High Power Dual Pack with High Reliability

Mechanical design of a converter will become much easier

The PrimePACK™ housing could become the new cost-effective standard for 2 in1-packages, which provides many mechanical, thermal and electrical advantages.

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Until now high power modules (HPM) in the well-known standard-housings rated for 1200A to 3600A at 1200V or 1700V with footprint 130*140 [mm] or 190*140 [mm] were only available in single switch configuration.
In other standard housings like 62mm-package, EconoDUAL™ or SEMIX3®-package with 1200V blocking voltage the maximum available rating is 600A from Fuji Electric.
With standard packages, up to now the gap has been filled out only by using the 130*140 [mm] HPM for 600A, 800A or 1200A with two separated switches. But in this case, it could only be used as a pair of arm when they were externally connected by separate bus bars. Of course, the connection of upper and lower arm is less inductive when this is provided inside the module itself. Furthermore, the mechanical design of a converter unit will become much easier and more cost efficient. Therefore many suppliers' specific solutions have been introduced to the market without multiple source alternatives for customers.
But now the new PrimePACK™ housing could become the new cost-effective standard for 2in1-packages, which provides many other mechanical, thermal and electrical advantages to be presented in this article.

Mechanical properties

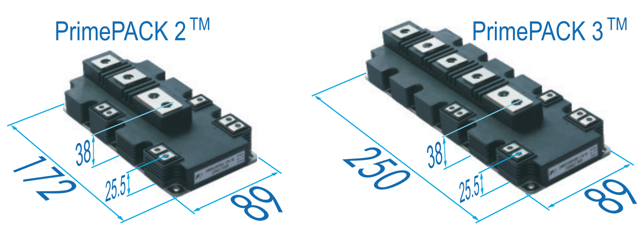


Figure 1: Mechanical dimensions

The PrimePACK™ is available in two different package sizes, called PP2 and PP3 see figure 1. PP3 is longer than PP2 and has got two DC-link terminals. As one can see from the front of the module the first terminal pairs are at the same position, both in the PP2 and in the PP3. Therefore it is possible to use different converter power ratings with the same mechanical design. According to the conventional high power modules the module height is 38mm.

The advantage of the slim shape is the easy parallel arrangement e.g. three modules for the widely used 2-level voltage source inverter. On the lower section at the front, a gate drive board can be mounted to drive upper arm and lower arm without being covered by a busbar The DC-terminals in the rear are free for the connection to the DC-link. It is possible to use a 3-layer bus bar for an AC and DC connection to cover all terminals. On the other hand, using a 2-layer bus bar would leave the AC-terminal free for separated connection. In any case, the specific configuration of each component does not mechanically affect the other one. Therefore, mounting, designing and maintenance are much easier and more cost-efficient. In addition, the reliably and mechanically stable connections are ensured by using M8 screws to fix the DC-link-bus bar respectively the phase output. For the gate drive board M4 screws guarantee a safe connection even under very rough conditions.

INTERNAL STRUCTURE

Ultrasonic welding

One of the challenges for the new package was to enhance the power density without having compromises or disadvantages, especially regarding reliability and size. It is clear that parts conducting high currents will heat up even when copper and/or aluminum are used to achieve low electrical resistance.

Table 1 shows from thermal, electrical and mechanical points of view that copper has the best properties for internal wiring. But until now the most effective way to join the terminals with the DCB (Direct copper bonded) substrate has been solder technique. Ultrasonic welding technology has been regularly used for aluminum.

Using solder material has got several difficulties: First of all it is a compound of different materials which can age chemically. Even worse cracks caused by thermal cycling due to mismatching expansion coefficients increase thermal resistance dramatically. Another weak spot is the 5 times lower mechanical strength of the solder material in comparison to copper.

Material	Electric resistance $[10^{-8}\,\Omega m]$	Strength $[N/mm^2]$	Thermal conductivity $[W/m.K]$
Aluminum	2,5	60	240
Copper	1,5	325	390
Solder (thin)	11,5	50	68

Table 1: Material properties of the metal used for IGBT module circuit

The challenges were done by developing new technologies which makes it possible to have ultrasonic welding of copper without any additional joining material like solder. This allows a direct connection of the internal bus bars to the DCB's copper foil. This is shown in figure 2.

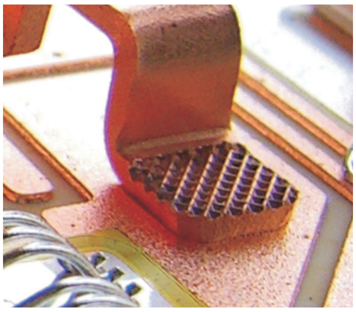


Figure 2: Copper terminal joint to DCB circuit by ultrasonic welding

Ultra sonic welding significantly improves the terminal joint reliability and vibration strength. Figure 3 shows a cross section of an ultrasonic welding joint after 300 passive thermal cycles of -40°C to 150°C without significant degradation of the mechanical strength.

Figure 3: Cross section of ultrasonic welding area after 300 thermal cycles (-40°C to 150°C)

The advantages of the welding process are clearly visible and can also be proven numerically. Figure 4 shows a comparison of tensile strength of the new welding method and a conventional solder joint before and after 300 thermal cycles. The pulling force for measuring the strength capability was applied in vertical direction.

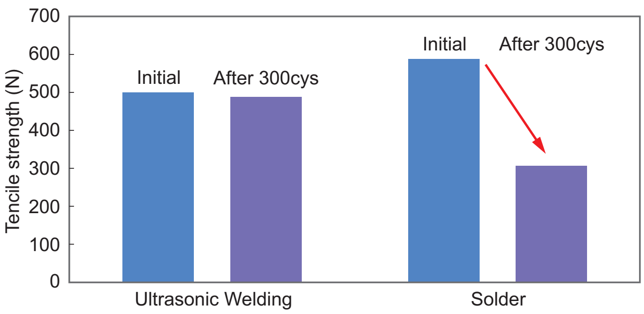


Figure 4: Relationship between Strength of terminal joint area and thermal cycling test

In fact, the new welding process provides improved mechanical strength and higher thermal cycling capability, even with increased current density.

Solder material under the DCB
The thermal cycling capability depends very much on the weakest link in the chain of layer connections. This means that the thermal cycling capabilities of the IGBT-module have to be improved not only for a particular part, but for the entire structure of the module. The thermal stress is mainly caused by shearing forces, which occur due to different thermal expansion coefficients of different materials. These shear forces can cause cracks in the solder layer and these increase the thermal resistance.
As a result, Fuji Electric improved the thermal cycling capability by a better matching of CTE (coefficient of thermal expansion) and by improving the interfaces of the different layers.
In IGBT modules, the biggest CTE mismatch can be found between the insulation ceramic substrate of the DCB and the copper base plate. The relating material properties are shown in table 2.

Fuji Electric did a lot of investigations to improve the reliability of solder join between copper base plat and DCB.

	Thermal conductivity [W/m.K]	Required thickness [mm]	CTE (coefficient of thermal expansion) [10^{-6}/K]
Al_2O_3	18-25	0,25-0,38	7,1
Si_3N_4	70-90	0,32	3,4
AlN	170	0,635	4,6
Copper (base)	390	3	6,8

Table 2: Material properties of available ceramic and copper

Tin-Silver (Sn-Ag) is the most widely used RoHS-compliant solder. It is able to withstand 100 cycles of the common passive thermal cycling test (-40°C (1h) ~ RT (0.5h) ~ +150°C (1h)) as an accelerated aging test.

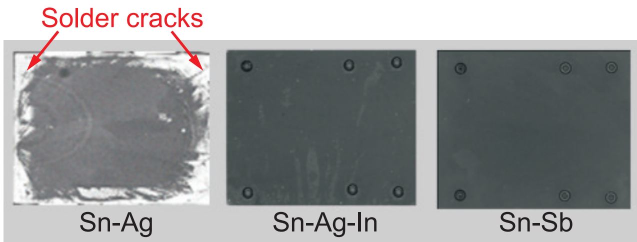


Figure 5: Comparison of crack areas between Sn-Ag solder, Sn-Ag-In-solder and Sn-Sb solder between Si3N4-DCB and copper base plate after 300 thermal cycles.

However, it is not able to withstand 300 thermal cycles like shown in the left SAT (Scanning Acoustic Tomography) picture of <<figure 5>>. Therefore Fuji Electric has introduced in 2002 RoHS compliant solder material containing Indium (In) for industrial application. In addition Fuji Electric has developed Tin-Antimony (Sn-Sb) solder material for automotive applications back in 2005. The record of <<figure5>> proofs that both solder materials are able to withstand 300 cycles under the same test conditions. The reason for the higher thermal cycle capability is, that the structures of Sn-Ag-In and Sn-Sb solder do not change on thermal impact. Therefore, the mechanical strength does not decrease relevantly. Sn-Sb has a higher melting point than Sn-Ag-In, which allows the assumption, that it also has a higher reliability. The respective tests are still going on.

For the first time Sn-Sb will be introduced for industrial applications in Fuji Electric's PrimePACK™ modules to increase again reliability for lead-free industrial products.

THERMAL FEATURES

Optimization in the chip arrangement
Beside to the performance (losses) of the silicon chip, the thermal behaviour of the module is the most relevant factor for the module rating. Mostly thermal cross coupling effects with the neighbouring IGBTs or diodes at smaller current ratings can be neglected. This rule does not apply in the same way for modules with higher current density like the PrimePACK™ module from Fuji Electric. Here, cross coupling effects have to be taken into account to reduce the impact on the chips, which are used in parallel for one arm. Therefore, upper and lower arm chips are arranged along the module length to reduce thermal coupling as much as possible. The resulting uniform temperature distribution shown in <<figure 6>> prevents occurrence of unnecessary hot spots.

Additionally, IGBTs are arranged alternately with the respective anti-parallel diodes see <<figure 6>>. This is especially advantageous when the absolute value of the power correction factor cos(φ) is high, i. e. near +1. Then load is concentrated more on the IGBTs than on the diodes.

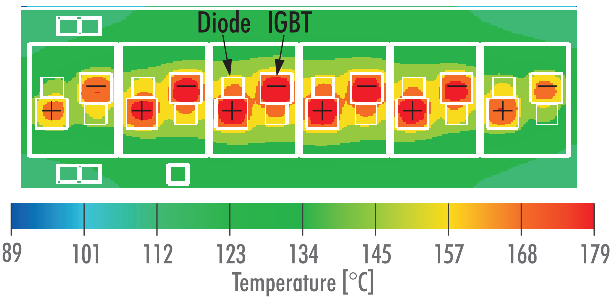


Figure 6: FEM simulation of thermal behaviour

Thermal contact to heat sink

All these thermal improvements can only become effective, if the resulting heat losses can be transferred well to the cooling system. From the thermal conductive point of view, thermal grease is a multiple worse than the other used materials like copper, solder and isolation ceramic. Thermal grease, even thinly applied, is a real bottleneck in the thermal network. To alleviate this effect, the base-plate is fixed by 10 respectively 14 M6-screws depending on the package size. The screws have a very short distance of 39mm in lengthways direction and 73mm across to achieve a well distributed pressure. The quality of the contact is given by the spreading behaviour of the thermal grease see <<figure 7>>.

Figure 7: spreading behavior after tighten up the screws

Figure 7 shows a module mounted on a glass block after the screws were tightened with 3,5Nm.The result shows a good spreading of the thermal grease, even for the long copper base of the PP3. Of course, to get such a good result the thermal grease was applied via a metal stencil mask. 2,1g HTC01K was used in total for the PP3 with a 40% open ratio stencil mask pattern to achieve target thickness of the thermal grease of 50µm as an extreme demonstration.

Electric characteristics

Output power capability of the semiconductor depends on low power losses, the highest possible junction temperature and thermal impedance. The enhanced 6th-generation IGBT was used with improved trench-gate and field-stop-technology, enabling continuous operating junction temperatures of 150°C and a maximum temperature of 175°C.

The power losses, on the other hand, are reduced among others by a thin chip structure resulting in lower on-resistance. The output characteristic of the IGBT 1000A 1700V is shown in figure 8a and the corresponding FWD is shown in <<figure 8b>>.

For Fuji Electric's PrimePACK™ module the 1200V V-IGBT-silicones are installed to achieve softer switching behaviour and a higher voltage safety margin. The 1700V V-Series die however is thicker and does not need any adaption to achieve softer switching.

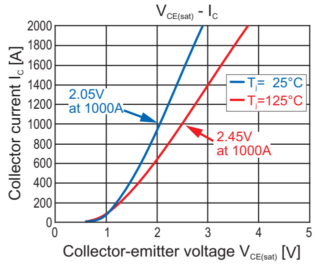


Figure 8a: Output characteristics of IGBT

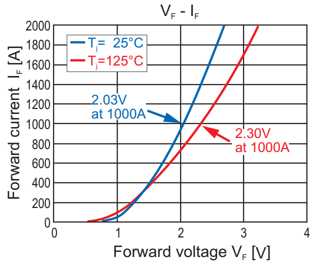


Figure 8b: Output characteristics of FWD

The improvement of the V-series' switching speed is related to the possibilities of higher surge voltages at turn-off caused by the energy stored in the stray inductance. Therefore efforts must be taken from both, module producer and converter manufacturer, to keep this as low as possible.

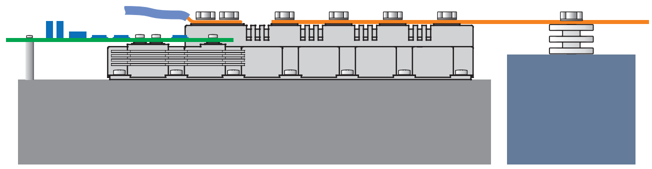


Figure 9: PP3 mounted and connected

Low inductance can be achieved by short, parallel and closely arranged bus-bars.

Fuji Electric's PrimePACK™ module features a design where the DC-link capacitors can be connected directly and with relatively short bus bars.

However, the rule is valid, that with a uniform and symmetric bus bar layout a lower stray inductance can be achieved. Therefore the terminals for the DC-link connections of the longer PrimePack™ module called PP3, alternate between positive side and negative side like shown in <<figure 10>>.

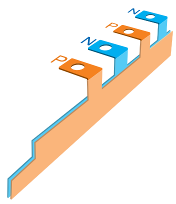


Figure 10: Alternation internal PN-Bus bar

The fact, that ultra low internal inductance was achieved for PP3 is proven by measurement. The corresponding theoretical equivalent circuit is shown in <<figure 11>>.

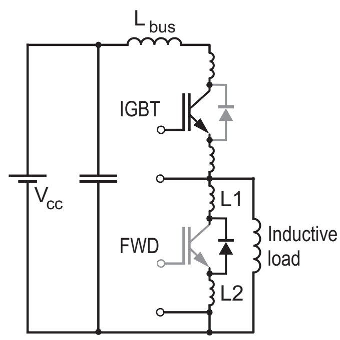


Figure 11 equivalent circuit and theoretical switching waveform

The experimental result is given in <<figure 12>>. It shows that according to formula $L_\sigma = L_1 + L_2 = \Delta V \frac{dt}{di}$ the stray inductance L_σ of one arm is about 5nH.

This means that the total stray inductance of the PP3 (upper and lower arm) is about 10nH and of the PP2 (because fewer DCBs in parallel) is about 18nH. In fact this is an excellent result in comparison to Fuji Electric's 2in1 High Power Module which has 21nH per switch without external wiring. This itself is a very good result and a unique value in the market for this housing.

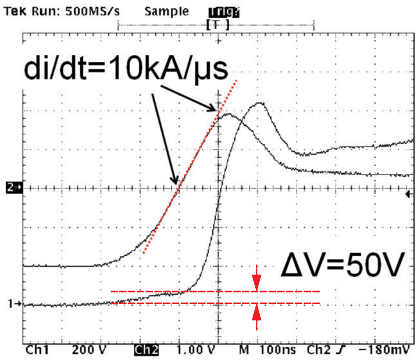


Figure 12: experimental result of internal inductance measurement (500A rep. 200V per division on y-axis, 100ns per division on x-axis)

Switching behaviour

The switching behaviour is a result of chip characteristic and package design.

Turn-off and turn-on waveform

A measured turn-off waveform of 1700V 1000A module is presented in figure 13. The measurement conditions are as following: DC-Voltage Vcc=900V, collector current Ic=1000A, gate voltage VGE=±15V, junction temperature Tj=125°C, gate resistance to turn off Rg(off)=0,17Ω

To assure switching performance for all applications, an extreme small resistance was chosen to achieve $\frac{dv}{dt} = 4250 \frac{V}{\mu s}$. The turn-off waveform is continuously and has no inflexion points.

Under same conditions, with exceptions of gate resistance, the turn-on wave form can be seen in <<figure 14>>. The gate resistance was adapted to Rg=0,17 Ω

Even under harsh conditions the switching behaviour still looks controllable. The maximum current gradient is $\frac{di}{dt} = 8750 \frac{A}{\mu s}$.

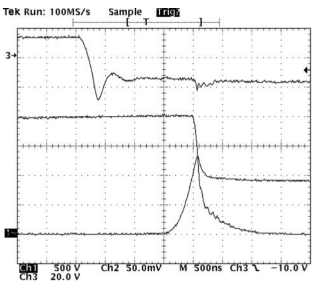


Figure 13: Turn off wave form of PP3 1700V 1000A (250A rep. 500V per division on y-axis, 500ns per division on x-axis)

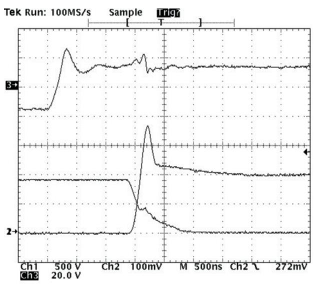


Figure 14: Turn on wave form of PP3 1700V 1000A (500A rep. 500V per division on y-axis, 500ns per division on x-axis)

Short circuit test

The module passed a short circuit test of 10µs with DC-link voltage of Vcc=1000V. The respective waveform can be seen in <<figure 15>>. The collector current arises to saturation, which corresponds to 4 to 4.5 times rated current. After 10µs a proper turn-off of the IGBT can be seen. The voltage does not exceed its maximum.

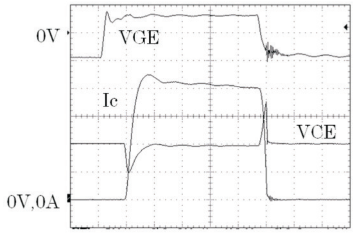


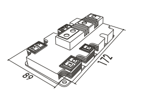
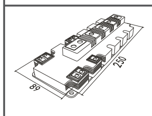
Figure 15: 10µs short circuit test (500V rep. 1000A per division on y-axis, 2µs per division on x-axis)

Applications

The presented module is easy to design in, has very good thermal and electrical performance and the reliability feature is promising a long product life-time. Therefore, this module fits to every application where one of these features in combination with high power density is needed. This could obviously be traction converters, even with copper base plate, but it would also fit to wind mills or big solar converters, all with a product life time longer than 20 years.

Product line up

The product line up is shown in table 3. These products will be available soon.

Package	V_{CES} [V]	I_C Rating [A]	Type name	$V_{CE(sat)}$ *) [V]	V_F *) [V]
	1200V	450	2MBi 450VXA-120	1.70	1.75
		600	2MBi 600VXA-120		
		900	2MBi 900VXA-120		
	1700V	450	2MBi 450VXA-170	2.00	1.85
		650	2MBi 650VXA-170		
	1200V	1400	2MBi 1400VXB-120	1.70	1.75
	1700V	1000	2MBi 1000VXB-170	2.00	1.85

Common features: *) Conditions: I_C=I_F=Rating Current; T_j=25°C

$T_{j,max}$= 175°C	$T_{j,op}$ = 150°C	V_{iso} = 4.0kV, 1min	CTI > 600	Base plate: Copper	DCB: Al_2O_3

Table 3: Product line up

References

[1] Y.Nishimura, etc, The relationship between IGBT module structure and reliability
Fuji Electric Systems, Semiconductors Development Group, Matsumoto, Japan,
[2] Y.Nishimura, etc, Development of ultrasonic welding for IGBT module structure
Fuji Electric Systems, Semiconductors Development Group, Matsumoto, Japan,