PROTON-ELECTROTEX
www.proton-electrotex.com

Application Note
Power Semiconductors

Application Note
for IGBT Modules
by Proton-Electrotex, JSC

1. Introduction

1.1 History of IGBT

MOSFET transistors that first made their appearance in 1980s possess properties close to properties of an ideal switch, making them the most popular commutation elements. However, application of MOSFET transistors is restricted by leakage voltage. So far there were no successful attempts to create high-voltage MOSFET transistors with sufficient properties because resistance of an open transistor grows as the square of discharge voltage. Chips of high voltage MOSFETs have large area. This implies a high price, unlike bipolar transistors. To be fair, it shall be mentioned that many companies keep working on high voltage field transistors. There are companies that produce transistors based on BI-MOSFET technology for voltages up to 1600V, however saturation voltage for such switches is around 7V, meaning extremely high dissipated power. This means harsher requirements to the cooling system.

In the beginning of 80s there were successful experiments to create a combined transistor consisting of a controlling MOSFET and an output bipolar cascade. They became known as an insulated-gate bipolar transistor (IGBT). Later researchers developed several methods to manufacture such transistors. The most successful of them became the modern circuit design of IGBT that combined all benefits of field and bipolar transistors operating in switch mode.

In 1985 a flat structure IGBT (with no V-channel) with high operating voltage was presented. High voltage and current result in very low losses in open state. At the same time the device has commutation and conductivity properties similar to those of a bipolar transistor, while control is based on voltage.

Currently there are transistors capable to commutate currents up to 2500A and voltages up to 10 000V.

1.2 Structure of an IGBT Module

Proton-Electrotex, JSC uses chips based on the Trench-FS technology. Usual structure of such chips is supplemented with a field-stop (FS) layer, planar gate is replaced with a vertical groove gate as shown on Figure 1. Baseplate is a thin low-alloyed n-plate with an additional n+ layer on the opposite p+ side of the collector. This FS layer helps to reduce electric field in the collector area.

Such transistor structure has a better temperature coefficient of forward voltage and higher resistance to overload. However, tail current occurring when the transistor is switched off is slightly higher, but it drops significantly faster than in switches with planar gate structure.

Gate elements are designed in so-called “p-channels”. Since such transistor structure increases effective area of silicon, it improves quality of field control in cross-section of the channels and reduces their resistance. It is possible to continue reducing cell area for each respective chip size, and this is why IGBTs with vertical gate structure have higher current density and operating voltage, lower conductivity and commutation losses, as well as better latch up resistance as compared to planar switches.

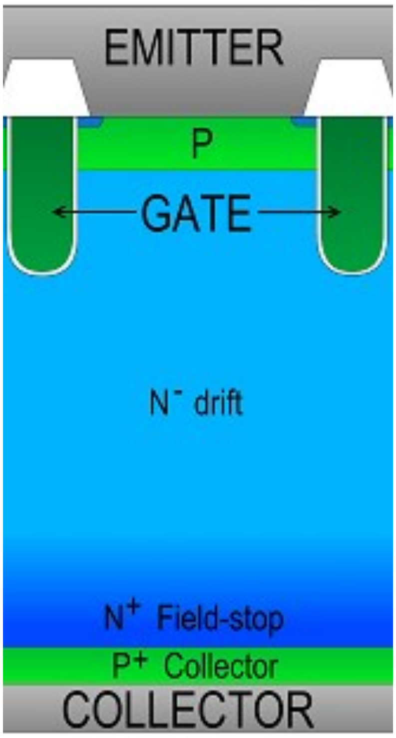
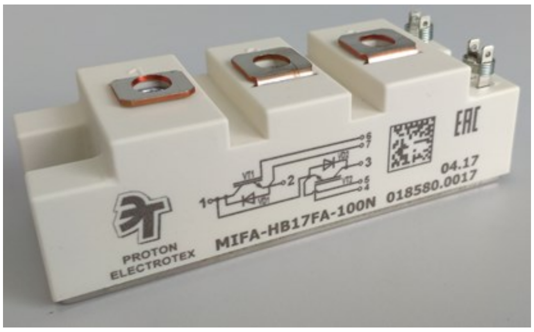


Fig. 1. Internal structure of a Trench -FS IGBT.

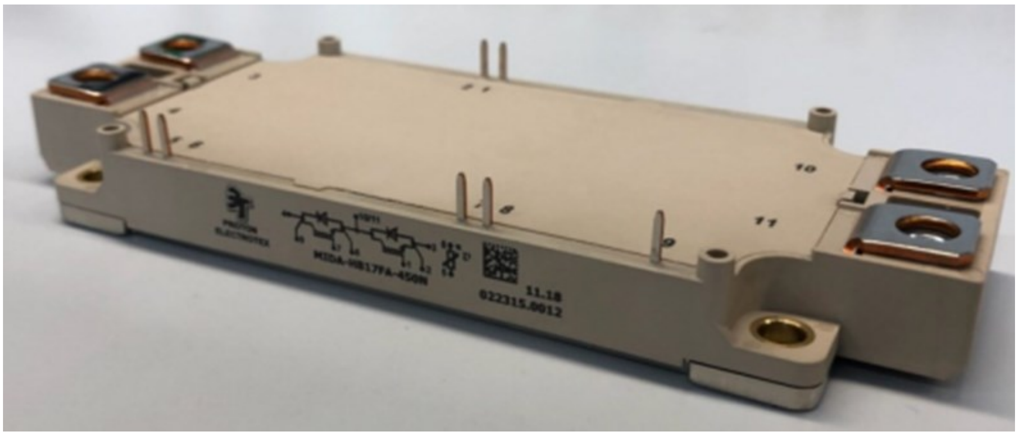
1.3 IGBTs Produced by Proton-Electrotex, JSC

As of today, Proton-Electrotex, JSC produces three types of modules: MIAA (industry standard design 62 mm), MIFA (34 mm) and low-inductance modules with housing height 17 mm (MIDA).

a



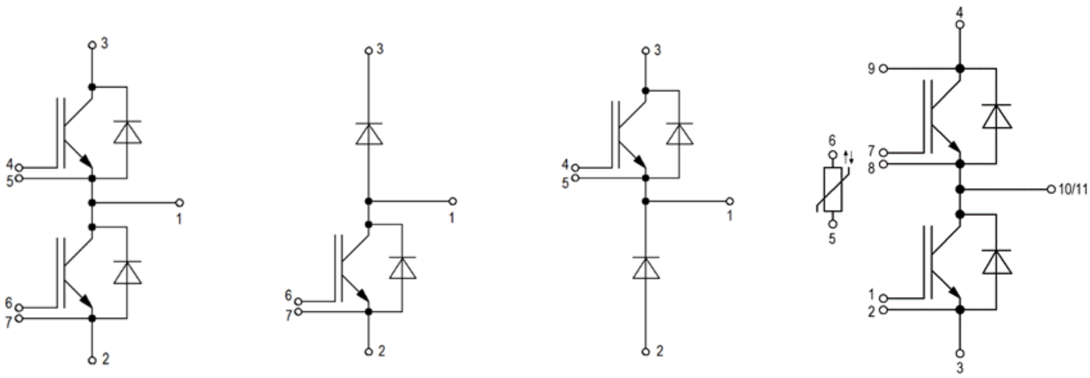
b



c

Fig 2. Industry standard classic modular design 62x106 mm (a), 34x94 mm (b) and 62x152 mm (c)

Proton-Electrotex, JSC focuses on manufacturing highly demanded products for converter market. We produce modules with 3 variants of engaging the transistor: half-bridge, lower and upper choppers.



a b c d

Fig. 3. Standard methods of engaging IGBT used in our products in standard packaging:

a – half-bridge, b – lower chopper, c – upper chopper, d – half-bridge in a MIDA module with a thermal resistor.

1.4 Assembly Technologies

Proton-Electrotex, JSC employs modern technologies used by many global manufacturers.

Technical Equipment

The first step in manufacturing IGBT modules is soldering. Soldered seam provides mechanical connection between module components, as well as electrical and heat conductivity.

The soldering process at Proton-Electrotex, JSC is based on a modern method of conductive heating in vacuum in vapor of formic acid using preforms. Such approach improves mechanical life and reliability of the devices thanks to the following:

- single pass soldering reduces heat stress in the components;
- a large selection of available soldering alloys, including various materials with required elasticity and melting temperature;
- cleaner preforms as compared to paste;
- no need for subsequent wet cleaning;
- high quality of soldered seams thanks to the vacuum resulting in minimal amount of caverns and voids;
- high thermal capacity components – the baseplate and DBC – are heated first. Chips are heated last, reducing influence of high temperatures on the chip;
- very flexible customization of soldering temperature profile – an important feature for lead-free technologies;
- voids area <3%.

The vacuum soldering at Proton-Electrotex, JSC is carried out in a high tech oven Vadu 200XL produced by PiNK.

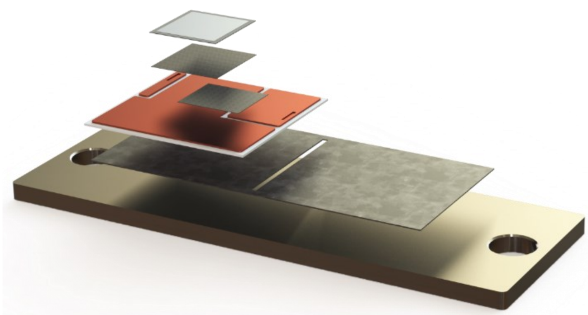


Fig 5. IGBT module layers soldering.

The next step is ultrasonic welding with aluminum wire and welding power terminals and connections.

Ultrasonic welding of power terminals, control terminals and chip connections is a new modern technological approach to manufacturing classic IGBT modules. The high technology ultrasonic welding allows Proton-Electrotex to produce high quality devices on par with world leaders of the semiconductor industry.

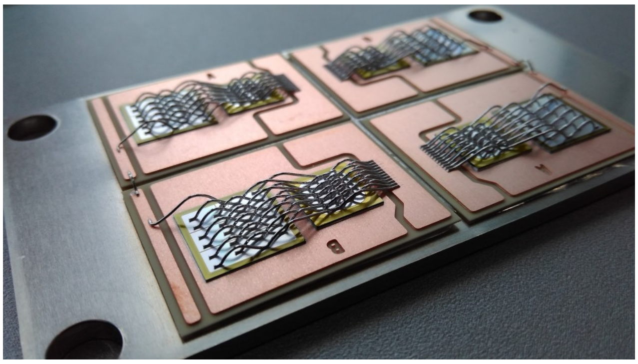


Fig 6. Wire welding of an IGBT module.

Thanks to the ultrasonic welding, service life of modules is no longer limited by reliability of contact connections of a conductor inside the device.

Since ultrasonic welding does not involve a soldering alloy, it makes the process cleaner and more cost-effective. Besides, ultrasonic welding allows to avoid scaling of the connections (after thermal cycling) typical for soldering with a soldering alloy.

One more advantage of this method is that the welding is made at temperature lower than metal melting temperature. It reduces thermal stress in the chips.

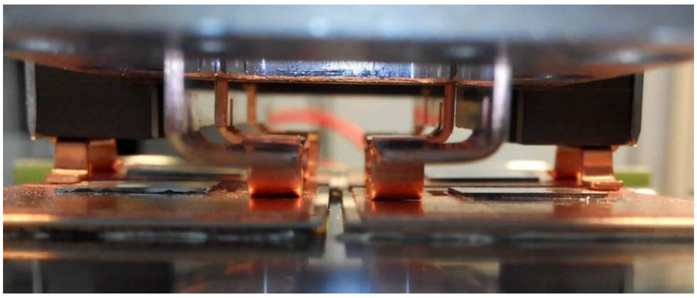


Fig 7. Welding of power terminals.

The above mentioned advantages and the new modern approach to production became possible thanks to ultrasonic welding machines F&K Delvotec 5650 and Delvotec G5 66000. These machines minimize human influence on the manufacturing process thanks to a high level of automation. It results in higher quality of our products. Besides all other advantages, Delvotec machines employ real time control of welding processes, self-diagnosis, documenting the welding process, collection and control of statistic data.

Testing demonstrated that the process of welding with large-diameter aluminum wire is:

- An easily controllable process thanks to fine tuning welding parameters and loop geometry.
- A highly repeatable process with low rejection rate thanks to a system of welding quality monitoring system based on real-time feedback.
- A process resistant to fluctuating properties of original components thanks to an advanced machine vision system.

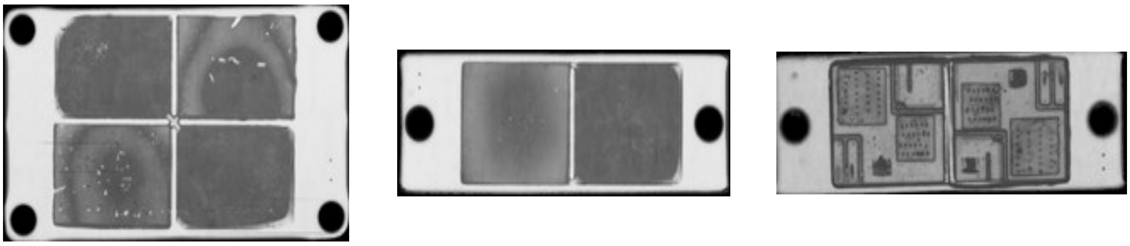
The data of cross-section welding contact testing indicate that properties of modules made by Proton-Electrotex, JSC match those of competing products.

Testing and Measurement Equipment

In order to control quality of soldering and welding connections we use a non-destructive acoustic microscope SONIX.

Acoustic defectoscopy has the following advantages:

- Easy identification of defects and near-zero thickness defects (absence of wetting);
- High accuracy;
- Integration into the production line.



a b c

Figure 8. Images received with the acoustic microscope: a – soldering of a MIAA type module, b – soldering of a MIFA type module, c – wire welding of a MIFA type module.

We employ modern testing equipment to control electrical parameters. Machines produced by Schuster allow us to make automatic measurements of all electrical parameters specified in technical requirements to the modules. These testers are also used by the leading European manufacturers. This equipment allows us to test 100% of static and dynamic parameters at Tj_max and room temperature.

Proton-Electrotex offers extensive experience of successful work on the market of power semiconductors, expertise of engineering staff, established relations with suppliers of components and materials, as well as well-organized business processes meeting high standards of quality management system.

1.5 RoHS Compliance

On October 21st, 2011 European directive 2011/65/EU RoHS2 came into effect. This directive limits content of harmful substances in electrical and electronic equipment and extends an earlier document 2002/95/EC (RoHS). It restricts usage of the following substances:

- Lead (Pb);
- Mercury (Hg);
- Hexavalent chromium (Cr6);
- Cadmium (Cd);
- Polybrominated biphenyl (PBB);
- Polybrominated diphenyl (PBDE);
- Decabromodiphenyl ether (decaDBE).

We completely follow this directive. You can find more details on our website:

https://www.en.proton-electrotex.com/sertification

1.6 UL Certification

Currently the modules are at certification testing phase.

2. IGBT Properties

2.1 Heat Losses

Heat losses occurring when the transistor is switched are combined from static losses in open state, dynamic switching losses, driving losses and losses from leakage in closed state.

Static losses may be calculated using a simplified formula: $P_{cond} = V_{CE(sat)} * I_{avg}$, where I_{avg} is average current for a specified period.

Loss power during periodic commutation may be calculated using formula:

$$P_n = \frac{1}{T}\int_0^T U_{CE}(t) * i_C(t)(dt)$$

, where T is commutation period, $V_{CE}(t)$ – collector-emitter voltage during the commutation period, $i_C(t)$ – collector current during the commutation period.

Power losses in the switch affect device's efficiency rate, so their reduction is one of the main objectives at design stage.

The dynamic losses component depends on the frequency of switch commutation. It limits maximal operating frequencies of power devices. It shall be mentioned that dynamic losses have prominent pulsing nature. It worsens their negative effect on the switch because of higher instantaneous temperature of the chip. Thus, maximal operating frequency of switch commutation is limited both by reduced response speed and higher dynamic losses.

Turn-on speed and turn-on losses may be controlled by changing resistance in the gate circuit, however it shall be noted that when the transistor is turned off only switch-off speed can be controlled, but not the residual current.

Modules produced by Proton-Electrotex are designed for average frequencies of 5–7 kHz.

2.2 Modes and Methods of Testing MIAA and MIFA Module Parameters

Tests meet requirements of IEC 60747-9 and GOST 24461-80.

2.2.1 $V_{BR(ces)}$ – collector-emitter breakdown voltage

This parameter defines the lower limit of breakdown voltage. As the temperature gets lower, breakdown voltage also reduces as a result of positive temperature coefficient.

Testing conditions:

- Transition temperature – 25±10°C;
- Off-state voltage:
  - Trapezoidal shape with a ramp leading edge;
  - Amplitude: maximal permissible breakdown voltage collector-emitter;
  - Duration: 10 µs;
  - Number of pulses – single pulse.
- Gate circuit mode – the gate-emitter circuit of the transistor is short-circuited.

Testing layout and method are identical to the method described in standard IEC 60747-9, Appendix A.

2.2.2 I_{CES} – collector-emitter leakage current

Collector current at zero gate voltage.

Testing conditions:

- Junction temperature – 25 ±10°C;
- Off-state voltage:
  - Trapezoidal shape with a linear ramp leading edge;
  - Amplitude: maximal permissible breakdown voltage collector-emitter (V_{CES});
  - Duration: 10 ms;
  - Number of pulses – single pulse.
- Gate circuit mode – the gate-emitter circuit of the transistor is short-circuited;
- Collector current – maximal value stated in testing program for the related type of module.

Testing layout and method are identical to the method described in standard IEC 60747-9, Item 6.3.4.

2.2.3 $V_{CE(sat)}$ – collector-emitter saturation voltage

Testing conditions:

- Junction temperature — 25 ±10°C;
- Voltage applied to the gate of transistor relatively to its emitter – 15V;
- Collector current pulse:
  - the amplitude is set equal to the nominal collector current (I_{C_nom}) for the related type of modules;
  - collector current pulse duration 300 µs;
  - number of pulses – single pulse;
- Reference measurement points must be placed on the module terminal in such a way that voltage drop at contacts and conductors caused by power current did not affect the measurements.

Testing layout and method are identical to the method described in standard IEC 60747-9, Item 6.3.2.

2.2.4 I_{GES} – gate-emitter leakage current

Testing conditions:

- Junction temperature — 25 ±10°C
- Gate circuit mode – the gate-emitter circuit is short-circuited;
- Voltage applied to the gate of transistor relatively to its emitter – initially 20V, then -20V.

Testing layout and method are identical to the method described in standard IEC 60747-9 Item 6.3.5.

2.2.5 $V_{CE(sat)}$ – collector-emitter saturation voltage

Testing conditions:

- Junction temperature — 25 ±10°C;
- Voltage applied to the gate of transistor relatively to its emitter – 15V;

- Collector current pulse:
  - the amplitude is set equal to the nominal collector current (I_{C_nom}) for the related type of modules;
  - collector current pulse duration 300 µs;
  - number of pulses – single pulse;
- Reference measurement points must be placed on the module terminal in such a way that voltage drop at contacts and conductors caused by power current did not affect the measurements.

Testing layout and method are identical to the method described in standard IEC 60747-9, Item 6.3.2.

2.2.6 I_{GES} – gate-emitter leakage current

Testing conditions:

- Junction temperature — 25 ±10°C
- Gate circuit mode – the gate-emitter circuit is short-circuited;
- Voltage applied to the gate of transistor relatively to its emitter – initially 20V, then -20V.

Testing layout and method are identical to the method described in standard IEC 60747-9 Item 6.3.5.

2.2.7 $V_{GE(th)}$ – gate-emitter threshold voltage

Collector current appearance voltage. It reduces as the temperature gets lower, similarly to $V_{BR\ (ces)}$.

Testing conditions:

- Junction temperature – 25 ±10°C;
- Collector-emitter voltage is equal to gate-emitter voltage (it is permissible to connect the gate and collector);

Testing layout and method are identical to the method described in standard IEC 60747-9, Item 6.3.3.

2.2.8 Turn On Parameters $t_{d(on)}$, t_{ri}, t_{on}, t_{fv}, dI_{Con}/dt, dV_{CEon}, E_{on} and Diode Reverse Recovery Parameters t_{rr}, I_{rrm}, Q_{rr}, E_{rec}

Testing conditions:

- Junction temperature – 150°C;
- Gate circuit mode:
  - voltage pulse amplitude at the gate of tested transistor relatively to its emitter: ±15V;
  - number of gating impulses of the tested transistor – two, with duration of the first current impulse much longer than duration of the second impulse and duration of the pause between the pulses;
  - internal resistance of trigger voltage and closing voltage sources at the gate of such type of modules must be documented in the testing program;
- Collector circuit mode:
  - voltage at the collector in closed state – 0,5 of breakdown voltage collector-emitter, unless the testing program states otherwise;

- the collector circuit includes an inductor coil, shorted with a freewheeling diode;
- time constant of a load L/R must significantly exceed the commutation time of the tested transistor included in the module;

- Open state current:
  - shape of the first current pulse – ramp pulse;
  - amplitude of the first collector current pulse (load current) is set equal to the nominal collector current for such type of modules;

Testing layout and method are identical to the method described in standard IEC 60747-9, Item 6.3.11.

2.2.9 Turn off Parameters $t_{d(off)}$, t_{fi}, t_{off}, t_{rv}, dI_{Coff}/dt, dV_{CEoff}, E_{off}

Testing conditions:

- Junction temperature - 150°C.
- Gate circuit mode:
  - amplitude of voltage impulses at the gate of the tested transistor relatively to its emitter: ±15V;
  - internal resistance of trigger voltage and closing voltage sources at the gate of such type of modules must be documented in the testing program;
- Collector circuit mode:
  - collector voltage in closed state – 0,5 of the breakdown voltage collector-emitter;
  - the collector circuit includes an inductor coil, shorted with a freewheeling diode;
  - time constant of a load L/R must significantly exceed the commutation time of the tested transistor included in the module;
- Open state current:
  - shape of the first current pulse – ramp pulse;
  - amplitude of the first collector current pulse (load current) is set equal to the nominal collector current for such type of modules.

Testing layout and method are identical to the method described in standard IEC 60747-9 Item 6.3.12.

2.2.10 Short-circuit Current Resistance Testing

Measurement conditions:

- Junction temperature - 150 °C or other value stated in the testing program.
- Gate circuit mode:
  - gating impulse voltage at the gate of the tested transistor relatively to its emitter: ±15V;
  - resistance of resistor in the gate circuit is documented in the testing program;
  - number of gating voltage impulses gate-emitter – one;
  - duration of gating voltage impulse gate-emitter at the level of 50% from maximal positive voltage (t_{psc}) – 10 µs.
- Collector circuit mode:
  - voltage at collector in closed state – value stated in the testing program;
  - the collector circuit must have minimal resistance and parasitic inductance;
  - amplitude of the collector current pulse must be limited by internal resistance of the tested transistor.

Testing layout and method are identical to the method described in standard IEC 60747-9 Item 6.2.6.

3. Selection of Modules for Converters

3.1 Selection of Modules by Specifications

Selection of IGBT modules for converter designs is a complex engineering task. The main problem that must be solved when selecting a module is selection of a generic “module-heatsink” assembly that would achieve heat balance between the amount of heat generated by semiconductor module components (chips) and the amount of heat radiated by the heatsink. The heat balance must be achieved at the module chip temperature not exceeding the maximal permissible temperature T_{j_max}.

The amount of heat generated by chips in a unit of time, or loss power, depends on many factors. The losses may be divided into two categories:

- **Static losses.** They are caused by non-ideal conductivity of semiconductor module components in active state and leakage currents in offline state;
- **Dynamic losses.** They are caused by finite turn-on time and turn-off time of semiconductor components.

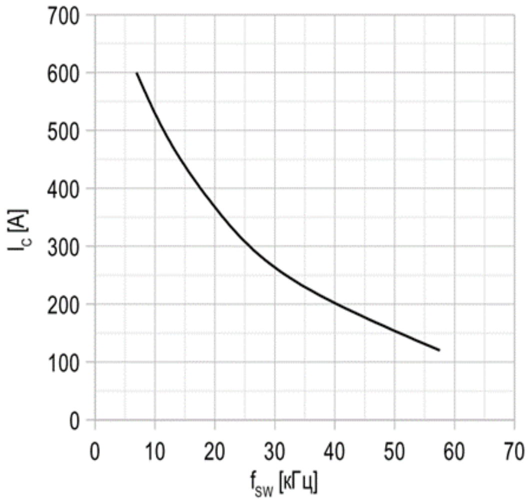


Figure 9. Typical relation between collector current and case temperature for a MIDA-HB12FA-600N module

Static losses in modern IGBT modules mainly depend on the amount and waveform of current. The amount of static losses caused by leakage current in offline state can be neglected in calculations.

Since IGBT modules are normally used as a switch, a diode is included in parallel to the IGBT transistor inside the module. For this reason transistor static losses need to be separated from static losses at the diode.

Calculation of static losses can be based on the relation between voltage drop at the transistor (diode) and current. Sufficient accuracy may be achieved using a linear model of voltage drop at a semiconductor element. It is assumed that the drop is described by relation $V_{(I)}=V_0*I_{avg}+r_d*I_{rms}*I_{rmc}$. If such model is used, static loss power makes $P=V_0*I_{avg}+r_d*I_{rms}*I_{rmc}$, where I_{avg} average current at the transistor (diode), and I_{rms} is root-mean-square current through transistor (diode).

Calculation of dynamic losses is a more complex task.

Dynamic losses at the transistor may be divided into two components: switch-on losses and switch-off losses. Both components depend on many factors such as collector voltage, current at the commutation moment, control voltage from driver, resistor value in the control circuit, chip temperature. Typical relations of commutation losses are shown on Fig. 10.

Dynamic losses at the diode are mainly characterized by losses of reverse recovery and depend on the value of applied reverse voltage, current flowing through the diode until the moment it is switched off, and control signal parameters of an IGBT transistor in serial connection with a diode in the IGBT module. The amount of dynamic losses also depends on the temperature of diode and transistor chips. Average relations between losses of diode recovery are shown on Fig. 11.

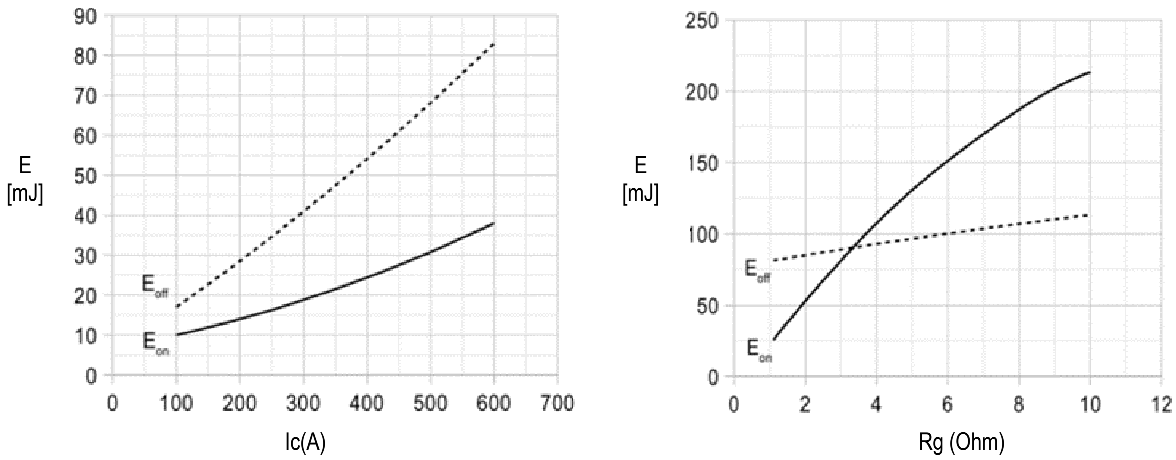


Fig. 10. Power loss at the transistor versus: a — collector current, b — resistance for a MIDA-HB12FA-600N module

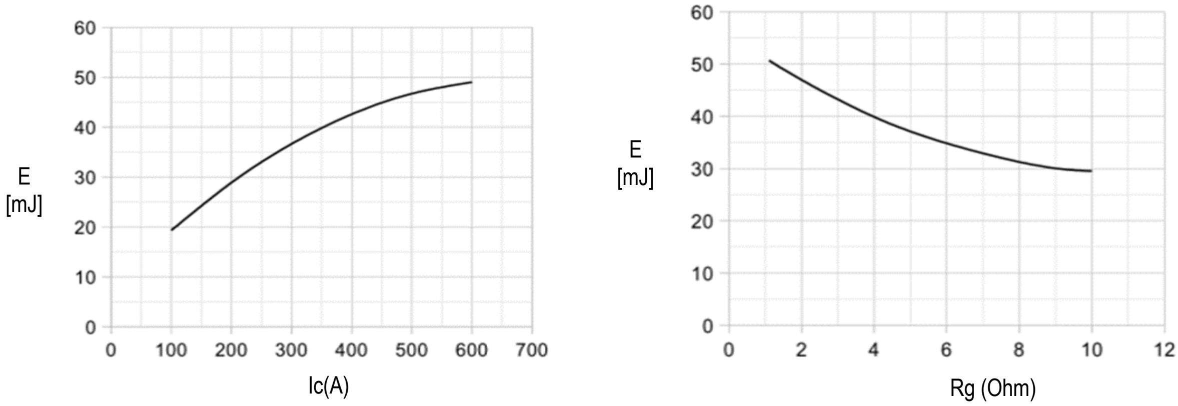


Fig. 11. Power losses: a — from collector current, b — from resistance for a MIDA-HB12FA-600N module.

Dynamic losses are directly related to commutation frequency. Calculations of dynamic losses must take into account current direction during commutation, since not every commutation automatically causes dynamic losses at every semiconductor element of the module.

We suggest the following algorithm to select a suitable type of module:

1. Define nominal and maximal permissible operation voltage in a forward current section;
2. Define the type of used module by classification voltage:

Recommended classes of IGBT voltage for standard industrial power supply systems			
Supply voltage (RMS)	220 V	380 V	690 V
V_{CES} IGBT	600 V	1200 V	1700 V

3. Define the value of maximal converter output current;
4. Define maximal permissible commutation frequency for the maximal converter output current;
5. Select a module of suitable class with a value of nominal current no less than the maximal converter output current;
6. Calculate static and dynamic losses at each semiconductor element of the module in peak modes of the converter operation. Calculations must be based on module chip temperature values close to maximal permissible;
7. Take into consideration thermal resistance of each module component in relation to the module baseplate and thermal resistance between the module baseplate and heatsink. Calculate maximal permissible temperature of the heatsink in the module installation area;

8. Calculate total losses at the module. Calculate heatsink temperature in the modules installation area on the basis of planned heatsink design and maximal permissible temperature of environment;
9. If the calculated temperature does not exceed the estimated value received in Item 7 with appropriate margin, consider the module selection complete;
10. If the margin of heatsink temperature in the module installation area is too high, consider using a module with lower nominal current value. If the module is replaced, redo the heat calculations;
11. If the margin of the heatsink temperature is not enough, consider using a module with higher nominal current value. If the module is replaced, repeat the heat calculations.

3.2 Understanding Datasheets

The purpose of this section is to help understand information resources available for IGBT modules. All the parameters listed in datasheets are explained here. The description is based on data and diagrams for MIAA – HB17FA – 300, however this reference also applies to all other modules.

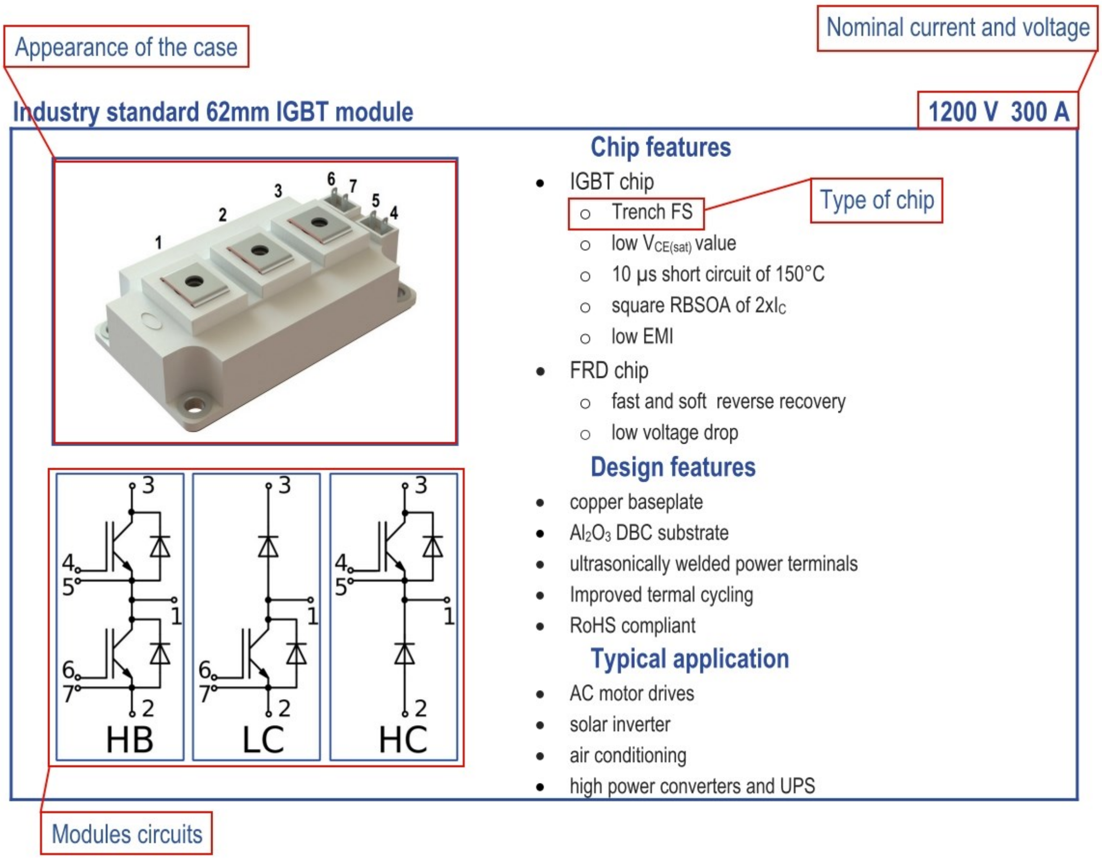


Fig 12. General module description

The figure below shows maximal parameters of the module.

Maximum rated values

Definition	Symbol	Conditions	Value	Unit
IGBT				
Collector-Emitter voltage	V_{CES}	V_{GE} = 0.	1200	V
Collector current (nominal)	$I_{C\ nom}$		300	A
Collector current (maximum continuous)	$I_{C\ 25}$	$T_{vj\ (max)}$ = 175°C; T_c = 25°C.	421	A
	$I_{C\ 80}$	$T_{vj\ (max)}$ = 175°C; T_c = 80°C.	300	A
Repetitive peak collector current*1	I_{CRM}	I_{CRM} = 3 x $I_{C\ nom}$; t_p = 1 ms.	900	A
Short-circuit duration	t_{psc}	T_{vj} = 25°C; V_{GE} = ±15 V; V_{CE} = 720 V; $R_{G\ on}$ = $R_{G\ off}$ = 2.2 Ω; $I_{C\ max}$ < 1600 A.	10	μs
		T_{vj} = 150°C; V_{GE} = ±15 V; V_{CE} = 720 V; $R_{G\ on}$ = $R_{G\ off}$ = 2.2 Ω; $I_{C\ max}$ < 1520 A.	10	
Gate-Emitter voltage	V_{GES}		±20	V
Junction operating temperature	$T_{vj\ (op)}$		-40...+150	ºC
Inverse diode \ Freewheeling diode				
Repetitive peak reverse voltage	V_{RRM}	V_{GE} = 0 V.	1200	V
Forward current (nominal)	$I_{F\ nom}$		300	A
Forward current (maximum continuous)	$I_{F\ 25}$	$T_{vj\ (max)}$ = 175°C; T_c = 25°C.	345	A
	$I_{F\ 80}$	$T_{vj\ (max)}$ = 175°C; T_c = 80°C.	260	A
Repetitive peak forward current*1	I_{FRM}	I_{FRM} = 3 x $I_{F\ nom}$; t_p = 1 ms.	900	A
Junction operating temperature	$T_{vj\ (op)}$		-40...+150	°C
Module				
Storage temperature	T_{stg}		-55...+50	°C
Isolation voltage	V_{isol}	AC sin 50 Hz; t = 1 min.	4000	V

*1 Pulse width and repetition rate should be such that device junction temperature does not exceed maximum T_{vj} rating

Calculated collector current for different temperatures

Calculated forward current of the diode for different temperatures

Fig 13. Maximal permissible module parameters.

Specifications:

Characteristics

Definition	Symbol	Conditions		Value min.	Value typ.	Value max.	Unit
IGBT							
Collector-Emitter saturation voltage	V_{CEsat}	V_{GE} = +15 V; I_C = 300 A; t_u = 1000 μs.	T_{vj} = 25°C	1.82	1.84	1.98	V
			T_{vj} = 150°C	2.40	2.45	2.57	V
Gate-Emitter threshold voltage	$V_{GE(th)}$	I_C = 12 mA; V_{CE} = V_{GE}; T_{vj} = 25°C; t_u = 2 ms.		5.65	6.07	6.45	V
Collector-Emitter cut-off current	I_{CES}	V_{CE} = 1200 V; t_u = 20 ms; V_{GE} = 0.	T_{vj} = 25°C	37.8	55.5	300	μA
			T_{vj} = 150°C	1.40	1.55	4.00	mA
Gate-Emitter leakage current	I_{GES}	V_{CE} = 0; V_{GE} = ±20 V; T_{vj} = 25°C; t_u = 30 ms.		8.36	11.6	400	nA
Input capacitance	C_{ies}	V_{CE} = 10 V; V_{GE} = 0 V; f = 1 MHz; T_{vj} = 25°C.		-	27.6	-	nF
Output capacitance	C_{oes}			-	2.00	-	nF
Reverse transfer capacitance	C_{res}			-	2.40	-	nF
Total gate charge	Q_G	I_C = 300 A; V_{CE} = 600 V; V_{GE} = - 8÷15 V.		-	3052	3255	nC
Internal gate resistance	R_{Gint}	T_{vj} = 25°C.		-	2.50	-	Ω
Turn-on delay time	$t_{d(on)}$	V_{CE} = 600 V; V_{GE} = ±15 V; $I_{C\ max}$ = 300 A; R_G = 2.2 Ω; L = 56 nH.	T_{vj} = 25°C	373	380	490	ns
			T_{vj} = 150°C	485	494	560	
Rise time	t_{ri}		T_{vj} = 25°C	59	64	85	ns
			T_{vj} = 150°C	73	76	90	
Turn-on energy	E_{on}		T_{vj} = 25°C	9.60	12.0	22.0	mJ
			T_{vj} = 150°C	24.5	28.0	34.0	
Turn-off delay time	$t_{d(off)}$		T_{vj} = 25°C	481	536	690	ns
			T_{vj} = 150°C	673	693	770	
Fall time	t_{fi}		T_{vj} = 25°C	209	234	290	ns
			T_{vj} = 150°C	276	288	390	
Turn-off energy	E_{off}		T_{vj} = 25°C	28.6	29.0	35.0	mJ
			T_{vj} = 150°C	36.9	37.8	46.0	
Collector-emitter threshold voltage	V_{CE0}	V_{GE} = +15 V; T_{vj} = 150°C; I_{CE1} = 75 A; I_{CE2} = 300 A; t_u = 1000 μs.		0.83	0.85	0.89	V
On-State slope resistance (IGBT)	r_{CE0}			5.20	5.34	6.00	mΩ
Thermal resistance junction to case	$R_{th(j-c)}$	DC; I_{CE} = 300±20 A; I_{test} = 1.0 A; V_{GE} = +15 V.		-	0.080	0.120	K/W
Inverse diode \ Freewheeling diode							
Forward voltage drop	V_F	I_F = 300 A; V_{GE} = 0; t_u = 500 μs.	T_{vj} = 25°C	1.83	1.87	2.10	V
			T_{vj} = 150°C	2.04	2.08	2.23	V
Reverse recovery time	t_{rr}	V_{GE} = ±15 V; V_{CE} = 600 V; $I_{C\ max}$ = 300 A; L = 56 nH; $R_{G\ on}$ = 2.2 Ω.	T_{vj} = 25°C	127	132	150	ns
			T_{vj} = 150°C	188	195	245	ns
Peak reverse recovery current	I_{rrM}		T_{vj} = 25°C	232	244	290	A
			T_{vj} = 150°C	291	301	340	A
Reverse recovered charge	Q_{rr}		T_{vj} = 25°C	17.0	19.0	22.0	μC
			T_{vj} = 150°C	32.0	33.0	40.0	μC
Reverse recovery energy	E_{rec}		T_{vj} = 25°C	9.00	10.0	14.0	mJ
			T_{vj} = 150°C	24.0	25.0	29.0	mJ
Threshold voltage	$V_{(T0)}$	T_{vj} = 150°C; V_{GE} = 0; I_{CE1} = 75 A; I_{CE2} = 300 A; t_u = 1000 μs.		0.82	0.83	0.88	V
Forward slope resistance	r_T			4.04	4.17	4.60	mΩ
Thermal resistance junction to case	$R_{th(JC-D)}$	DC; I_{CE} = 250±20 A; I_{test} = 1.0 A; V_{GE} = +15 V.		-	0.156	0.180	K/W

Parameters are specified for one transistor

Dynamic characteristics of the module

Fig. 14. Specifications of IGBT and FRD chips

Starting from Page 4, the datasheets contain graphs of all key parameters and their measurement conditions. Pay attention to graphs of dynamic properties of the transistor. Besides, take into consideration graph of the gate charge to make correct calculation of the needed driver capacity.

The last page of the datasheets contains dimensions and part numbering guide. Since parameters for various circuits are identical, while capacity, charge and gate resistance are listed for one switch, datasheets may be used for all available (for a given packaging) circuits.

3.3 Key Parameters

Maximal collector current – I_C. Datasheets of Proton-Electrotex indicate this parameter at two temperatures: normal 25°C and increased 80°C. For a more detailed analysis turn to the datasheet graph “Collector current vs casing temperature”.

Engineers must ensure nominal thermal conditions to prevent the chip overheating and early failure of the transistor.

Amplitude and duration of the current surges must not exceed the value stated in the transistor datasheet. Repetitive peak current must not exceed 70–80% of I_C. Duration of short-circuit current caused by a load emergency must not exceed 10 μs.

Collector-emitter voltage – V_{CE}. V_{CE} defines the class of transistor. Voltage surges in IGBT modules must always be avoided, however the transistor is capable of withstanding 5-10-fold non-repetitive current surges. Section 3.1 includes a table of recommended IGBT classes for standard industrial power supply networks. Always provide for a voltage margin. For example, rectifying standard voltage from a 380V three-phase network results in 540V received by the transistor. In this case it is not recommended to use a 600V IGBT, since the voltage margin is too low and switches may not withstand commutation surges throughout their operation.

Maximal operating collector-emitter voltage – V_{CES}. Physical meaning of the parameter is defined in Appendix 1, but it’s worth mentioning that normal operation of IGBT requires peak operating voltage not to exceed 80% of nominal, and normal operating voltage not to exceed 60% of nominal.

Gate charge – Q_G. Gate charge is needed to calculate properties of the transistor control driver.

Saturation voltage – V_{CEsat}. This is loss of voltage in a completely open transistor. Value of this parameter for mid-frequency IGBTs is below 3V.

Formula to calculate current for IGBT is as follows (assuming form factor k=1)

$$I_C = \sqrt{\left(\frac{V_{CE0}}{2 * r_{CE0}}\right)^2 + \frac{T_j - T_C}{R_{th(j-c)} * r_{CE0}}} - \frac{V_{CE0}}{2 * r_{CE0}}$$

where V_{CE0} – collector-emitter threshold voltage;
r_{CE0} – dynamic resistance;
$R_{th(j-c)}$ – thermal resistance transition-case of the IGBT;
T_j – maximal junction temperature of the chip;
T_C – casing temperature.

Calculation of diode current is made in identical manner, except replacing r_{CE0} with r_T, replacing V_{CE0} with $V_{(T0)}$, and replacing $R_{th(j-c)}$ with $R_{th(JC-D)}$ – thermal resistance of the diode.

Resistance of the thermistor — R_t. This parameter applies only to modules in MIDA housing. These modules have an integrated thermistor with a negative temperature coefficient of resistance (NTC-thermistor) (pins 5-6), which is used to measure the substrate temperature of the IGBT module. The thermistor can only measure the temperature of the module housing in stable state.

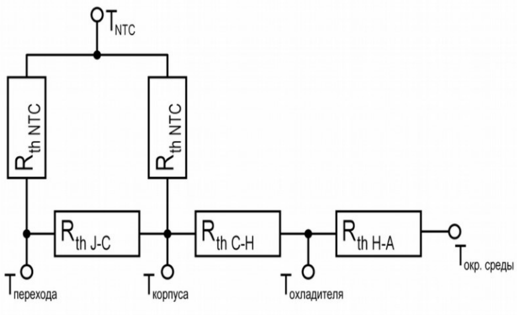


Figure 15: Equivalent circuit of the NTC-thermistor.

The equivalent circuit of the NTC thermistor is shown in Figure 15, while the location of the thermistor inside the module case in Figure 16.

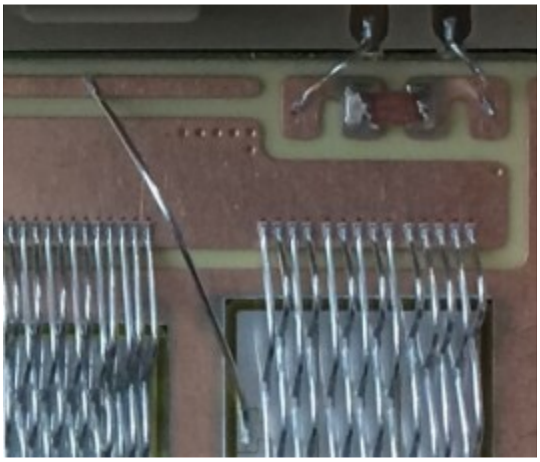


Figure 16. Location of the NTC-thermistor inside the MIDA module.

A thermistor connected according to the resistive divider circuit changes its resistance relative to the temperature of the substrate. The change in voltage at the output of the divider can be used to calculate the actual value of the resistance at the thermistor (R_{NTC}). One can find the temperature of the thermistor by inserting R_{NTC} into the following formula:

$$T_{NTC} = 1/\left(\frac{\ln(Rntc/Rt)}{B} + \frac{1}{T0}\right)$$

where:

T_{NTC} – temperature of the thermistor;

R_{NTC} – resistance at the thermistor;

R_t – resistance at nominal temperature;

T_0 – nominal temperature;

B – B-parameter = 3375K±2% (only for thermistor in MIDA modules).

3.4 Protection of IGBT switches

In order to protect modules from commutation overloads in the collector-emitter circuit it is recommended to use snubber RC- and RCD-circuits placed directly on power terminals, Fig. 17:

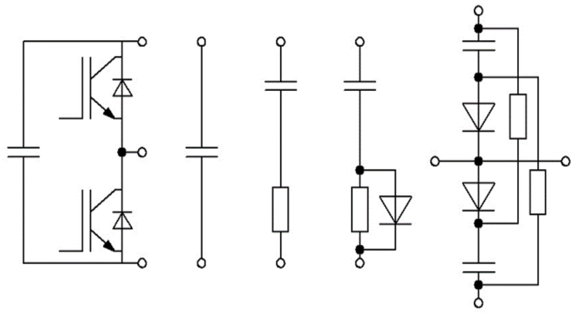


Fig. 17. Typical connection layouts of snubber circuits.

If several modules are connected to the same driver, maximal value of the load gate total charge ($n*Q_G$) must be lower than values allowed for the driver, while equivalent resistor total charge (R_g/n) must be higher than values allowed for the driver. Average value of I_{AV} driver power source output current must meet a relation $I_{AV} > n*Q_g*f_{SW}$

where f_{SW} is maximal commutation frequency; n – number of drivers; Q_g – gate charge.

In order to eliminate ground loop it is recommended to install a resistor in the emitter signal circuit. The resistor must have nominal resistance from 0.5 Ohm to 1.2 R_G allowing to limit such current and dampen parasitic circuits.

Besides, in order to remove load from modules with a significant difference in switching delay it is recommended to use symmetrized inductances for even distribution of currents. The formula for inductance calculation is

$$L_{min} = \frac{V_{CC} * dt_{max}}{\Delta I_{out}}$$

where dt_{max} is maximum difference in switching time;

ΔI_{out} – acceptable deviation from average current value;

V_{cc} – power bus voltage.

In order to limit shortcut current it is recommended to include a protection circuit between gate and emitter, Figure 18. It would prevent increase of V_{GE} in a case of rapid growth of I_C and the transistor leaving the state of saturation.

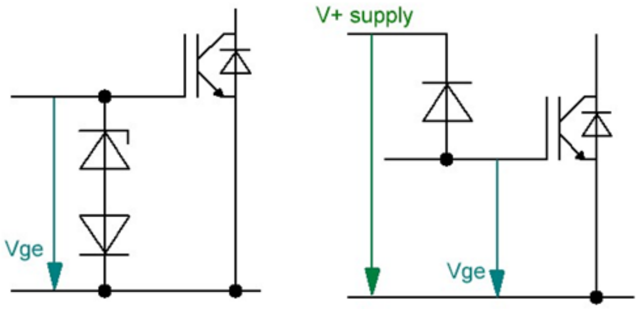


Fig. 18. Typical configurations of gate voltage limitation.

In order to prevent high switching voltage surges after leaving short-circuit mode and to avoid module breakdown it is recommended to take the following measures:

- Reducing voltage at the driver terminal at a lower rate than during module turn off in normal operation;
- Module shutdown in two stages:
  1. Driver terminal is changed to a third state and a resistor is connected to the gate-emitter circuit;
  2. The module is rapidly shut down after the collector current is reduced to a nominal value.

IGBT modules are sensitive to electrostatic breakdown. For this reason, it is required to fulfill the following requirements during their transportation, installation and operation:

- To protect the gate from static breakdown directly in the circuit it is required to connect a 10 … 20 kOhm resistor in parallel to the gate-emitter circuit;
- When modules are being transported, gate and controlling emitter terminals should be shorted out with conductive jumpers that must not be removed until the module is installed in the system;
- Mounting works involving IGBT modules are only permissible if the staff is grounded with a resistor with resistance value of no less than 1 MOhm (antistatic wrist strap);
- All tooling and fixtures that the module may come in contact with must be grounded;
- Make sure that electrostatic charge is removed from measurement equipment before taking any measurements or tests.

3.5 Cooling

Effective cooling ensures long service life of the device. Heat generation as a destructive factor may not show up immediately and the device may keep working for some time in nominal mode. In order to select operation modes ensuring reliable operation of the module it is necessary to make heat calculations. Heat calculations in first approximation may be based on heat model represented on Figure 19.

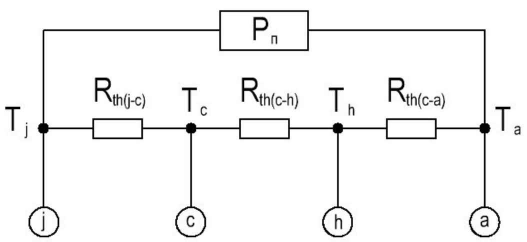


Fig. 19. Thermal Model

Thermal model is comprised of three thermal resistances: $R_{th(j-c)}$ (junction — case), $R_{th(c-h)}$ (case – heatsink) и $R_{th(h-a)}$ (heatsink – ambient). Value $R_{th(c-h)}$ also includes heat resistance of heat conductive material $R_{th(p)}$. Often it is indicated in datasheets for related material:

$$R_{th(p)} = \frac{\delta_p}{\lambda^* S_p},$$

where δ_p is thickness of heat-conducting layer;

λ — thermal conductivity of the material W/m * C°;

S_P – thermal interface area (one side) (insert or paste).

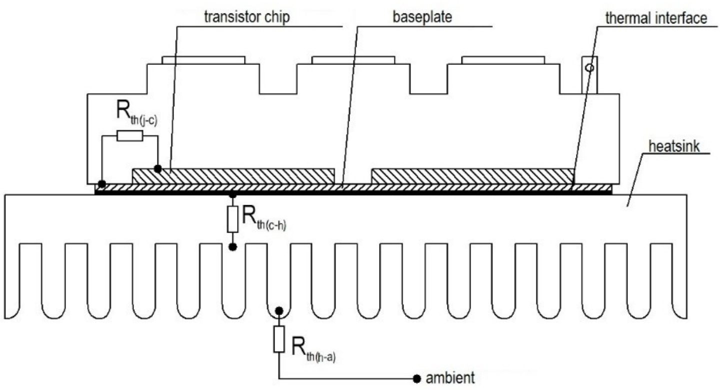


Fig. 20. Heat model of a semiconductor element on a heatsink.

Thermal model shown on Figure 17 allows to determine T_j.

$$T_j = T_a + (R_{th(j-c)} + R_{th(c-h)} + R_{th(h-a)})^* P_l,$$

where P_l is power of loss at the semiconductor element.

If there are several modules installed on one heatsink, the heat model must be modified. The modified heat model is shown on Figure 21.

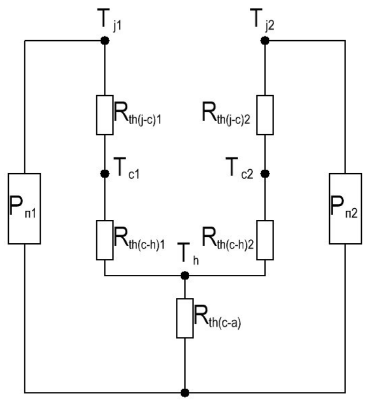


Fig. 21. Heat model of several modules.

3.6 Control

Design of control systems must be based on several simple rules to ensure good performance of IGBTs throughout their entire service life:

- fast rises and falls of control impulses to reduce heat losses during switching;
- ensuring fast recharge of the transistor’s input capacitance with a high peak value of the control current;
- compatibility of the driver input with digital control signals TTL/CMOS;
- ensuring “floating” control potential of “upper” switch in half bridge layout.

Recommended operating parameters of an IGBT driver:

- Value V_{GE} at turn on must be equal to +15±10% V (to ensure minimal losses in online state);
- Value V_{GE} at turn off must be from –7V to –15 V (to reduce losses during shutdown and ensure high resistance of the transistor to dv/dt);
- Maximal gate-emitter voltage must not exceed ±20 V;
- Duration of voltage pulse fronts at the driver terminal must be at least 5…10 times lower than the switching time values stated in datasheet for the related device;
- Recommended internal resistance of a control driver must be selected within acceptable values stated for the related device taking into consideration minimal dynamic losses and excluding overloads caused by inductance reload;
- Latch out voltage must guarantee complete shutdown of the module in any operation conditions;
- Control circuit must have minimal length. It is recommended to use twisted pair wire or directly mount the driver board on the module control terminals;
- Control circuits must be isolated from potential interference sources;
- Power voltage must be applied in the following order:
    1. Control system and drivers;
    2. IGBT modules.

Method of manufacturing complementary output cascades of the driver may create a parasite thyristor p-n-p-n structure that can “latch up” and cause burnoff the driver’s output cascade. You can avoid this if you connect general output of the chip, source of a high-grade transistor and negative contact of a smoothing filter blocking transformer to the same bus.

Recommendations on Installing the Driver

Control terminals of MIAA and MIFA-type IGBT modules are designed for clamping contacts compliant to DIN 46244 – A 2.8–0.5 (faston) (Figure 22). Axial mounting force applied to control terminals must not exceed 60 N, while engaging and disengaging force must not exceed 53 and 13 N respectively.

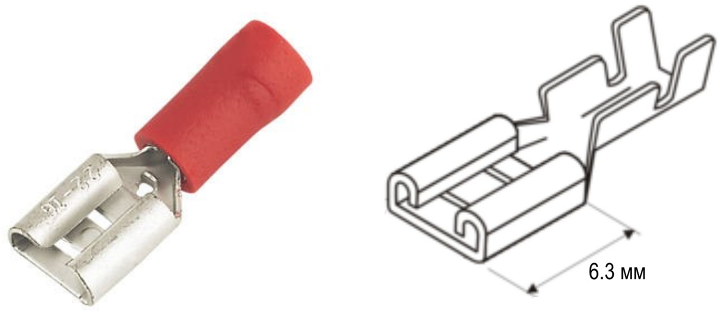


Figure 22. Faston-type terminal.

Drivers for a MIDA-type module must be mounted using self-tapping screws in location 1 (Figure 23a), 4 to 10 mm long and 2.5 mm in diameter (DIN 7981 / GOST 11650-80 "Self-tapping screws with a semicircular head and a pointed end for metal and plastic. Design and dimensions”), taking into account the thickness of the driver board. A drawing of the mounting hole is shown in Figure 23b. In order to prevent damage to the housing, it is necessary to observe the alignment of the holes of the case and the printed circuit board. Mounting is recommended to do manually with a force of 0.4 ± 0.05 N·m.

To solder the control contacts in location 2 (Figure 23a) it is recommended to use a manual soldering iron with power of at least 90 W using a soft soldering alloy for manual soldering of electronic equipment (for example, Sn37Pb63; SAC305; Sn96Ag4) in modes recommended by the manufacturer of soldering materials. To improve wettability, it is recommended to additionally use medium-active (RMA) non-wash flux, for example EFD 6-412-A. At the same time, avoid overheating the control contacts during soldering that may result in damage to the housing. To do this, do not exceed the temperature of the soldering iron over 300°C and keep the time of each soldering contact under 10 seconds.

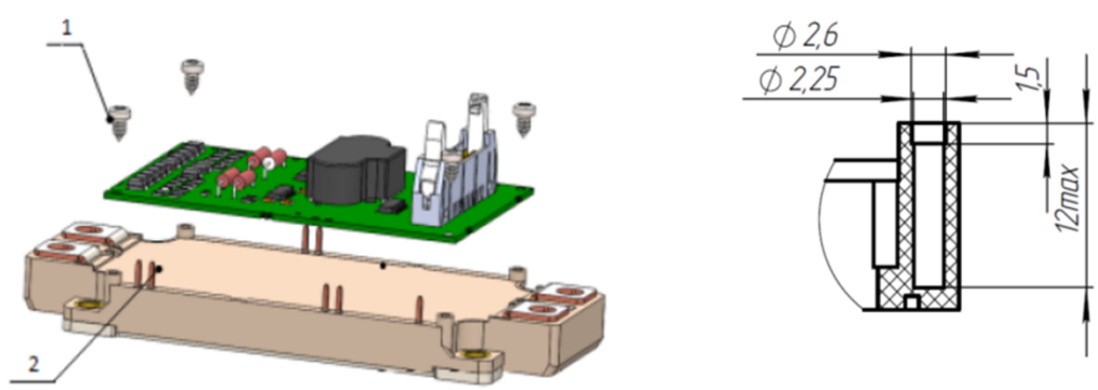


Figure 23. a — scheme of mounting, b — mounting hole

Attention! Control terminals of MIAA and MIFA-type IGBT modules are not designed for soldering! However if it is absolutely necessary, Proton-Electrotex recommends using active fluxes to remove oxides from the surface of terminals, for example, such as type 1.1.3.A DIN EN 29454. They are neutral and do not require wet rinsing after soldering. It is also possible to use lead-free material Sn96Ag04 with a core composed of non-corrosive flux based on modified rosin that does not require rinsing. Temperature of soldering must not exceed 260°C at duration of not more than 10 seconds. The soldering iron must be grounded.

Please follow ESD recommendations when installing the driver to prevent an electrostatic breakdown (see last paragraph of Item 3.4).

3.7 Parallel Connection

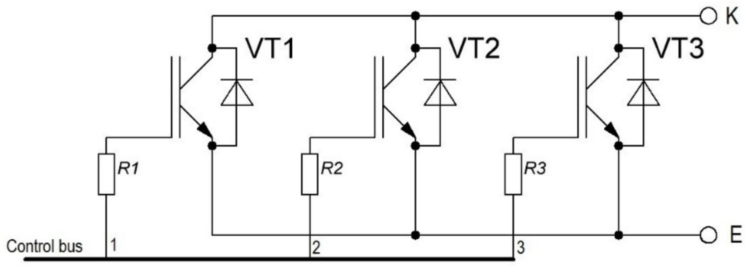


Fig. 24. An example of IGBT modules parallel connection (high side of the bridge)

There are many cases when it is necessary to switch significant current with values exceeding threshold current value for the given type of transistor. In such cases you may install several lower -current transistors in parallel connection.

Control circuit must have low internal resistance.

To avoid incorrect operation of the circuit and resulting burnoff of the switches try to select an IGBT with matching threshold voltage. Any difference in threshold voltage affects distribution of current in parallel to enabled transistors. The ideal solution is parallel connection of transistors from the same batch manufactured in identical conditions.

All devices must be placed on the same heatsink as close to each other as possible. It ensures even heat dissipation. Current load must not exceed 80-90% to provide a certain margin for asymmetrical distribution of currents with parallel connection.

Do not forget that transistors in parallel connection have increased input capacity. It means that circuit controlling the transistors in parallel connection must provide the necessary time of switch commutation.

In order to eliminate influence of transistor gates on each other it is recommended to install a separate resistor in control circuit of each gate. It is selected on the basis of recommended values taking into consideration using modules in the circuit.

Then it is necessary to define current provided by the driver. To achieve this divide the value of R_g by the amount of parallel transistors.

Increasing the length of conductors between the transistors may cause higher parasitic inductance of the installation, resulting in dangerous voltage surges and uncontrollable behavior of switches.

Threshold voltage of parallel transistors cannot be achieved for all devices at the same time, so separate switches accept a part of load current from those IGBTs that were switched off earlier.

As it follows from the above, IGBTs must be selected on the basis of voltage in open state. If two modules are connected in parallel, sorting by voltage in open state is not required. Thanks to their high overload capacity IGBTs are resistant to current surges typical for start of switching.

3.8 Mounting the Modules

To ensure efficient heat exchange between insulating substrate of the power module and heatsink their surfaces must meet the following requirements:

- there must not be any hard particles on them;
- the surfaces must be degreased before the installation;
- surface roughness must not exceed 10 µm (Rz: < 10 µm);
- flatness deviation must not exceed 20 µm at 100 mm distance.

The following recommendations must be met when the modules are screwed:

- Fastening screws must be tightened with equal force and specified torque;
- It is recommended to use electronically controlled tooling or at least an electric screwdriver with low rotation speed;
- It is not recommended to use pneumatic screwdrivers because of their low precision.

After installation is complete it is recommended to protect the fixtures with anticorrosive greases meeting DIN 51825.

Modules tightening procedure:

1. Lightly fixate the module with two diagonal screws. Slightly press the module down with your hand and smoothly distribute paste with light movements.
2. Tighten the crossline screws with torque 0.5 Nm ±15%.
3. Wait at least 30 min. Let the paste spread out and fill in cavities.
4. Tighten the screws with torque 3…5 Nm in the same order.

IGBT modules are mounted to the cooling unit with high hardness screws with obligatory usage of flat and spring washers. The sequence of tightening the screw is illustrated on Figure 25.

Screws used for the installation must not deform at higher temperature (like brass screw). It may cause additional stresses and cracking of internal module components.

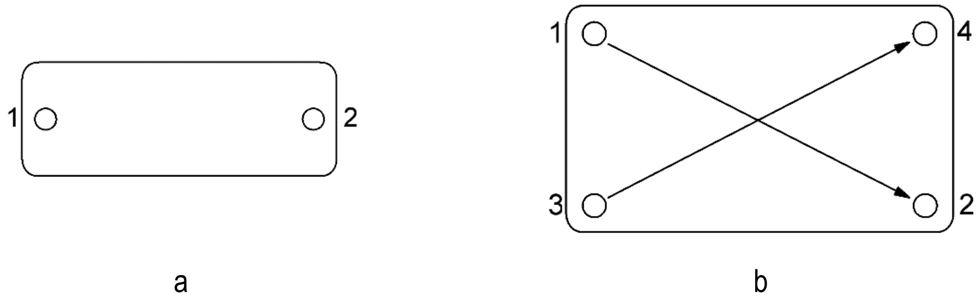


Fig. 25. Sequence of tightening the screws

The modules are uninstalled in reverse order.

3.8.1 Thermal interface materials

Thermally conductive materials (TIM) are used to increase the efficiency of heat transfer from the base of the module to the heatsink. 3 types of materials are most common:

1. Thermal paste
2. Phase change materials (PCM)
3. Graphite thermal padding

Thermal paste is most common among electronics developers. Thermal pastes are typically silicone-based lubricants. This type of material has a low thermal resistance, is good at filling the cavities and caverns of the surfaces of the heatsink and the device. However, despite its advantages, it also has a number of disadvantages, such as: drying and cracking after thermal cycling, the pump effect, as well as thermal pastes being “messy” materials that can contaminate adjacent components and surfaces.

Requirements to the thermal paste:

- The heat paste must not include any hard particles to avoid damaging the surface;
- The heat paste must preserve its properties for the entire service life of the device;
- Maximal temperature of the paste must be at least equal to the maximal temperature of the device under load (temperature margin at least 10%);
- Service life of the paste must be at least equal to the service life of the module.

Surfaces of the device and radiator must be cleaned and degreased before the heat paste is applied. It is recommended to use lint free cloth and gloves during the cleaning. Avoid putting the paste on the cooling unit since paste in threaded openings may lead to incorrect tightening torque.

Thickness of the paste layer may be evaluated with a wet film comb, see Fig. 26. The paste thickness is defined as an average between the maximal "covered" (or "wet") tooth and the minimal "uncovered" (or "dry") tooth.

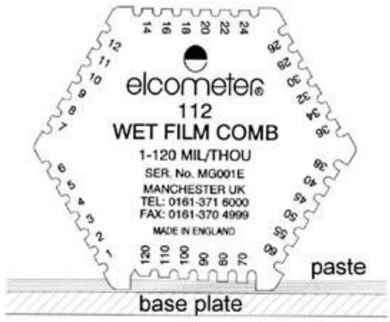


Fig. 26. A wet film comb used to measure thickness of paste

PCM is a paraffin-based polymer. When heated, the paraffin undergoes a phase transition from a solid to liquid or gel. The melting process occurs when the melting temperature is exceeded, usually in the range from 45°C to 70°C. PCMs combine the advantages of thermal pads with properties of thermal pastes. Like thermal pastes, PCMs provide low thermal resistance, but do not have problems with bleeding, drying out and other types of material degradation. PCM can be supplied both on tear-off liners and in paste containers diluted with solvent. Using modules with pre-applied PCM allows to avoid the messy process of applying TIM to the device.

Graphite thermal pads are made by pressing and rolling graphite with a binder. When pressure is applied, the material is distributed over the surface filling any gaps and irregularities. Unlike pastes, thermal pads can be reused. Graphite thermal pads are characterized by a high value of thermal conductivity and a wide range of operating temperatures from -60 to +500°C.

It is recommended to use the following materials with power modules produced by PROTON-ELECTROTEX:

- Thermal paste: КПТ-8, Wacker P12.
- PCM: HALA TPC-Z-PC-P7, Loctite TCP 4000 PM, PSX-Pm
- Graphite thermal pads: Panasonic Soft PGS.

TIM layout

In order to avoid excessive waste of thermal paste or TIM and to prevent their squeezing out when installing the module, it is recommended to apply the material using a honeycomb stencil.

PROTON ELECTROTEX has developed special stencils for each type of IGBT module. These stencils are made of stainless steel with a thickness of 100 microns. Layout of the stencils allows you to avoid excessive squeezing of TIM from beneath the module and prevents the material from getting into the mounting holes. This eliminates the need for tightening the fixing screws after thermal cycling. The pattern of the stencil ensures uniform distribution of the material across the entire base of the module, excluding places where direct metal-metal contact is ensured.

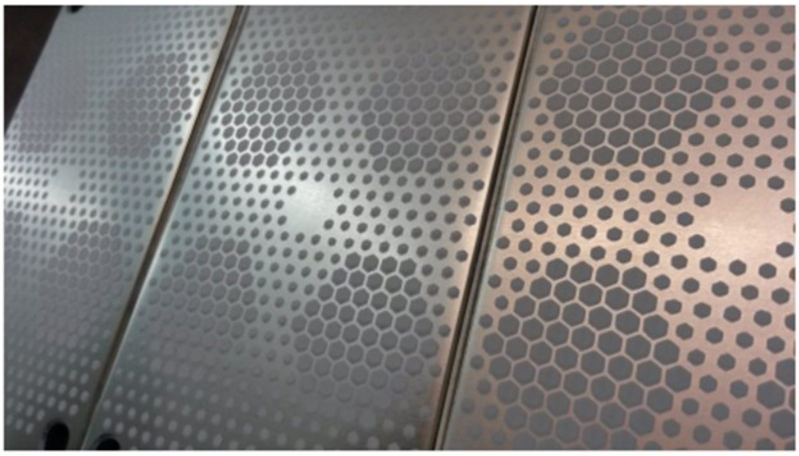


Figure 27. PCM applied to MIAA modules with a stencil.

The PROTON-ELECTROTEX company is ready to provide drawings of its stencils to the customers. Feel free to request them by phone +7 (4862) 44-04-55 or email inbox@proton-electrotex.com, marketing@proton-electrotex.com.

TIM is applied through the stencil using a stencil printing machine (automatic or semi-automatic). It is also possible to apply the material manually, however, this requires special equipment to lock the stencil and the module in it. It is necessary to eliminate any displacement relative to the plane of the module base in order to ensure a uniform cellular pattern. When applying the material, the stencil should be placed close to the base of the module. After application carefully separate the stencil and the module. A hard plastic squeegee (squeegee canvas) should be used for application. Soft squeegees are not recommended because they have a negative effect on the thickness of the material after application.

3.8.2 Connection Buses

The simplest method to reduce parasitic inductivity of powered conductors is placing them in immediate proximity so that their inductances compensate each other.

In order to avoid voltage surges at power switches during switching of high frequency currents buses must provide:

- Identical topology in all parallel circuits for static and dynamic current balancing;
- Minimal inductivity of source current circuit. It is recommended to use flat bifilar buses separated with an isolator;
- Minimal resistance values;
- Sufficient cross section to provide acceptable current density;
- Sufficient isolation voltage.

If modules are connected with a bus take into consideration heat expansion of the buses or use flexible buses..

The ideal solution is using a multilayer bus. Multilayer power bus relies on even distribution of current among the layers, while upper and lower layers screen internal ones, ensuring low interference.

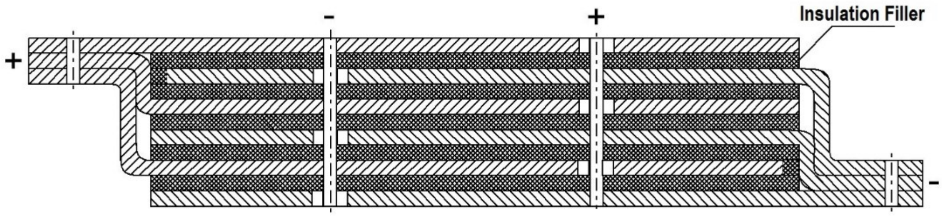


Fig. 28. Multilayer bus.

Besides, it’s worth mentioning filter capacitors here since they are located directly on power buses.

Place filter capacitors in parallel direction of current flowing in the power conductors. It reduces parasitic inductance by minimizing the surface area of “current loop”. Besides, replacing a high-capacity capacitor with two lower-capacity models allows to reduce the area of the current loop

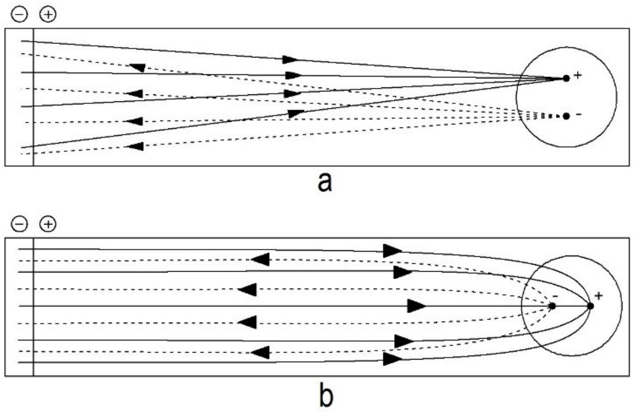


Fig. 29. Placement of capacitor terminals perpendicular to the current direction - a,
placement of capacitor terminals in parallel to the current direction - b.

3.8.3 Mechanical and Environmental Impact

Structure of the modules includes fragile ceramic details. For this reason, the following is prohibited:

- Bending power and control terminals or applying significant mechanical stresses to them to avoid mechanical damage of modules;
- Dropping modules or hitting their casing or baseplate;
- Module terminals including places where they are attached to the module must be firmly attached.

- Applying engaging force of more than 23 N to clamping contacts.

- Exceeding the following torque values applied to power terminals:

  * for modules in MIAA cases – 2.5±0.25 Nm;

  * for modules in MIFA cases – 2.0±0.25 Nm;

  * for modules in MIDA cases – 4.50±1.50 Nm.

To ensure normal operation of the modules it is recommended to meet the following conditions (climatic category N, placement category 2 according to GOST 15150-69):

- Modules must operate in conditions preventing moisture condensation on their cases;

- Modules must be protected from direct drops of water;

- Modules must be protected from gases contributing to corrosion of terminals and substrates (acid vapors, sulfur dioxide, chlorine gas and so on).

APPENDIX 1
LIST OF IGBT MODULE PARAMETERS

Designation	Parameter	Parameter description
V_{CES}	Collector-Emitter voltage	Collector-emitter voltage at which the collector current has a specified low (absolute) value with gate-emitter short-circuited
I_C	Collector current (maximum continuous)	Maximum continuous collector current
I_{CRM}	Repetitive peak collector current	Maximum value for rectangular pulses with specified pulse duration and duty cycle.
t_{psc}	Short-circuit duration	Maximal period of IGBT short-circuit load state
V_{GES}	Gate-Emitter voltage	Maximal voltage between gate and emitter. Collector-emitter are shorted out.
V_{RRM}	Repetitive peak reverse voltage	Maximal instantaneous value of reverse voltage, including repetitive, but excluding non-repetitive surges.
I_F	Forward current (maximum continuous)	Continuous forward current of the diode.
I_{FRM}	Repetitive peak forward current	Maximal value of repeating diode peak current.
RBSOA	Reverse bias safe operating area	Collector current versus collector emitter voltage where the IGBT is able to turn-off without failure
V_{CEsat}	Collector-Emitter saturation voltage	Collector-emitter voltage under conditions of gate-emitter voltage at which the collector current is essentially independent of the gate-emitter voltage
$V_{GE(th)}$	Gate-Emitter threshold voltage	Gate-emitter voltage at which the collector current has a specified low (absolute) value
I_{CES}	Collector-Emitter cut-off current	Collector-emitter current at a given collector-emitter voltage in closed state.
I_{GES}	Gate-Emitter leakage current	Leakage current into the gate terminal at a specified gate-emitter voltage with the collector terminal short-circuited to the emitter terminal
C_{ies}	Input capacitance	Capacitance between the gate and emitter terminals with the collector terminal short-circuited to the emitter terminal for a.c.
C_{oes}	Output capacitance	Capacitance between the collector and emitter terminals with the gate terminal short-circuited to the emitter terminal for a.c.
C_{res}	Reverse transfer capacitance	Capacitance between the collector and gate terminals

Q_G	Total gate charge	Charge required to raise the gate-emitter voltage from a specified low to a specified high level
R_{Gint}	Internal gate resistance	Internal series resistance
$t_{d(on)}$	Turn-on delay time	Time interval between the beginning of a voltage pulse across the input terminals which switches the IGBT from the off-state to the on-state and the beginning of the rise of the collector current
t_r	Rise time	Time interval between the instants at which the rise of the collector current reaches specified lower and upper limits, respectively, when the IGBT is being switched from the off-state to the on-state
E_{on}	Turn-on energy	Energy dissipated inside the IGBT during the turn-on of a single collector current pulse
$t_{d(off)}$	Turn-off delay time	Time interval between the end of the voltage pulse across the input terminals which has held the IGBT in its on-state and the beginning of the fall of the collector current when the IGBT is switched from the on-state to the off-state
t_f	Fall time	Time interval between the instants at which the fall of the collector current reaches specified upper and lower limits, respectively, when the IGBT is switched from the on-state to the off-state
E_{off}	Turn-off energy	Energy dissipated inside the IGBT during the turn-off time plus the tail time of a single collector current pulse
$R_{th(j\text{-}c)}$	Thermal resistance junction to case (baseplate)	Maximum value of thermal resistance junction to a specified reference point at the case (base plate)
V_F	Continuous forward voltage	Voltage across the terminals which results from the flow of current in the forward direction
t_{rr}	Reverse recovery time	Duration of switching a diode from a given forward current to a given reverse voltage starting from the moment when the current passes zero value to the moment when reverse voltage (or its linear approximation) reaches a defined value after reducing from maximal peak value.
I_{RRM}	Repetitive peak reverse current	Highest instantaneous impulse reverse current of a diode in closed state, excluding current during diode recovery.

Q_{rr}	Reverse recovered charge	Charge flowing through external circuit in an-ode (cathode) of the diode throughout the time of its reverse recovery.
E_{rec}	Reverse recovery energy	Diode losses energy in transition process of reverse recovery.
$V_{(TO)}$	Threshold voltage	Value of the forward voltage obtained at the intersection of the straight line approximation of the forward characteristic with the voltage axis
r_T	Forward slope resistance	Value of the resistance calculated from the slope of the straight line approximation of the forward characteristic

PROTON-ELECTROTEX

www.proton-electrotex.com

2020