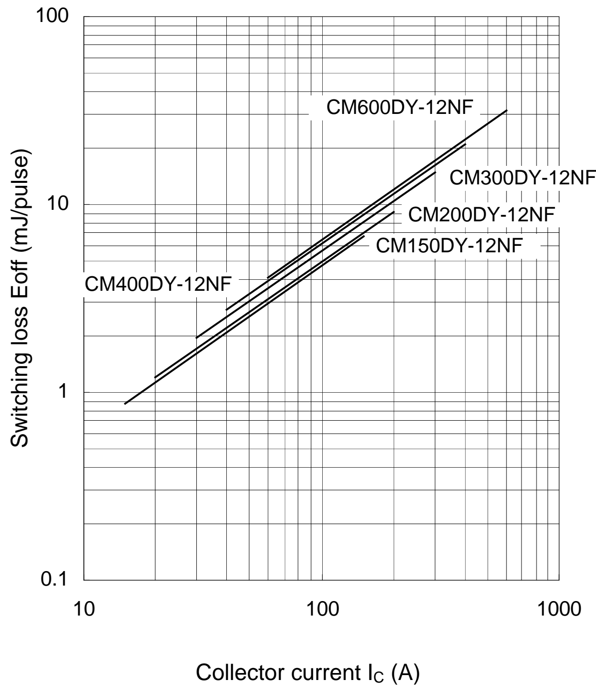


Fig.23.2 Turn-off switching Loss

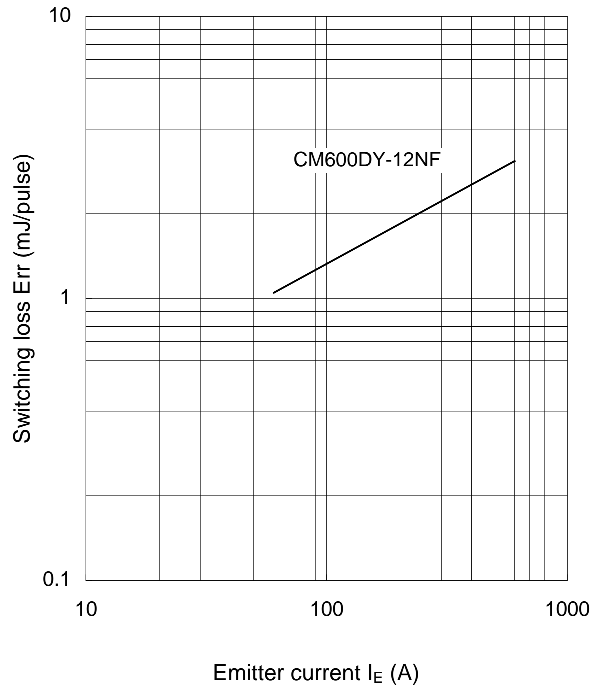


Fig.23.4 Recovery Loss

Fig.23 Inductive load half-bridge switching loss "12NF-Dual"

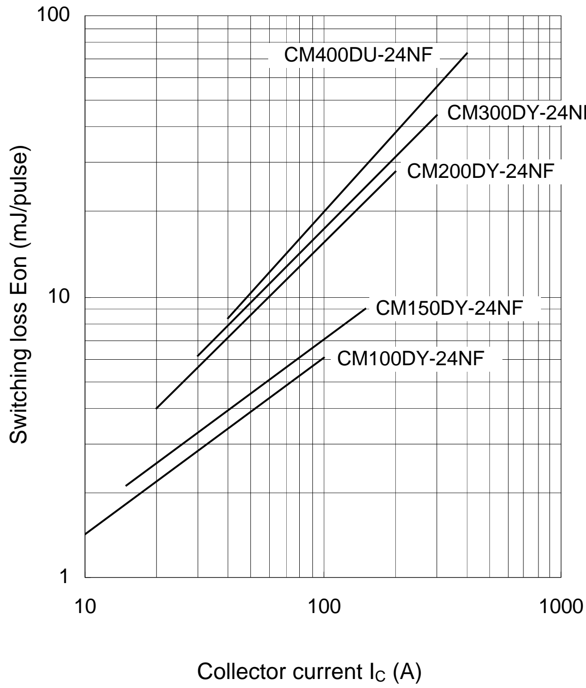


Fig.24-1 Turn-on switching Loss

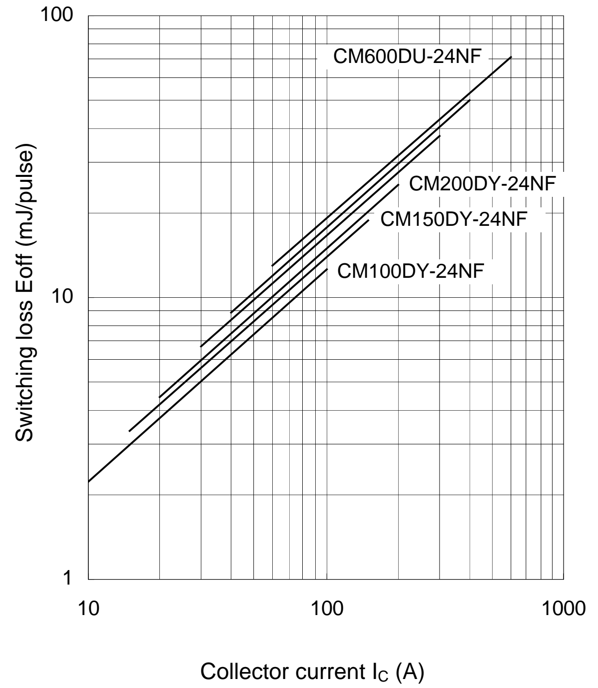


Fig.24-3 Turn-off switching Loss

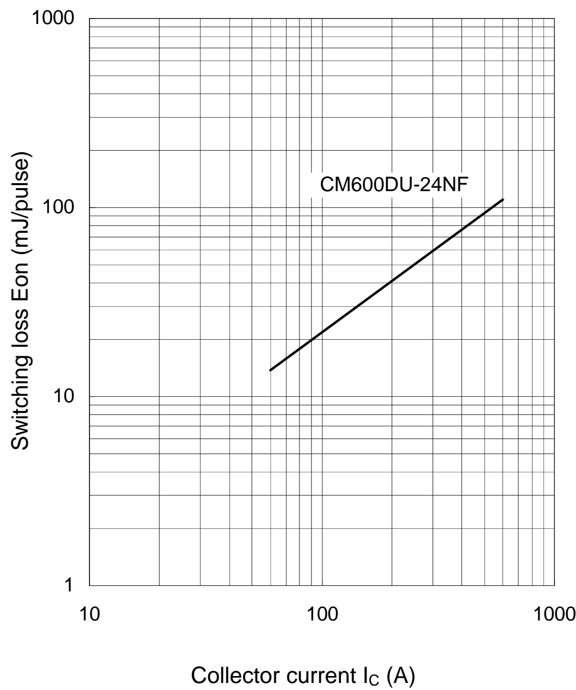


Fig.24-2 Turn-off switching Loss

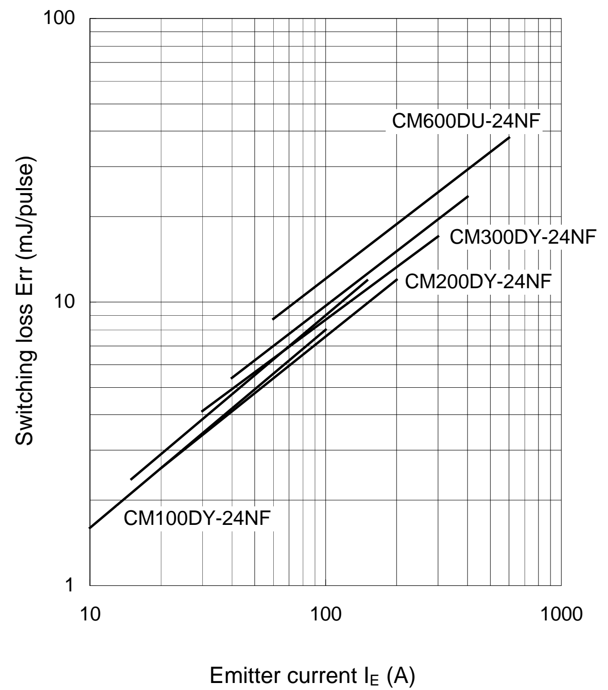


Fig.24-4 Recovery Loss

図24 Inductive load half-bridge switching loss "24NF-Dual"

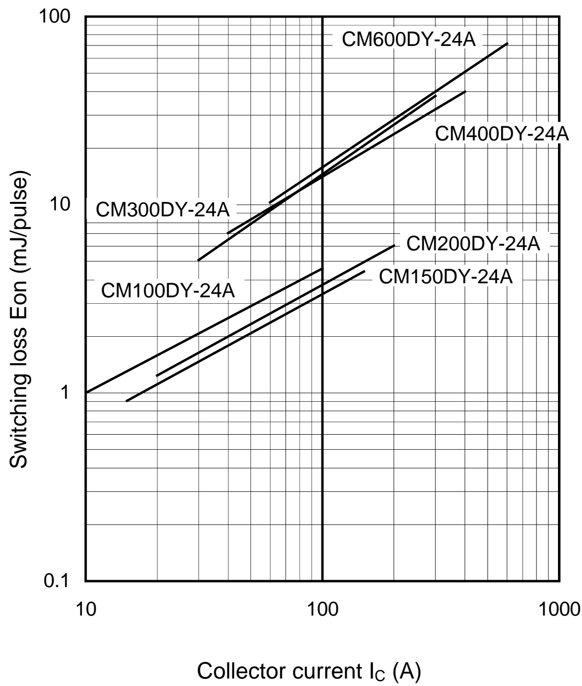


Fig.25-1 Turn-on switching Loss

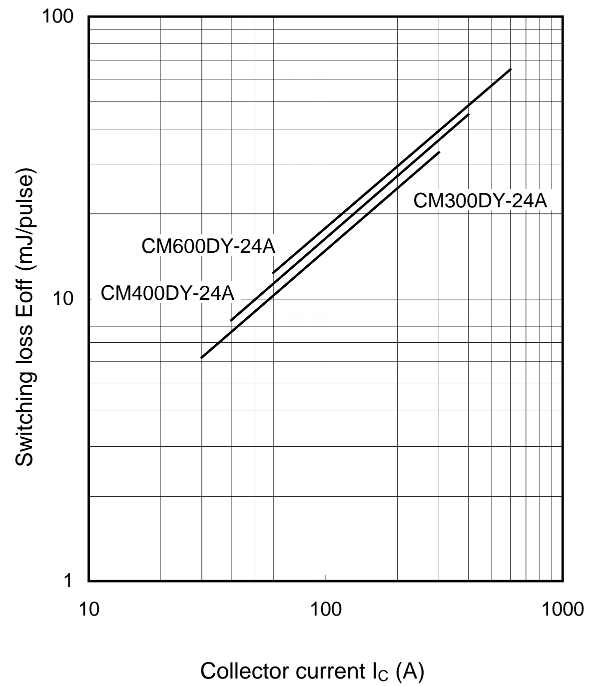


Fig.25-3 Turn-off switching Loss

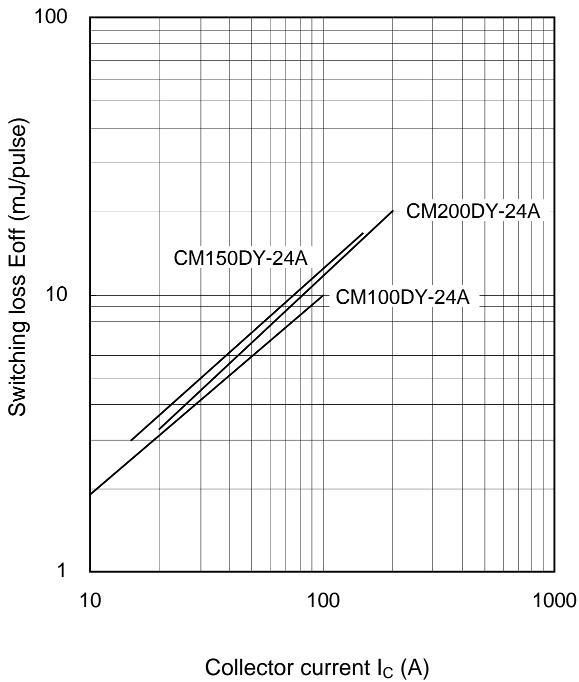


Fig.25-2 Turn-off switching Loss

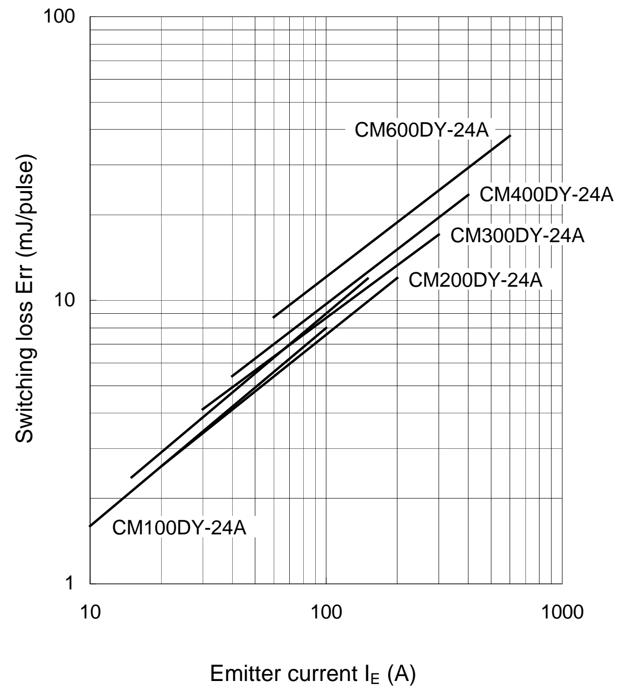


Fig.25-4 Recovery Loss

Fig.25 Inductive load half-bridge switching loss "24A-Dual"

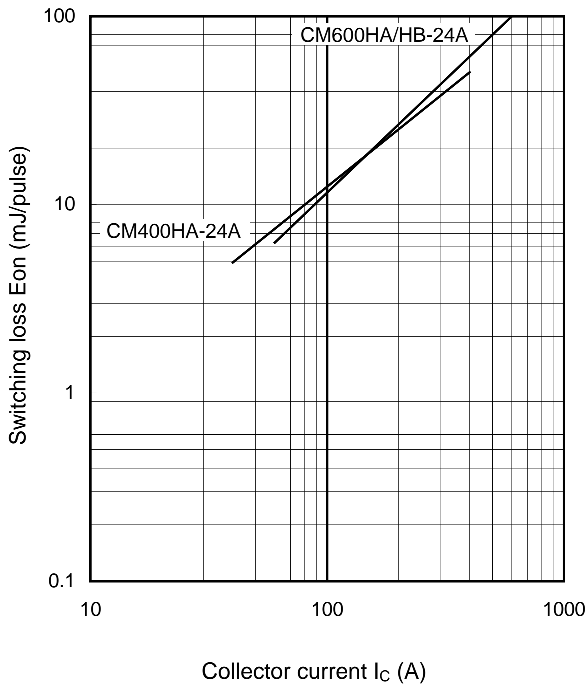


Fig.26-1 Turn-on switching Loss

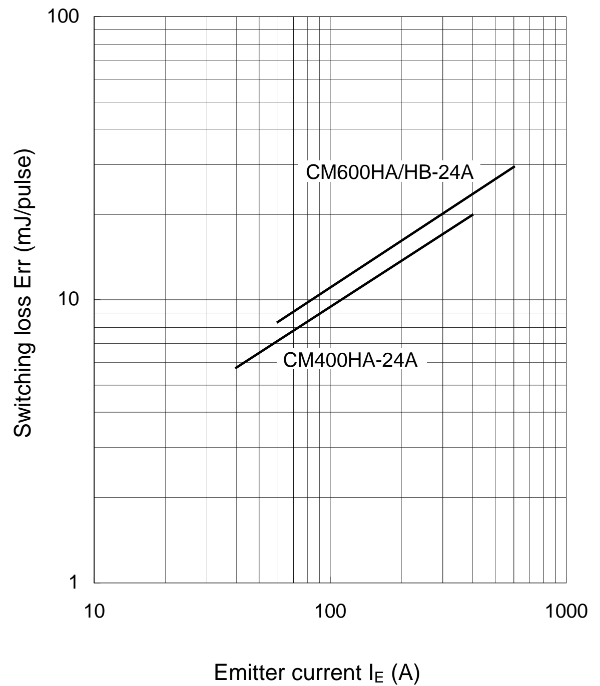


Fig.26-3 Recovery Loss

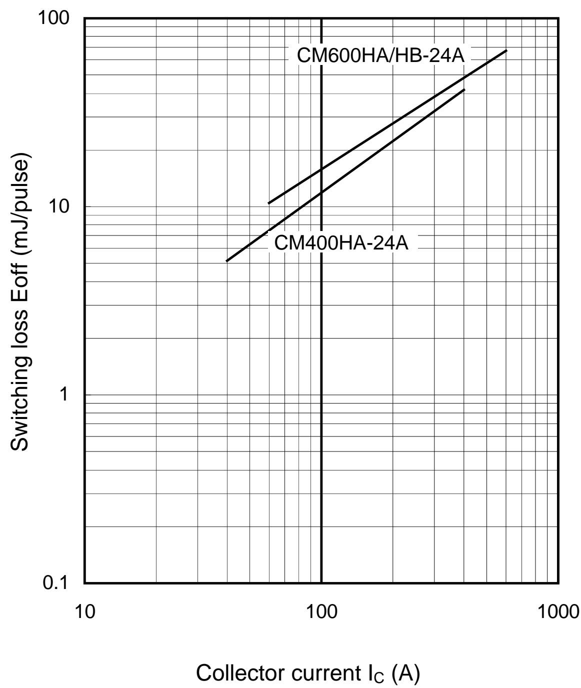


Fig.26-2 Turn-off switching Loss

Fig.26 Inductive load half-bridge switching loss "24A-Single"

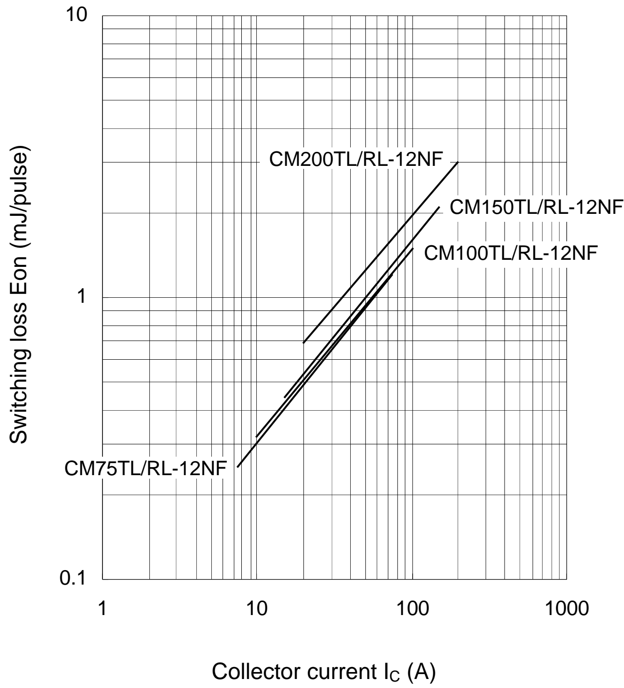


Fig.27-1 Turn-on switching Loss

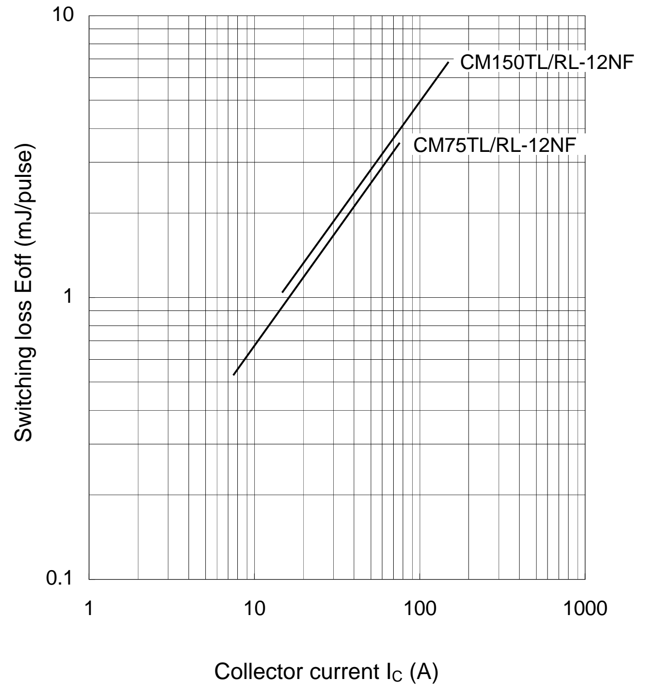


Fig.27-3 Turn-off switching Loss

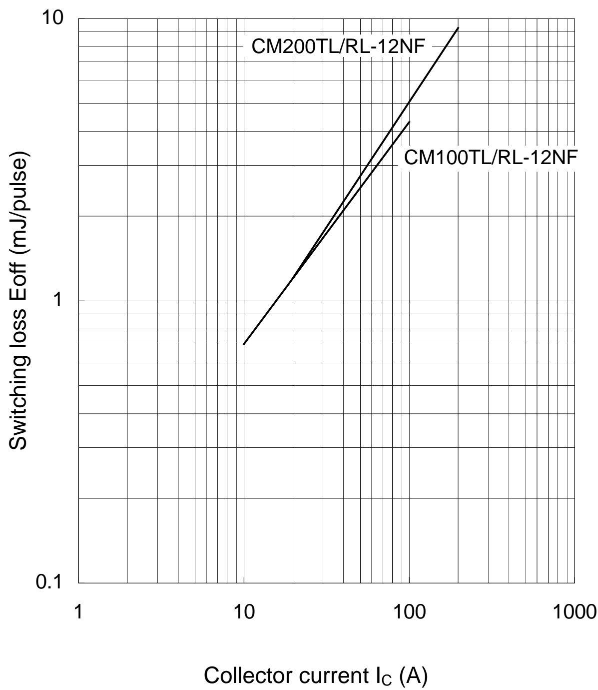


Fig.27-2 Turn-off switching Loss

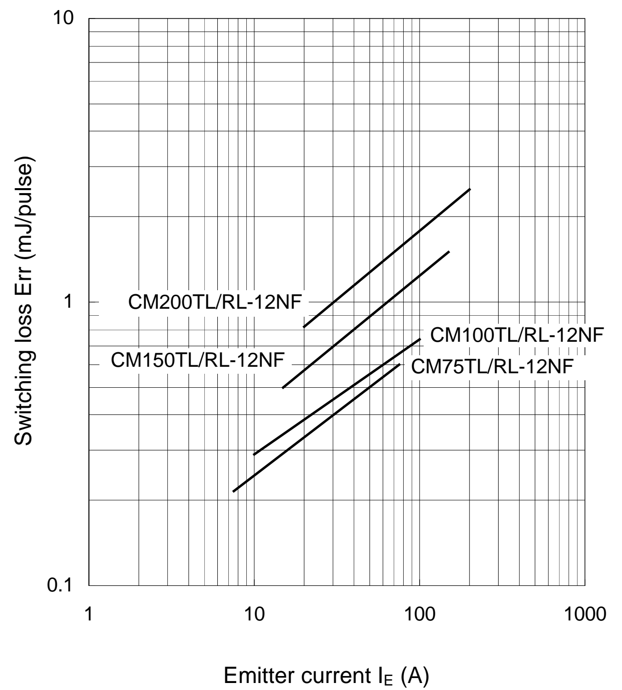


Fig.27-4 Recovery Loss

Fig.27 Inductive load half-bridge switching loss "12NF-6pack/7pack Inverter part"

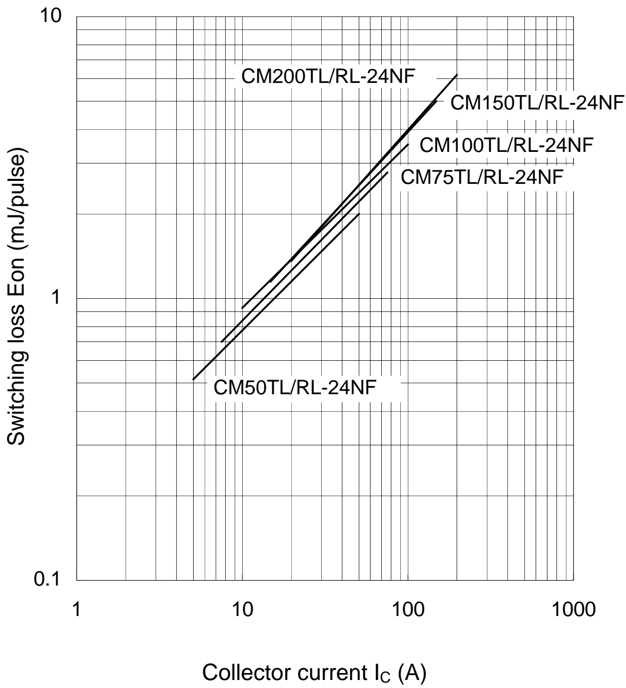


Fig.28-1 Turn-on switching Loss

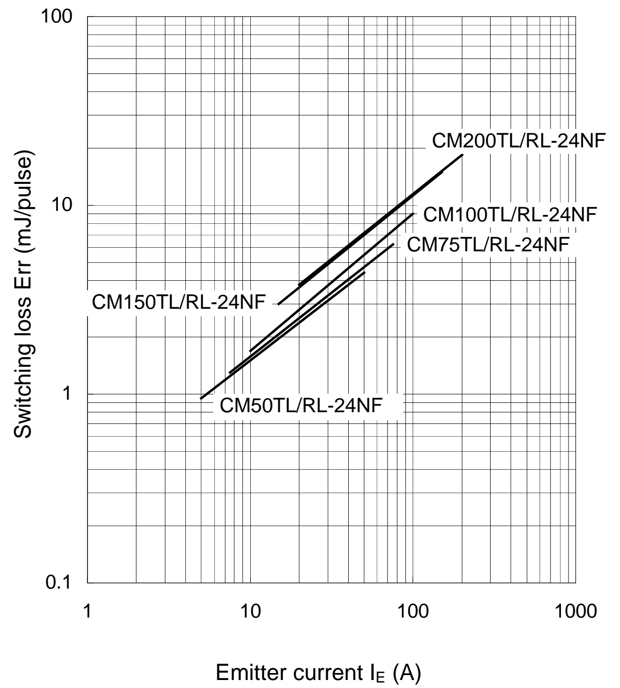


Fig.28-3 Recovery Loss

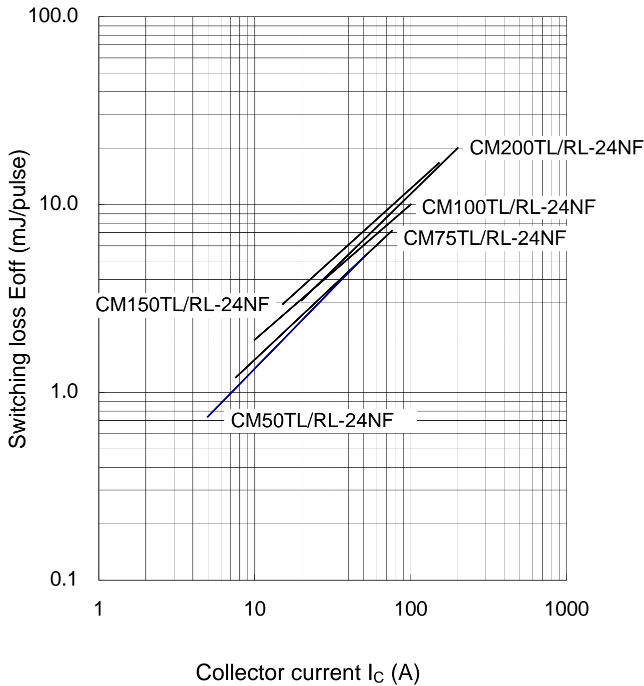


Fig.28-2 Turn-off switching Loss

Fig.28 Inductive load half-bridge switching loss "24NF-6pack/7pack Inverter part"

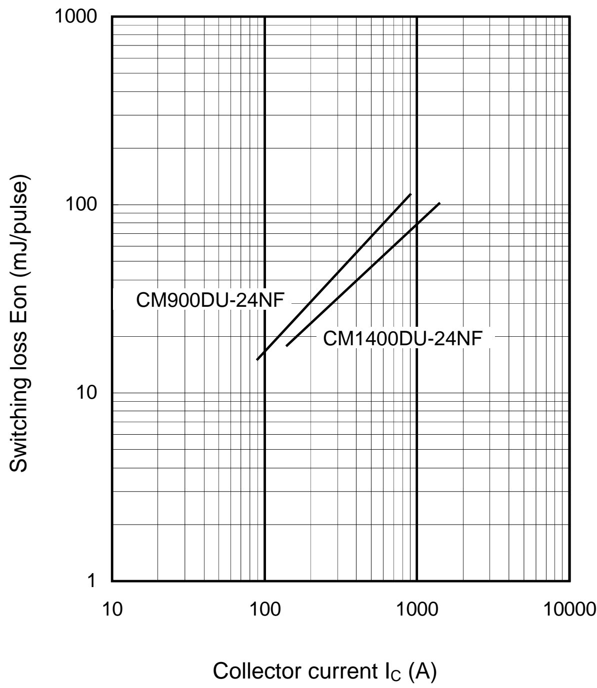


Fig.29-1 Turn-on switching Loss

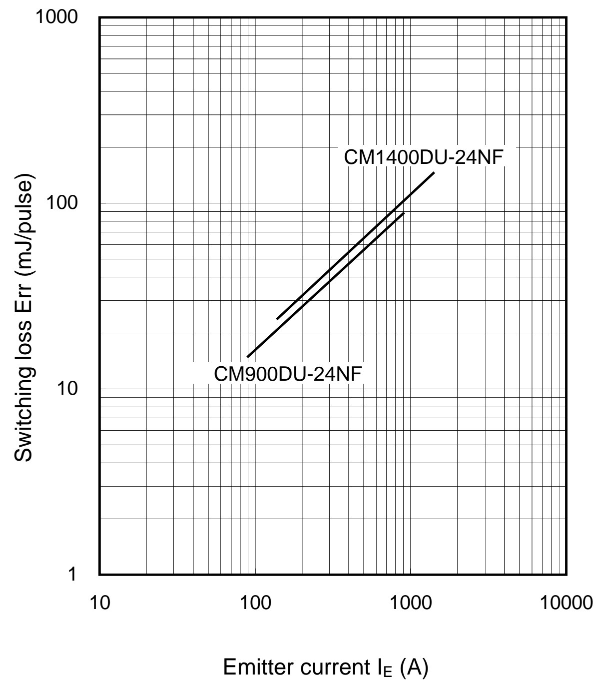


Fig.29-3 Recovery Loss

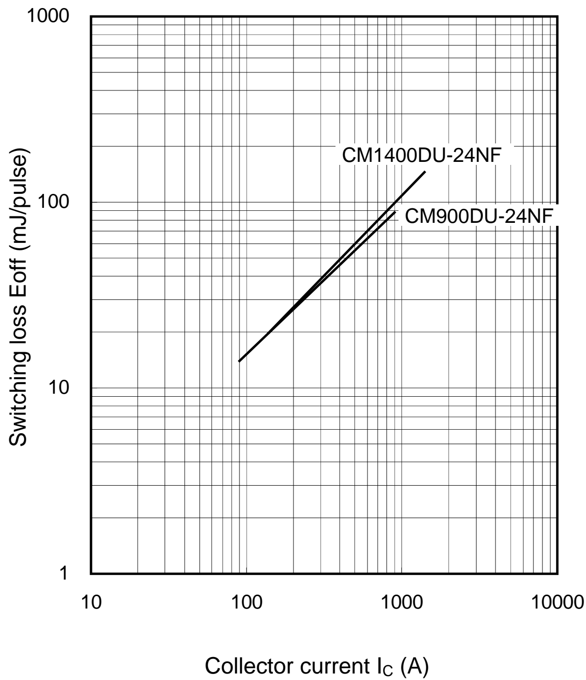


Fig.29-2 Turn-off switching Loss

Fig.29 Inductive load half-bridge switching loss "MPD"

Table1. Recommended Gate Resistance and R_G value used for power loss measurement (LOSS)

Module	R_G (Ω)	LOSS (Ω)	Module	R_G (Ω)	LOSS (Ω)	Module	R_G (Ω)	LOSS (Ω)
CM150DY-12NF	4.2～42	4.2	CM600DU-24NF	1.0～10	1.0	CM 75TL/RL-12NF	8.3～83	8.3
CM200DY-12NF	3.1～31	3.1	CM900DU-24NF	0.35～2.2	0.35	CM100TL/RL-12NF	6.3～63	6.3
CM300DY-12NF	2.1～21	2.1	CM1400DU-24NF	0.22～2.2	0.22	CM150TL/RL-12NF	4.2～42	4.2
CM400DY-12NF	1.6～16	1.6	CM100DY-24A	3.1～42	3.1	CM200TL/RL-12NF	3.1～31	3.1
CM600DY-12NF	1.0～10	4.2	CM150DY-24A	2.1～31	2.1	CM 50TL/RL-24NF	6.3～96	6.3
CM100DY-24NF	3.1～31	3.1	CM200DY-24A	1.6～21	1.6	CM 75TL/RL-24NF	4.2～63	4.2
CM150DY-24NF	2.1～21	2.1	CM300DY-24A	1.0～16	1.0	CM100TL/RL-24NF	3.1～42	3.1
CM200DY-24NF	1.6～16	1.6	CM400DY/HA-24A	0.78～10	0.78	CM150TL/RL-24NF	2.1～31	2.1
CM300DY-24NF	1.0～10	1.0	CM600DY/HA-24A CM600HB-24A	0.52～7.8	0.52	CM200TL/RL-24NF	1.6～21	1.6
CM400DY-24NF	0.78～7.8	0.73						

*:In case of type CM**RL, LOSS refer for inverter part only

Table2. Internal gate resistance

Part number	Int. R_G (Ω)	Part number	Int. R_G (Ω)	Part number	Int. R_G (Ω)	Part number	Int. R_G (Ω)
CM400DY-12NF	0.8	CM200DY-24NF	3	CM900DU-24NF	1	CM600DY-24A	2
CM600DY-12NF	0.8	CM300DY-24NF	2	CM1400DU-24NF	0.67	CM400HA-24A	1.5
		CM400DY-24NF	2	CM300DY-24A	3	CM600HA-24A	1
		CM600DU-24NF	1.5	CM400DY-24A	2	CM600HB-24A	1

Example of connectors used in 6pack and 7pack modules (for gate drive circuit)
2 pins (upper side):B2P-VH-FB-B
8 pins (lower side):B8P-VH-FB-B
manufactured by J.S.T connector company

Homepage : http://www.jst-mfg.com/index.html

Test Circuit and Waveform

Half-Bridge Switching Test Circuit

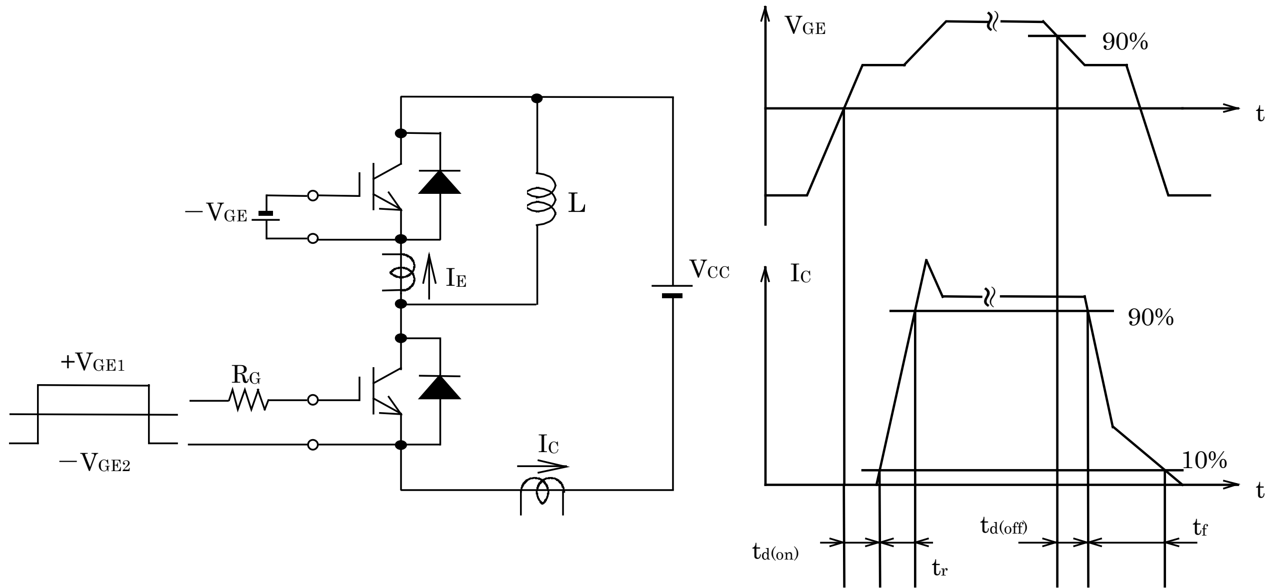


Fig.30-1

Switching loss Integral range

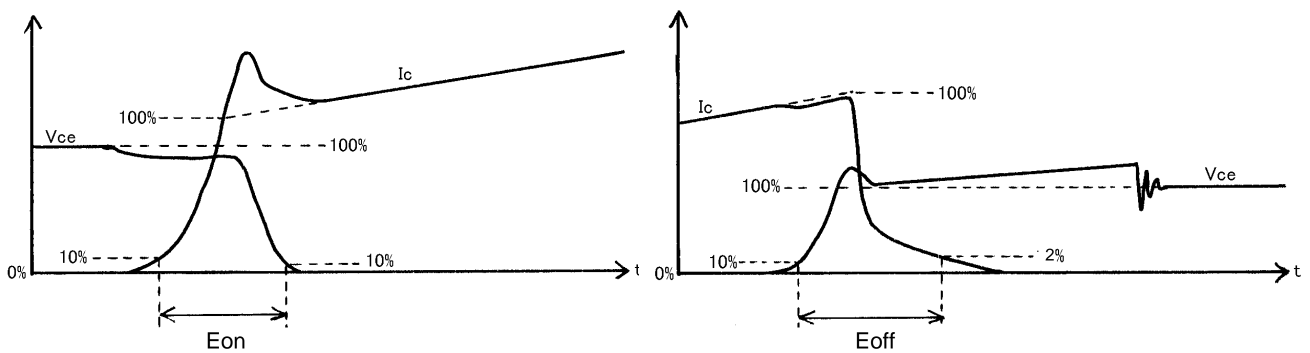


Fig30-2

100 % to fix each 10 % and 2 % don't include the electric current, which is caused by the recovery current and the stray-capacitance of load of FWDi, a surge voltage and a voltage drop by the floating inductance.

100 % of VCE is Vcc.

An influence over the switching loss by the corrugated change, which is caused by these, is reflected in the switching loss just as it is.

Also, for the reactive-power, we are included in the integration value because it is impossible to separate.

Strictly, 0 % of the I_C is not I_C=0A and it is Ices. 0 % of V_{CE} is not V_{CE}=0V and it is $V_{CE(sat)}$.

When it isn't possible to sufficiently remove the vibration, which is caused by the wiring inductance, a range is fixed based on the line, which estimated the center of the vibration.

But, when the same estimation is difficult, we sometimes suppose that it does the time to have intersected with 10 % most on the inside in the range.

6. Parallel Operation

(1) Parallel Specification

The following sub-sections outline the basic requirements and considerations for parallel operation of single IGBT modules with ratings of 200A or more.

With proper attention to circuit design and device selection several modules can be reliably operated in parallel.

- ●A parallel number is specified when ordering and parallel connected devices should be selected with matched saturation voltages.
- ●The saturation voltage rank (G, H, J and so on) will be indicated on the label.

Table 3 NF/A series saturation voltage ranks for parallel applications (I_C=rated current, V_{GE}=15V, Tj=25°C)

12NF				24NF		24A	
Rank	$V_{CE(sat)}$ (V)			Rank	$V_{CE(sat)}$ (V)	Rank	$V_{CE(sat)}$ (V)
E	1.50 ~ 1.60	K	1.75 ~ 1.85	C	1.62 ~ 1.81	D	1.76 ~ 1.96
F	1.55 ~ 1.65	L	1.80 ~ 1.95	D	1.76 ~ 2.00	E	1.92 ~ 2.16
G	1.60 ~ 1.70	M	1.90 ~ 2.05	E	1.95 ~ 2.26	F	2.12 ~ 2.41
H	1.65 ~ 1.75	N	2.00 ~ 2.20	-	-	G	2.37 ~ 2.69
J	1.70 ~ 1.80	-	-	-	-	H	2.65 ~ 3.00

(2) Parallel Operation Notes

All devices to be operated in parallel should have the same saturation voltage rank.

Modules of different saturation voltage ranks may be used in the same inverter provided that devices connected in parallel are of the same rank.

When modules of the same saturation voltage rank are paralleled the static current imbalance will be minimized so that the following recommended deratings can be applied: For 600V class derate I_C by 10%, For 1200V class derate I_C by 15%.

The imbalance rate is defined when more than two modules are paralleled. The collector current easily concentrates on one element with the parallel number increasing. Therefore, Derating is important for parallel operation.
(reference Fig.35)

When more than two modules are paralleled the derating can be computed using the following formula:

$$(1-((n-1)\times(1-x)/(1+x)+1)/n)\times 100\%$$

For example, in case of four IGBT modules of 600V class connected in parallel, the current derating is

$$(1-((4-1)\times(1-0.1)/(1+0.1)+1)/4)\times 100\%=13.6\%$$

, so the derated current with 4 parallel 300A modules is

$$300\times(1-0.136)\times 4=1036A$$

Parallel No.	derating (%)	
n	600V class	1200V class
2	10.0	15.0
3	12.1	17.4
4	13.6	19.6

Matching $V_{CE(sat)}$ is effective for maintaining good static steady state current balance. This matching also helps some with turn off current balance because of the fundamental inverse relationship of fall time and saturation voltage. However, gate drive conditions and power circuit layout have by far the greatest impact on dynamic current balance between paralleled devices. The application circuit of IGBT modules should be connected with a short, low impedance symmetric connection in order to minimize the current imbalance.

(3) Current Imbalance Factors and Notes

① Device Characteristics

a) On-state Voltage Difference

Under static on state (di/dt=0) the collector to emitter saturation voltage $V_{CE(sat)}$ has influence on current sharing. (reference Fig.32, Fig.34)

b) Temperature Difference

Under static on state (di/dt=0) the junction temperature has influence on current sharing.

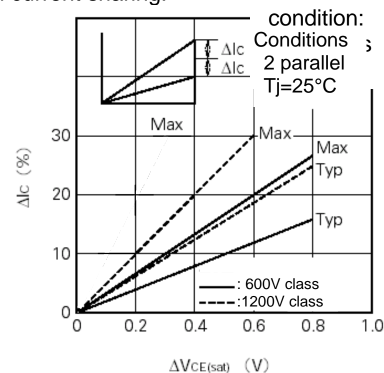


Fig.31 Current imbalance rate of IGBT modules in parallel

Temperature differences between paralleled modules are also a factor because of the resulting effect on delay time. (reference Fig.32, Fig.34)

Note) Power loss imbalance due to instantaneous transient current imbalance is very small.

- ●Use modules of the same saturation voltage rank in parallel.
- ●Devices should be mounted on the heat sink near to each other with cooling arranged to maintain uniform base plate temperatures between paralleled modules.

② Circuit Layout

a) Main Circuit Layout

a-1) Difference of the inductance between power supply elements

Difference of the inductance in the power circuit between the main supply capacitors and devices may result in current imbalance at the moment of turn-on or turn-off switching.
(reference Fig.33, Fig.35)

a-2) Difference of the total loop including a load

The difference of the total loop including a load causes current imbalance at turn-on (di/dt≠0).
(reference Fig.36, Fig.38)

● An asymmetric connection can result in current imbalance at the moment of turn-on or turn-off switching. In order to minimize the current imbalance, circuit connection should be low inductance symmetric.

b) Gate Drive Wiring

b-1) Difference between gate drive wirings may result in nonuniform switching and current imbalance. (reference Fig.33, 35 and Fig.37)

b-2) The output impedance of gate drive circuit has influence on current balance. High impedance consisting of gate resistance and stray inductance of drive circuit may raise switching speed difference at turn-on or turn-off and increase current imbalance. (reference Fig.33, 35 and Fig.37)

● Use short tightly twisted wires of equal length.

● Recommend to use relatively small values of series gate resistance.
($R_G \leqq$ recommended on the datasheet $R_G \times 10$)

● Avoid running a drive circuit parallel to the main circuit.

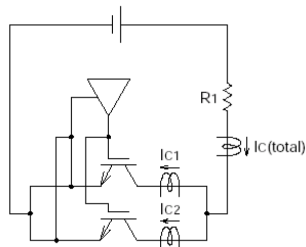


Fig.32 Example of R Load Switching Circuit

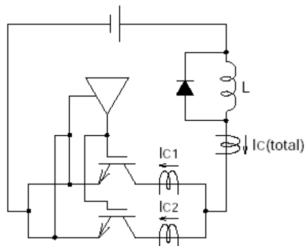


Fig.33 Example of L Load Switching Circuit

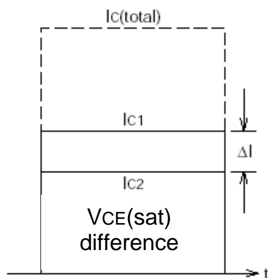


Fig.34

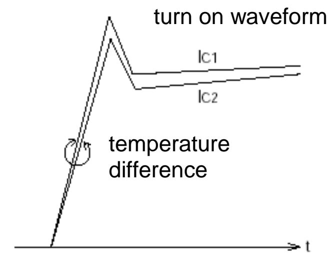


Fig.35

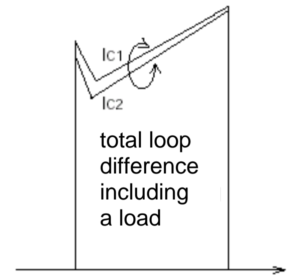


Fig.36 Typical Turn-on Waveform with Current Imbalance Caused by Asymmetric Main Circuit Inductance

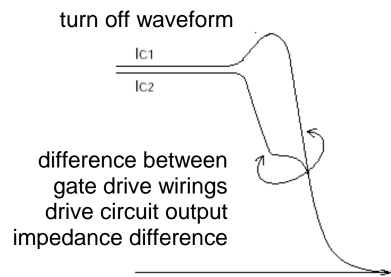


Fig.37 Typical Current Waveform Showing Imbalance at Turn-off Due to Improper Gate Drive

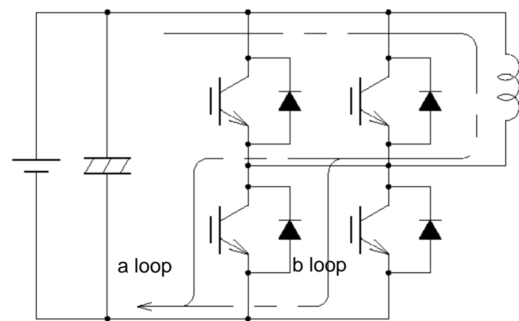


Fig.38

● Because the possibility of catching fire is large if only the fault module is replaced by new one. It is suggested to exchange all parts connected in parallel when fault occurs. Moreover, modules with same lot number are recommended to use in parallel operation for the purpose of current balance improvement.

7. Safe Operation Area

7.1 Turn-off Switching SOA (RBSOA)

Unlike MOSFETs, the turn-off switching SOA of IGBTs is the locus of points defining the maximum allowable simultaneous occurrence of collector current and collector to emitter voltage during turn-off, shown in Fig.39.

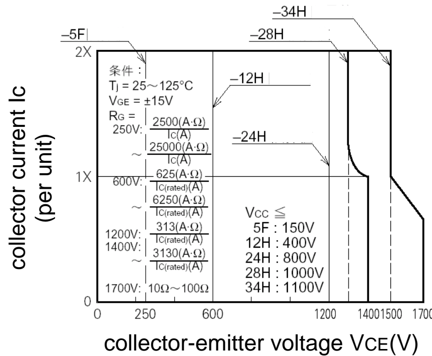


Fig.39 Turn-off Switching SOA

7.2 Short Circuit Capability

Most power conversion applications require that the applied switch should survive a short circuit on the system output without any damage. However, there is a limit on the amount of short circuit capability of IGBT modules.

(1) Limit Value Probability

There is a limit value probability depending on the period within which the short circuit current has to be cut off as shown in Fig.40.

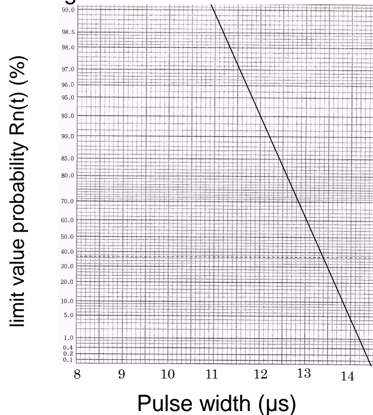


Fig.40 Short Circuit Limit Value Probability

7.3 Short Circuit SOA (SCSOA)

Fig.41-1 shows short circuit SOA curve.

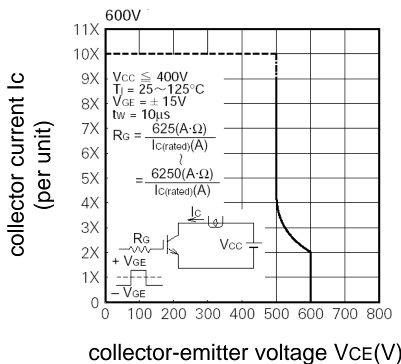


Fig.41-1 Short-Circuit SOA for Modules 600V Class

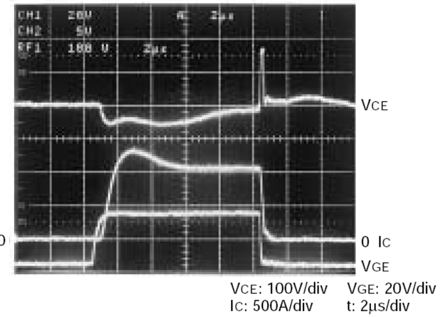


Fig.41-2 Waveform example

(1) Gate-Emitter Voltage (V_{GE})

Due to the limit of short circuit time, the gate-emitter voltage may be beyond 16.5V. However, under the case of vibration with duty of 0.1μs or less, gate voltage should never exceed 16.5V.

(2) Short Circuit Times

The non-repetitive short circuit is limited to 100 times and short-circuited elements should be replaced as soon as possible.

(3) Short Circuit Protection

Once a short circuit is detected, several techniques can be employed to protect the IGBT from destruction. The most elementary technique is to simply turn off the IGBT. (See Fig.42)

The peak of the short circuit current depends on V_{GE}, which is augmented by the feedback of dv/dt through the gate-collector capacitance. The effect can be overcome by using V_{GE} clamping circuit shown in Fig.43. The short circuit current waveforms are displayed in Fig.44.

Short Circuit Detection

The method of measuring Vce(sat) instead of the collector current at turn-on moment is used to detect short circuit. This method can effectively detect the IGBT short circuit, but it is not working on overcurrent detection, e.g. the load short circuit, which the current is limited by the wiring impedance. (It is a difficult technique to adjust each device for Vce of IGBT measurement in respect of the reproducibility of noise.) It is necessary to measure the collector current directly in case of the overcurrent. In order to lower Vce and avoid rapid thermal rising due to overcurrent, usually there is enough time allowance in thermal design so that a relatively low speed current detector could be used. Especially for high current usage, a high-speed measurement of the collector current is needed to decrease the capacity of the snubber circuit used to lower the overcurrent level.

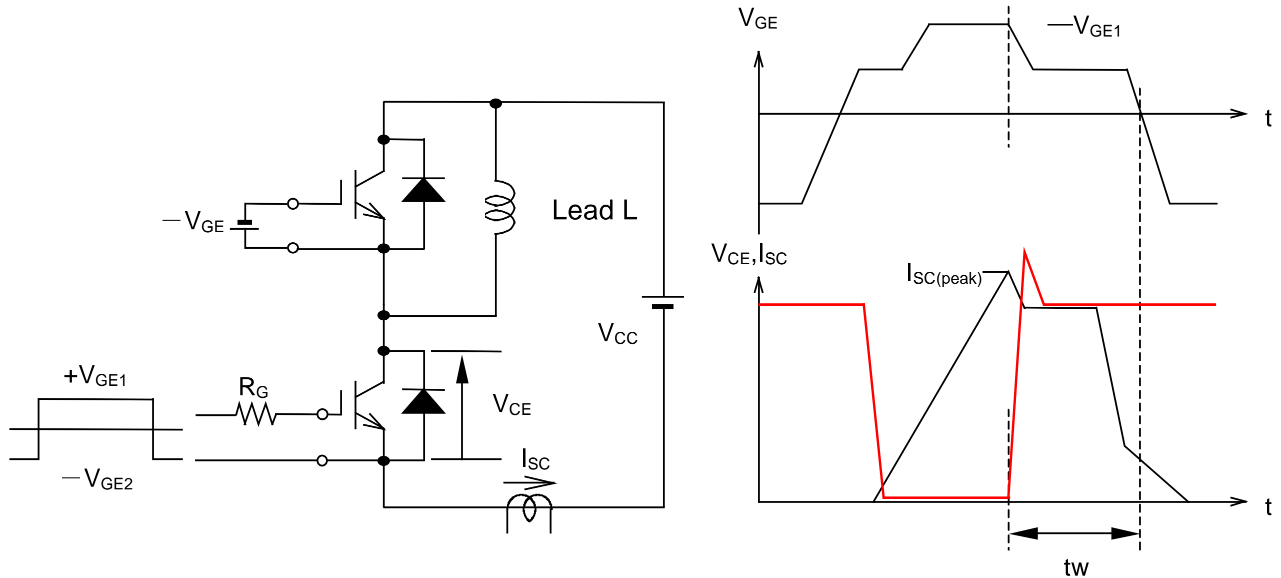
Definition of Pulse width at Short Circuit SOA of IGBT Module

Definition of pulse width (tw) at Short Circuit SOA (SCSOA) is shown following figures.

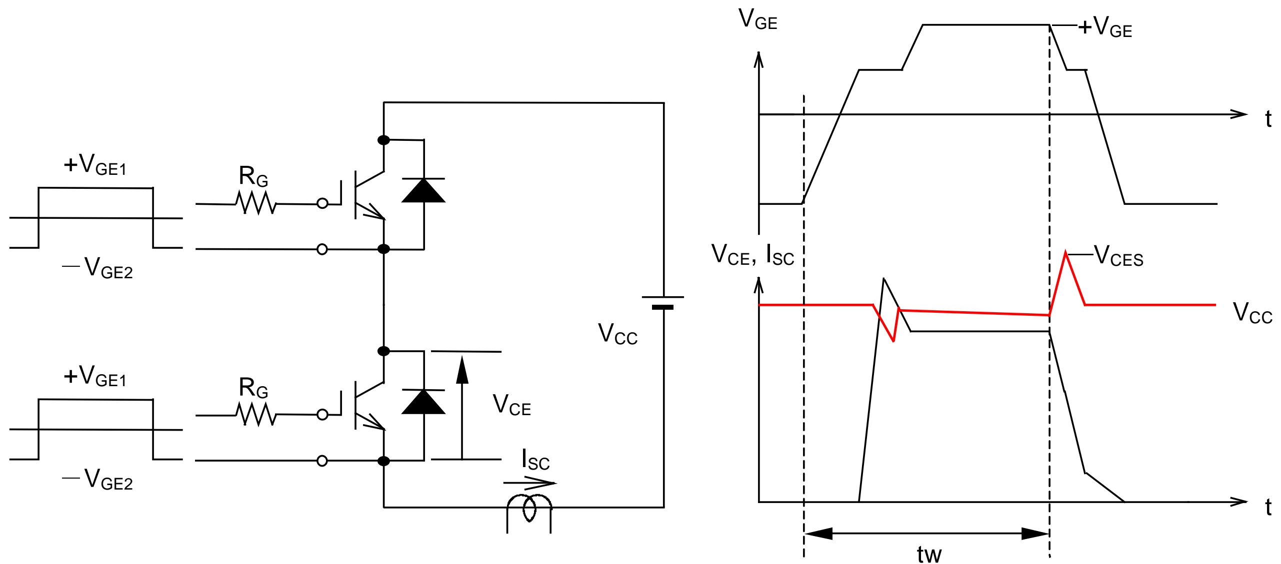
The system design for the time (tw), that is shown in each short circuit mode, should be equal to or less than 10μs of SCSOA.
** This application note dose not define the SCSOA. Please refer each specification sheet and SCSOA.

Condition example:
V_{CC}: 200~400V (600V class IGBT), 400~800V (1200V class IGBT)
V_{GE1}=+15V, $I_{SC(peak)max}$=$I_{C(rating)}$×10[A], Tj=125°C start,
R_G: 6250/$I_{C(rating)}$~625/$I_{C(rating)}$ (600V class IGBT), 3130/$I_{C(rating)}$~313/$I_{C(rating)}$ (1200V class IGBT)
*1. In case of above condition, generally $I_{SC(peak)}$ is less than 5 to 6 times of the current rating.
*2: V_{CEp} should be equal to or less than V_{CES}.
*3: R_G limitation may be defined individualy for some part number.

1. Load short circuit



2. Arm short circuit



I^2t value for 12NF/24NF/24A series

6/7pack

Part number	I^2t (kA^2s)	Part number	I^2t (kA^2s)
—	—	CM50TL(RL)-24NF	1.5
CM75TL(RL)-12NF	1.5	CM75TL(RL)-24NF	2.5
CM100TL(RL)-12NF	2.5	CM100TL(RL)-24NF	2.5
CM150TL(RL)-12NF	3.0	CM150TL(RL)-24NF	4.0
CM200TL(RL)-12NF	4.0	CM200TL(RL)-24NF	4.0

*:In case of RL, apply to only the Inverter part.

Dual

Part number	I^2t (kA^2s)	Part number	I^2t (kA^2s)
CM150DY-12NF	2.5	CM100DY-24NF	1.8
CM200DY-12NF	3.5	CM150DY-24NF	2.5
CM300DY-12NF	5.0	CM200DY-24NF	3.5
CM400DY-12NF	7.0	CM300DY-24NF	5.0
CM600DY-12NF	10.0	CM400DY-24NF	6.8
—	—	CM600DU-24NF	18.0

MPD

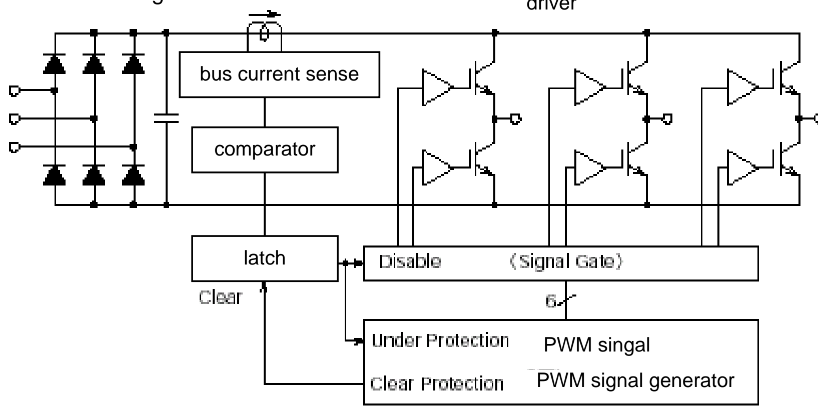
Part number	I^2t (kA^2s)	Part number	I^2t (kA^2s)
CM900DU-24NF	27.0	CM1400DU-24NF	40.5

A series

Part number	I^2t (kA^2s)	Part number	I^2t (kA^2s)
CM100DY-24A	1.8	CM400HA-24A	13.0
CM150DY-24A	3.0	CM600HA-24A	19.5
CM200DY-24A	3.5	CM600HB-24A	19.5
CM300DY-24A	6.0	—	—
CM400DY-24A	7.5	—	—
CM600DY-24A	10.0	—	—

Note) The above value is a value with the wire which blows out after the chip destroys.
When using a fuse, use the one of the rating which is smaller than of above value.
When using as the converter, the FWDi part doesn't become the design to have supported an inrush current, I2t of the non destruction like the general rectifier diode can not be guaranteed.
The peak of the inrush current use by equal to or less than twice of the rated emitter current and moreover the within the limits which is no problem in case of thermal design.

A System Block Diagram



Logic Diagram for Over Current Protection

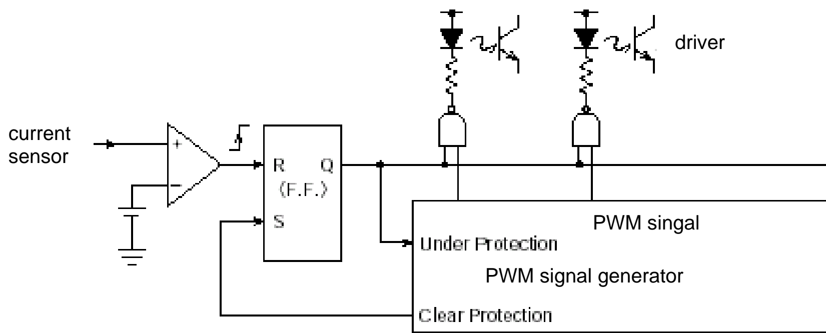


Fig.42 Short-Circuit Protection Scheme (Example)

VGE Clamping

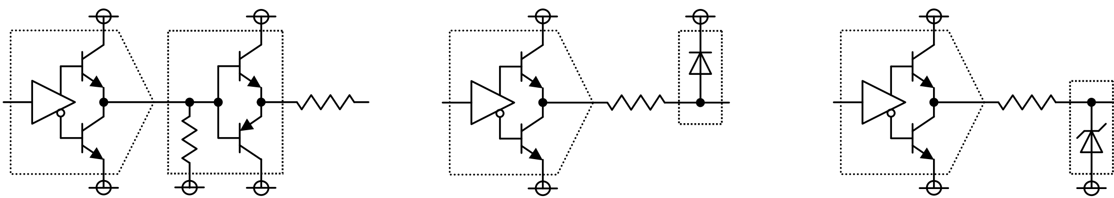


Fig.43 VGE Clamping Circuit

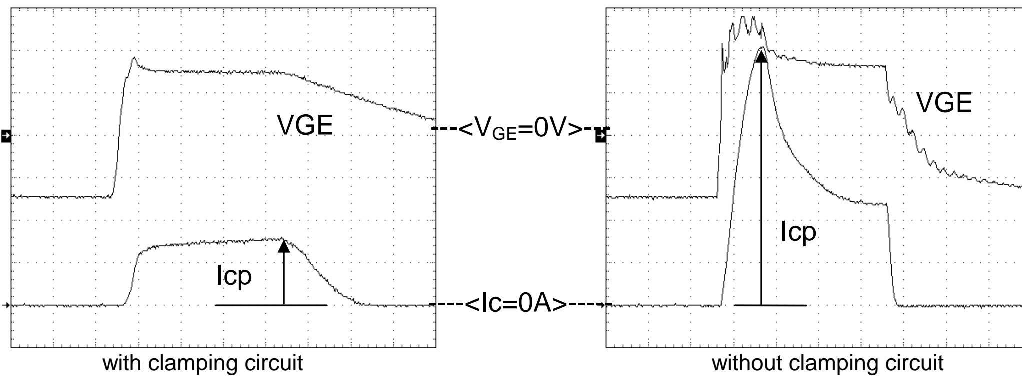


Fig.44 Short-Circuit Current Waveforms

8. Power Loss and Junction Temperature

Junction temperature can be used as an indication of IGBT module situation. This section will discuss how to calculate junction temperature and give an example based on waveform shown in Fig.45. Here, only power loss of IGBT part is given. The power loss of Diode can be obtained by using the same method as IGBT part. Moreover, junction temperature must never be outside of the maximum allowable value. It also has impact on the power cycle life.

Fig.45

a. Power Loss

In order to estimate junction temperature for thermal design, it is necessary to compute total power loss. The first step is the calculation of power loss per pulse.
Two most important sources of power dissipation that must be considered are conduction losses and switching losses. (Fig.46)

(1) Conduction Losses

The total power dissipation during conduction is computed by multiplying the on-state saturation voltage by the on-state current.

$$E_{(sat)} = \frac{I_{C1} \times V_{CE(sat)1} + I_{C2} \times V_{CE(sat)2}}{2} \times t_{w1} \quad (J)$$

Note)The above equation is a simplification of the below one

$$E_{(sat)} = \int_0^{t_w'} I_C(t) \bullet V_{CE}(t)dt$$

V_{CE}(sat) VS. Ic characteristics at Tj=125°C is used in power loss calculation.

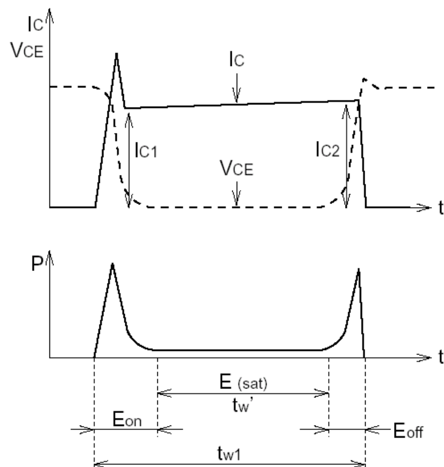


Fig.46

(2) Switching Losses

The most accurate method of determining switching losses is to plot the Ic and V_{CE} waveforms during the switching transition. Multiply the waveforms point by point to get an instantaneous power waveform. The area under the power waveform is the switching energy expressed in watt-seconds/pulse or J/pulse.

$$E_{on} = \int_{ta}^{tb} I_C(t) \bullet V_{CE}(t)dt = \frac{1}{n}\sum_{n-1}^{n} P_n \times (t_b - t_a)$$

n:number of partitions
(divide interval between ta and tb equally into n parts, compute average power loss for each interval.)
Calculation of Eoff has the same method.
The total power loss of one pulse is the sum of (1) and (2).

$$E_1 = E_{(sat)} + E_{on} + E_{off}$$

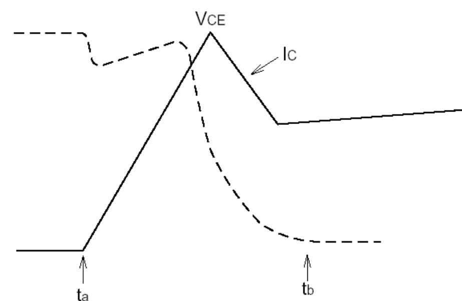


Fig.47

(3) Average Power Loss

The average power loss per pulse is

$$P_1 = \frac{E_1}{t_{w1}} \quad (W)$$

Fig.48 is approximation of Fig.45 by using rectangle wave.

Fig.48

Average power loss during period of tw2 is (See Fig.49)

$$P_{av} = \frac{E_1}{t_{w2}} \times N \quad (W)$$

N : pulse numbers in tw2 period

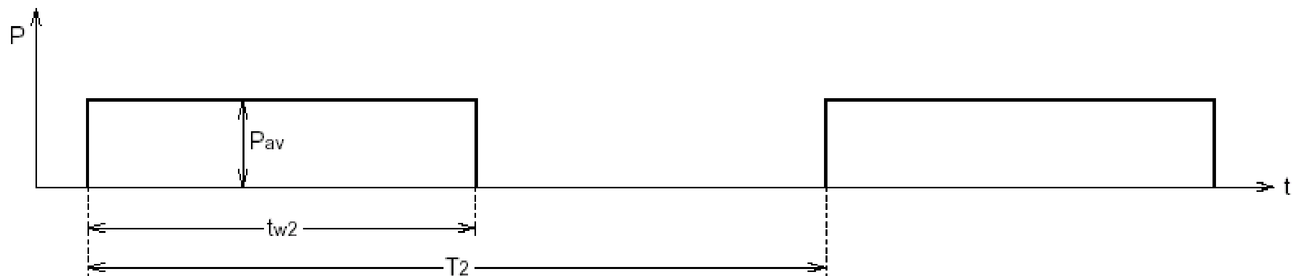


Fig.49

Total average power loss is (See Fig.50)

$$P_{AV} = P_{av} \times \frac{t_{w2}}{T_2} \quad (W)$$

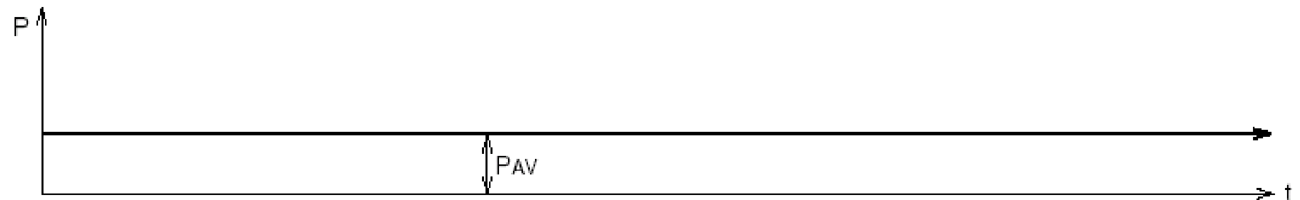


Fig.50

b. Junction Temperature Calculation

Junction temperature can be calculated by using P1, Pav, and PAV that has been obtained so far.
Three cases should be considered according to pulse width.

(1) tw1 is short (tw1<<1ms)
(2) Both of tw1 and tw2 are long(1ms<tw1<tw2<1s)
(3) tw2 is longer than 1s.(tw2>1s)

(1) tw1<<1ms
In case of short on interval or low duty as in Fig.49, Junction temperatures rise to the highest value at the turn-off moment of tw2 while the case temperature is stationary. (See Fig.51)

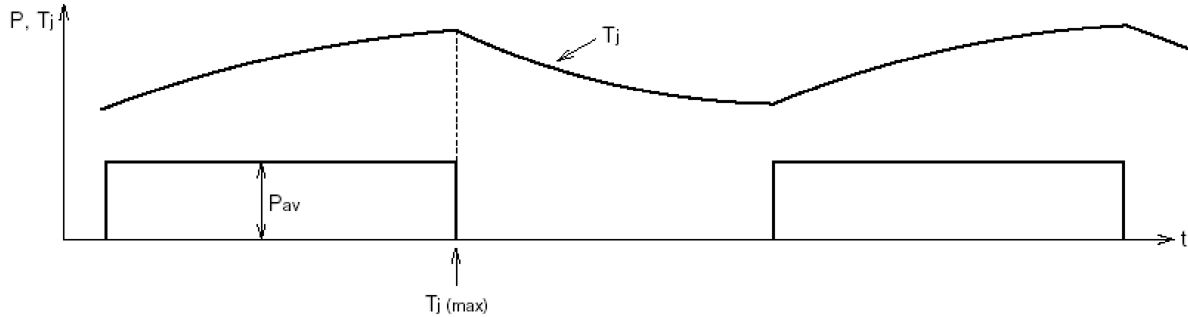


Fig.51

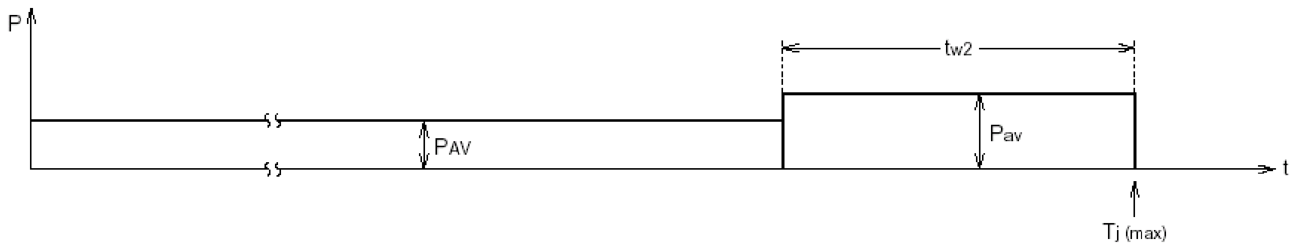


Fig.52

Temperature difference between junction and case can be calculated by using the following formula.

$$\Delta T(j\text{-}c) = R_{th(j\text{-}c)} \times P_{AV} - Z_{th(j\text{-}c)(tw2)} \times P_{AV} + Z_{th(j\text{-}c)(tw2)} \times Pav = R_{th(j\text{-}c)} \times P_{AV} + (Pav - P_{AV}) \times Z_{th(j\text{-}c)(tw2)}$$

$R_{th(j\text{-}c)}$ ……thermal resistance between junction and case

$Z_{th(j\text{-}c)(tw2)}$ ……thermal impedance between junction and case at tw2 moment

$\therefore Tj = Tc + \Delta T(j\text{-}c)$ (Tc is measured by thermo-couple.)

Tj(max)=150°C, therefore the allowable case temperature Tc(max) is, Tc(max)=150-ΔT(j-c).

(2) 1ms<tw1<tw2<1s
In this case, ripple should be considered in calculation of average power loss P1.
Using approximation similar to (1) Fig.53 is obtained for calculation.

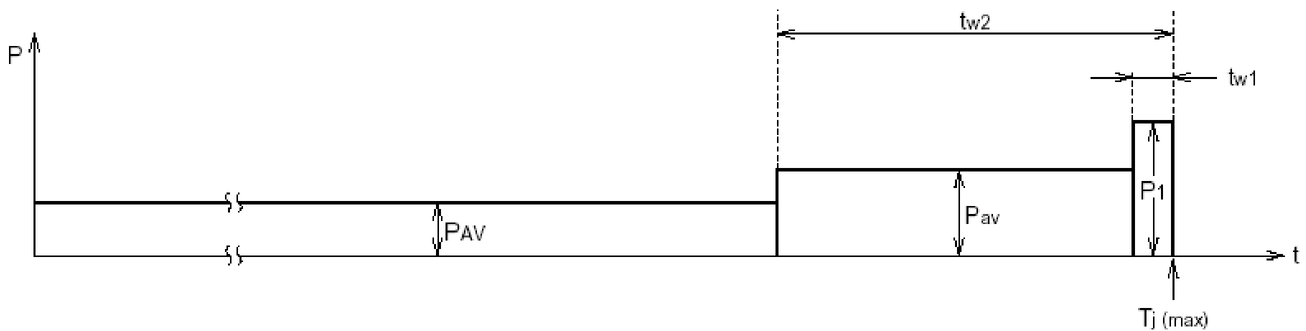


Fig.53

$$\Delta T(j\text{-}c) = R_{th(j\text{-}c)} \times P_{AV} - Z_{th(j\text{-}c)(tw2)} \times PAV + Z_{th(j\text{-}c)(tw2)} \times Pav - Z_{th(j\text{-}c)(tw1)} \times Pav + Z_{th(j\text{-}c)(tw1)} \times P1$$
$$= R_{th(j\text{-}c)} \times P_{AV} + (Pav - P_{AV}) \times Z_{th(j\text{-}c)(tW2)} + (P1 - Pav) \times Z_{th(j\text{-}c)(tw1)}$$

$R_{th(j\text{-}c)}$ ……thermal resistance between junction and case

$Z_{th(j\text{-}c)(tw2)}$ ……thermal impedance between junction and case at tw2 moment

$Z_{th(j\text{-}c)(tw1)}$ ……thermal impedance between junction and case at tw1 moment

$\therefore Tj = Tc + \Delta T(j\text{-}c)$ (Tc is measured by thermo-couple.)

$Tc(max) = 150 - \Delta T(j\text{-}c)$

(3) tw2>1s

In a similar way to (2), temperature change of heat sink should be taken into consideration as well. It is necessary to know the transient heat impedance of the heat sink. (Fig.54)

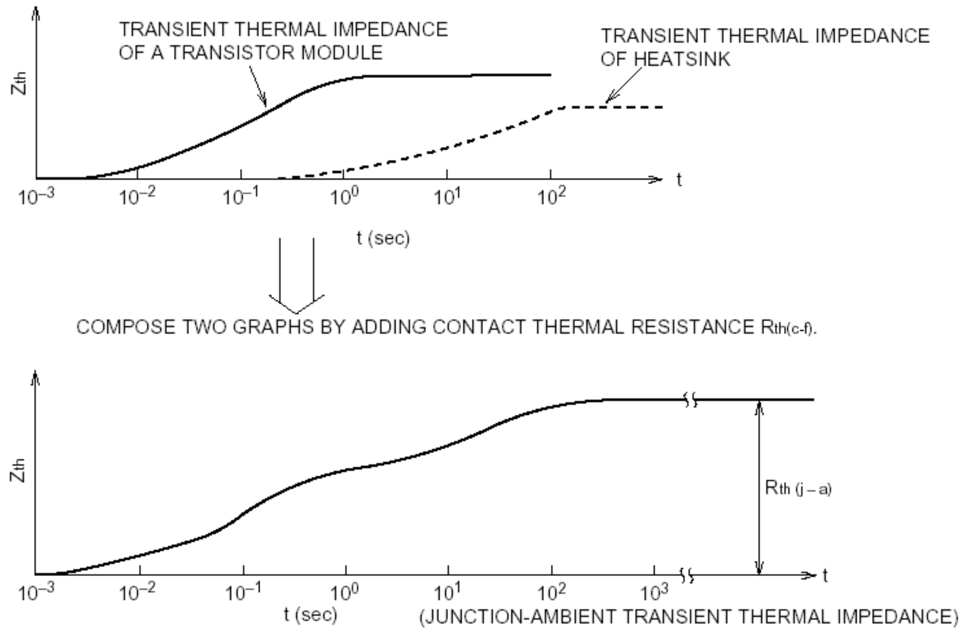


Fig.54

Similarly, the temperature difference between junction and ambient can be calculated by using the following formula.

$$\Delta T(j\text{-}a) = R_{th(j\text{-}a)} \times P_{AV} - Z_{th(j\text{-}a)(tw2)} \times P_{AV} + Z_{th(j\text{-}a)(tw2)} \times Pav - Z_{th(j\text{-}a)(tw1)} \times Pav + Z_{th(j\text{-}a)(tw1)} \times P1$$
$$= R_{th(j\text{-}a)} \times P_{AV} + (P_{av} - P_{AV}) \times Z_{th(j\text{-}c)(tw2)} + (P1 - Pav) \times Z_{th(j\text{-}c)(tw1)}$$

$\therefore Tj = Ta + \Delta T(j\text{-}a)$ (Ta is measured by a thermometer.)

c. Heat Sink Selection

Fig.55 shows the thermal equivalent circuit when two or more modules are mounted on one heat sink.

According to this equivalent circuit, the temperature of the heat sink is

$Tf = Ta + (P_{T(AV)} + P_{D(AV)}) \times N \times R_{th(f\text{-}a)}$

Ta : Ambient temperature
$P_{T(AV)}$:Average power loss of IGBT
$P_{D(AV)}$:Average power loss of FWDi
N:Arm number
$R_{th(f\text{-}a)}$:The heat sink to ambient thermal resistance

The case temperature Tc is,

$Tc = Tf + (P_{T(AV)} + P_{D(AV)}) \times R_{th(c\text{-}f)}$

Rth(c-f) : The case to heat sink thermal resistance

Tc(max) can be calculated by using the below formula.

$\therefore T_{c(max)} = Ta + (P_{T(AV)} + P_{D(AV)}) \times N \times R_{th(f\text{-}a)} + (P_{T(AV)} + P_{D(AV)}) \times R_{th(c\text{-}f)}$

Therefore, the heat sink to ambient thermal resistance can be computed as

$$R_{th(f-a)} = \frac{T_{C(max)} - T_a - (P_{T(AV)} + P_{D(AV)}) \times R_{th(c-f)}}{(P_{T(AV)} + P_{D(AV)}) \times N}$$

Moreover, power loss of FWDi should be considered as well. In thermal design, the allowable case temperature Tc(max) is up to the smaller one of IGBT power loss and FWDi part.

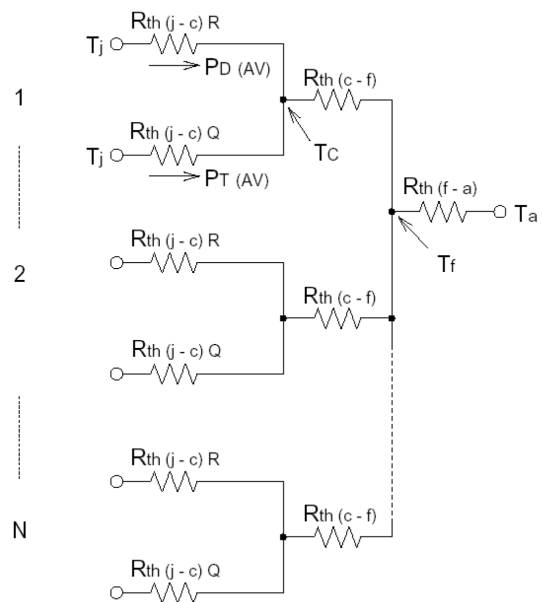


Fig.55 Thermal Calculation Model

Average Power Loss Simplified Calculation

For Mitsubishi Electric's modules in a variable voltage variable frequency (VVVF) inverter, power loss of IGBT or average power loss of IPM can be computed by using the software recommended in the following link.

http://www.MitsubishiElectric.co.jp/semiconductors/

Link to the above URL and click the button of Simulation Soft
Or, directly access the download page through the following URL.

https://www.semicon.melco.co.jp/dm/bin/u_als_form.pl

After input necessary information, the software can be downloaded.
The requirement for operation system (OS) is at least Windows®98SE.

Average Power Loss Simplified Calculation

(1) VVVF Inverter

■Applicability Range
It is applicable to total power loss calculation for selection of IGBTs used in VVVF inverters.
It is not applicable in the thermal design of the device (limit design).

■Assumption Condition
① PWM modulation used to synthesize sinusoidal output currents in VVVF inverters
② PWM signal generated by comparing sinusoidal wave to triangular wave
③ Duty cycle of PWM among the rank of $\frac{1-D}{2} \sim \frac{1+D}{2}(\%/100)$ D : modulation rate
④ Output current of $I_{CP} \cdot \sin x$ without ripple
⑤ With inductive load rate of $\cos\theta$

■Calculation Equation
Duty cycle of PWM is constantly changing and its value equal to time x $\frac{1+D\times\sin x}{2}$ at the corresponding moment.
The output current corresponds to the output voltage change and this relationship is represented by power factor $\cos\theta$.
Therefore, the duty cycle of PWM corresponding to output current at arbitrary phase x is

$$\text{Output current} = Ip \times \sin x$$

$$\text{PWM Duty} = \frac{1 + D \times \sin(x+\theta)}{2}$$

$V_{CE(sat)}$ and V_{EC} at this moment are

$$Vce(sat) = Vce(sat)(@Ip \times \sin x)$$

$$Vec = Vec(@(-1) \times Ip \times \sin x)$$

Static power loss of IGBT is

$$\frac{1}{2\pi}\int_0^{\pi}(Ip \times \sin x) \times Vce(sat)(@Ip \times \sin x) \times \frac{1 + D\sin(x+\theta)}{2} \bullet dx$$

Similarly, static power loss of FWDi is

$$\frac{1}{2\pi}\int_{\pi}^{2\pi}((-1) \times Ip \times \sin x) \times (Vec(@(-1) \times Ip \times \sin x) \times \frac{1 + D\sin(x+\theta)}{2} \bullet dx$$

On the other hand, dynamic power loss of IGBT is not dependent on the PWM duty and can be expressed as the following formula.

$$\frac{1}{2\pi}\int_0^{\pi}(Eon(@Ip \times \sin x) + Eoff(@Ip \times \sin x)) \times fc \bullet dx$$

As for dynamic power loss of free-wheeling diode, calculation is given by an example of ideal diode shown in Fig.52.

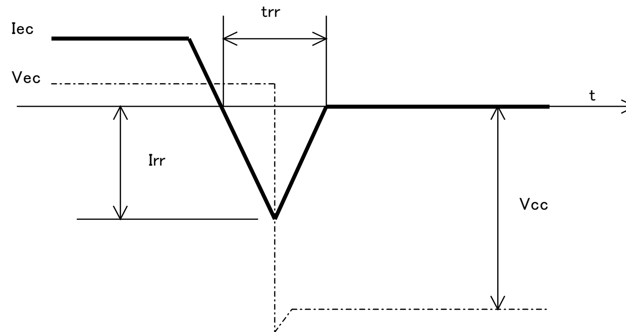


Fig.56. Dynamic Power Loss of FWDi

$$Err = \frac{Irr \times Vcc \;\; trr}{4}$$

Because reverse recovery of free-wheeling diodes occurs in half cycle of the output current, the dynamic power loss of FWDi is

$$\frac{1}{2}\int_{\pi}^{2\pi} \frac{Irr(@Ip \times \sin x) \times Vcc \times trr(@Ip \times \sin x)}{4} \times fc \bullet dx$$
$$= \frac{1}{8}\int_{\pi}^{2\pi} Irr(@Ip \times \sin x) \times Vcc \times trr(@Ip \times \sin x) \times fc \bullet dx$$

■Inverter Loss Calculation Notes

- Divide one cycle of output current into many equal intervals, then calculate actual "PWM duty", "Output current", and "$V_{CE(sat)}$, V_{EC}, Eon, Eoff and Err responding to the current" in each interval. The power loss during one cycle is the sum of each interval.
- The PWM duty depends on the method of generating the signal.
- The output current waveform and the relationship between output current and PWM duty cycle are dependent on signal generator, load and other factors. Therefore, calculation should always be done with actual waveforms.
- $V_{CE(sat)}$ uses the value of Tj=125°C.
- Eon, Eoff and Err uses the value under half bridge operating case at Tj=125°C.

■ Thermal Design Notes

① It is necessary to examine the worst switching condition.

② Consideration of temperature variation due to current cycle should be given in thermal design.
(Temperature variation rate is 30% to 35% for 60Hz case. When the output current of several Hz switches for a few seconds, it almost has equal temperature to a direct current with the same peak value continuously flowing.)

③ Temperature ripple caused by switching operation should be considered especially when switching frequency is much lower than 10kHz.