Small Size, Low Thermal Resistance and High Reliability Packaging Technologies of IGBT Module for Wind Power Applications

K.Sasaki*1, M.Hiyoshi*1, K.Horiuchi*2, Hitachi, Ltd. *1 Power Systems Company, *2 Mechanical Engineering Research Laboratory, Japan, koji.sasaki.jn@hitachi.com

Abstract

In order to feature in next generation wind power generation systems, a new 600A-1700V IGBT module has been developed. The module has (1) low thermal resistance realized by thermal-greaseless “direct-liquid-cooling” technology with pin-fin, whose pressure drop and fin efficiency are optimally designed, (2) small package size, which enables compact power conditioner system, (3) high reliability and long lifetime realized by high strength Si_3N_4 insulated substrate and newly developed RoHS bonding technologies. The thermal resistance Rj-w of the IGBT module is reduced by 35 percent when compared to “indirect-cooling” conventional modules using thermal grease. The developed IGBT module and channel cover jacket are approximately 37 percent lighter and 45 percent smaller when compared to conventional modules with the same power capability.

1. Introduction

1.1. Motivation

According to the increasing consciousness for global ecological tribulations, the market of wind power generation devices continues to increase rapidly. IGBT modules for wind power systems should be small, lightweight, high power and highly reliable in order to minimize maintenance cost throughout the product lifetime. In order to satisfy these needs, a new 600A-1700V IGBT module is developed.

1.2. Outline of new IGBT module

The outline of the new IGBT module is shown in Fig. 1. Basic structure and maximum ratings are shown in Fig. 2 and Fig. 3. The module has an integrated copper base and pin-fin used for thermal-greaseless “direct-liquid-cooling”, which realizes an extremely low thermal resistance. The module also adopts Si_3N_4 insulated substrate that has high fracture strength and enables high reliability of the module; newly designed lead-free solder that has longer life compared to conventional lead solder; and ultrasonic bonding technology for main terminals that enables RoHS compliant packaging technology.

The exploded view of the new IGBT module and exclusively designed channel cover jacket are shown in Fig. 4. The open area of the coolant flow channel of the jacket is covered by the copper base and pin-fin of the IGBT backside. Pin-fin layout is optimized for pressure drop and fin efficiency by fluid and thermal simulation technologies. An O-ring is used to seal the flow channel. The footprint size of the jacket is just the same as the size of two IGBT modules.

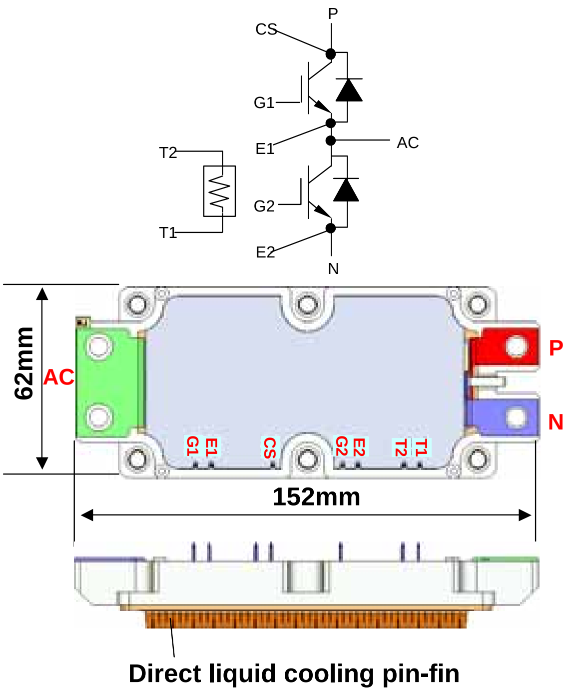


Fig. 1. Outlines of new “direct-liquid-cooling” IGBT module

Items	Specification/Remarks
RoHS regulation	Lead free solder
Comparative tracking index	CTI>600V
Ceramic	Si_3N_4 substrate
Flammability	UL94V-0
Creepage distance	16mm
Stray inductance of module	22nH
Weight IGBT	0.45kg
Weight Fluid Channel Jacket	3.0kg (for 6 IGBTs)

Fig. 2. Basic structure of new “direct-liquid-cooling” IGBT module

Item		Symbol	Unit	Specification
Collector Emitter Voltage		V_{CES}	V	1,700
Gate Emitter Voltage		V_{GES}	V	±20
Collector Current	DC	I_C	A	600
	1ms	I_{Cp}		1200
Forward Current	DC	I_F	A	600
	1ms	I_{FM}		1200
Maximum Junction Temperature		T_{jmax}	degC	175
Temperature under Switching Conditions		T_{jop}	degC	-50~+150
Storage Temperature		T_{stg}	degC	-50~+150
Isolation Voltage		V_{ISO}	V_{RMS}	4,000(AC 50Hz, 1minute)

Fig. 3. Maximum ratings of new IGBT module

1.3. Module layout example

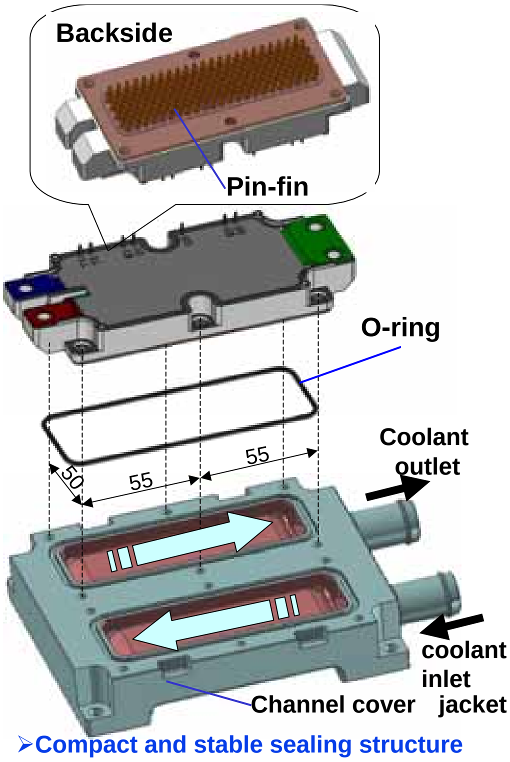
IGBT module layout example is shown in Fig. 5. A 500A-1100V power conditioner layout example is shown in the figure. Footprint size of the jacket is the same size as six IGBT modules. Depending on the ability of the coolant pump, users can choose the jacket with serial flow channel, 2-parallel flow channels, 3-parallel flow channels or 6-parallel flow channels. In each jacket, junctions of the flow channels are located in the jacket with each jacket having only two connections; one inlet and one outlet. Therefore, flow channel layout out of the jacket is kept very simple. Power unit is 37% lighter and 45% smaller than conventional power unit of equivalent power capacity, which consists of “indirect-liquid-cooling” IGBT modules and heatsink.

2. Packaging technologies

2.1. Thermal resistance

Thermal resistance of the new IGBT module is reduced by “direct-liquid-cooling” technology. Cross sectional views of conventional “indirect liquid cooling” IGBT module and new IGBT module are shown in Fig.6. In “indirect-liquid-cooling” IGBT module, heat from IGBT die flows through solder layer, metal layer, ceramic layer and thermal grease layer to heatsink. Thermal conductivity of thermal grease is almost a hundredth smaller than thermal conductivity of copper. Therefore thermal resistance of “indirect-liquid-cooling” IGBT becomes large. On the other hand, “direct-liquid-cooling” IGBT module does not use thermal grease. Therefore thermal resistance of “direct-liquid-cooling” IGBT becomes small.

Temperature distributions under heat generation in IGBT die are given in Fig. 7. The temperature distribution is presented using thermal-fluid simulation. In Fig. 7, the new “direct-liquid-cooling” IGBT module is compared with a conventional indirect cooling IGBT module. Junction-water thermal resistance Rj-w is 35 percent reduced by using new “direct-liquid-cooling” system. Relationship between coolant flow rate and thermal resistance is shown in Fig. 8. The figure shows that the new IGBT module and channel cover jacket show an excellent cooling capacity. Its thermal resistance is approximately 35% lower than conventional “indirect-liquid-cooling” IGBT module. Depending on the thermal conductivity and thickness of thermal grease used in conventional “indirect-liquid-cooling” IGBT module, improvement of thermal resistance by “direct-liquid-cooling” IGBT module varies from 25%-80%[3].



➢Compact and stable sealing structure
➢Free IGBT from thermal grease

Fig. 4. Exploded view of new IGBT module and exclusively designed channel cover jacket

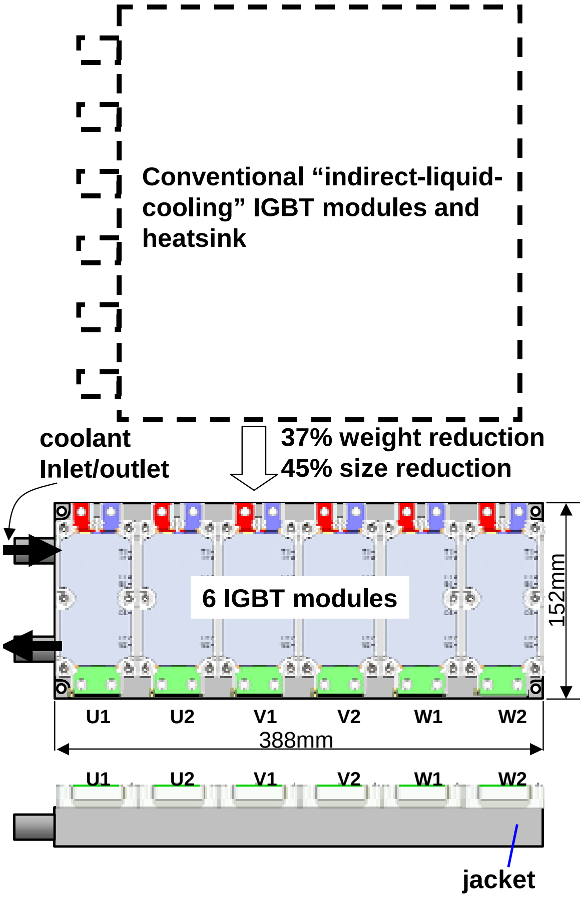


Fig. 5. Power unit layout example of 500A-1100V three-phase power conditioner. With exclusively designed channel cover jacket, footprint size is almost same as the IGBT package size.

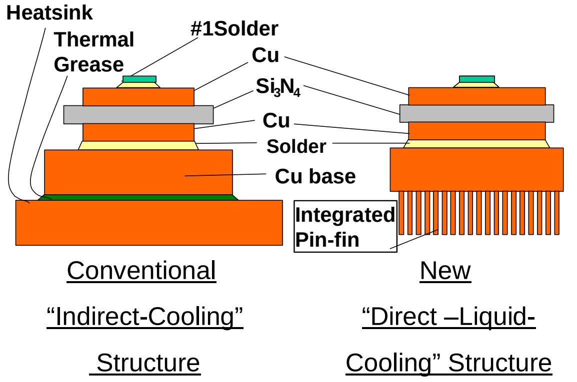
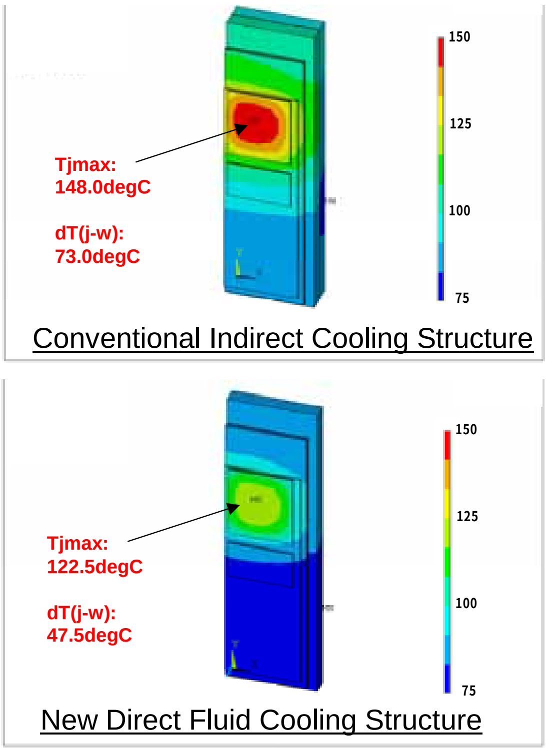


Fig. 6. Cross-sectional view of conventional "indirect-liquid-cooling" IGBT module and new "direct-liquid-cooling" IGBT module

Assumptions:
Same loss on same size of
1700V-200A IGBT die
Coolant Temperature 75degC



Improvement of Cooling Performance is approx. 35%

Fig. 7. Temperature distribution around IGBT die, comparing "direct-liquid-cooling" and "indirect-cooling" with thermal grease. The simulation results indicate that thermal resistance of "direct-cooling" module is 25-80% lower than "indirect-cooling" module.

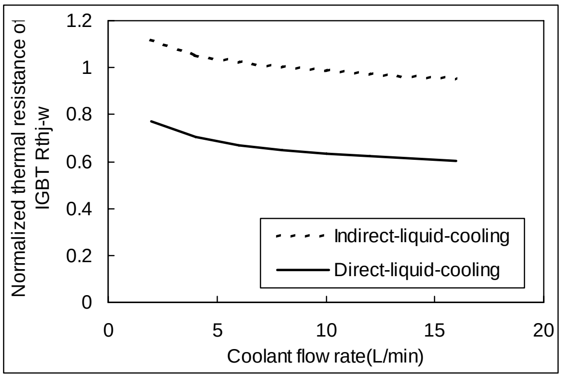


Fig. 8. Relationship between coolant flow rate and thermal resistance

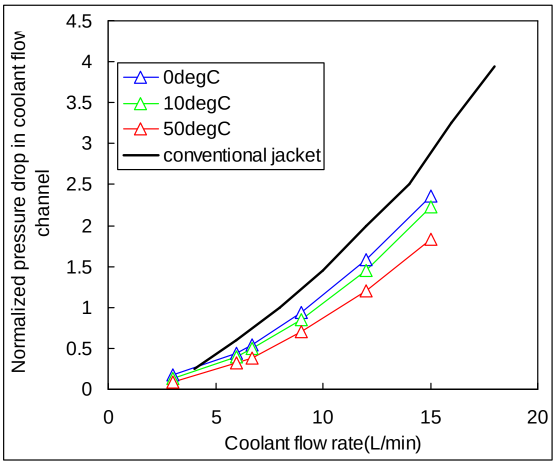


Fig. 9. Pressure drop in coolant flow channel

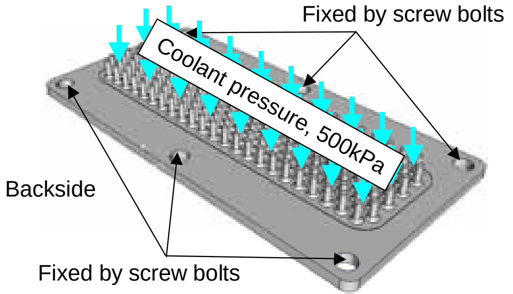
2.2. Pressure drop in coolant channel

Pressure drop in coolant channel is measured with a coolant jacket of a serial flow channel for 2 IGBT modules. Coolant served for the experiment is 50% ethylene glycol / 50% water. Coolant temperatures are 0degC, 10degC and 50degC. Experimental results are shown in Fig. 9. Newly designed pin fin base plate and channel cover jacket realized less pressure drop than conventional "indirect-liquid-cooling" heatsink.

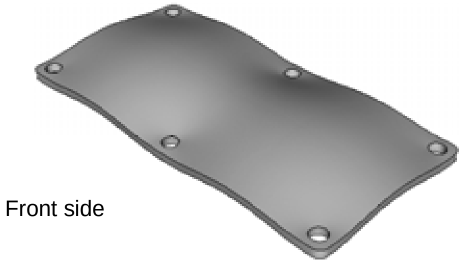
2.3. Reliability against coolant leakage

Reliability of the new IGBT module is highly affected by the reliability of leakage of coolant. In order to predict the risk of leakage under operating coolant pressure, stress simulation was conducted (see Fig. 10). Maximum warpage deformation at the O-ring contact surface points under 500kPa coolant pressure, which is regarded as the typical discharge pressure of coolant pump, is approximately 0.04mm. This value is smaller than the accepted deformation to avoid coolant leakage. The module can endure coolant pressure under operation and avoid coolant leakage.

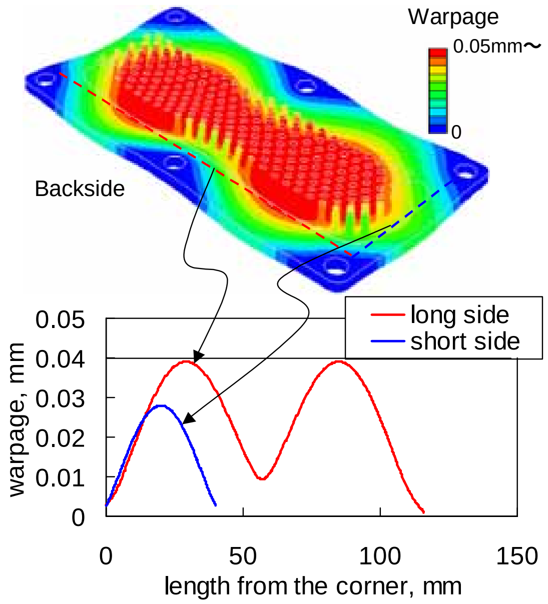
Coolant leakage test is also conducted. A channel jacket for 2 IGBT modules is used in the test. First, coolant pressure in the jacket is boosted to 500kPa by test pump with jacket outlet terminated. Then shut the inlet valve and keep it for 10 minutes. After 10 minutes, evaluate the pressure in the jacket and compare it with its initial pressure. Coolant pressure after 10 minutes shows no decrease. It confirms that there is no coolant leakage by 500kPa coolant pressure. It is also confirmed by investigating the gap of pin fin base plate and channel cover jacket.



(a) Boundary conditions



(b) Deformed shape (x50)



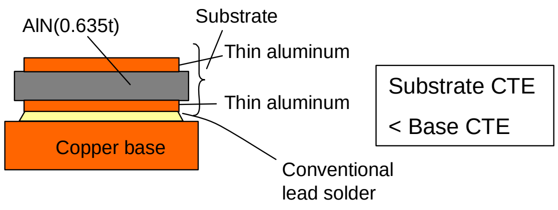
(c) Warpage at the edge of base

Max. warpage under coolant pressure 500kPa < 0.04mm

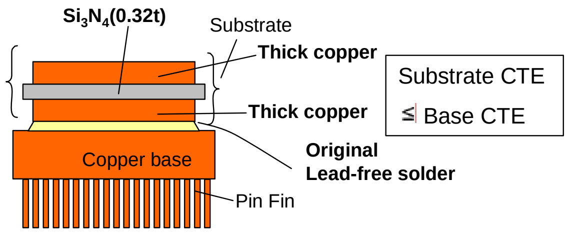
Fig. 10. Warp deformation of direct cooling pin-fin under coolant pressure. Reliability of coolant sealing structure is guaranteed by optimized pin-fin design with simulation technologies.

2.4. Reliability of solder layer

Thermal fatigue life of solder layer is improved by using "coefficient of thermal expansion matching technology." Cross-sectional outline of conventional IGBT module and new IGBT module are shown in Fig.11. In conventional IGBT module, thick AlN(Aluminum Nitride) substrate with thin aluminum layer is used to insulate the IGBT circuit. On the other hand, new IGBT module uses thin Si_3N_4 (Silicon Nitride) substrate with a thick Copper layer is used to insulate the circuit. Large fracture toughness of Si_3N_4 compared to AlN enables the use of a thick Copper layer. Thin Si_3N_4 substrate and thick copper layer increases the equivalent coefficient of thermal expansion of Si_3N_4 and Copper laminate. Then the difference between CTE of Si_3N_4 and Copper laminate and CTE of Copper pin fin base plate becomes small. Thus, the thermal stress of substrate-base plate connecting solder layer is reduced and the thermal fatigue life of the solder layer is improved. Original lead-free solder also improves the fatigue life of the solder. Thermal fatigue life diagram of new IGBT module is shown in Fig.12. Power cycling life diagram of new IGBT is shown in Fig.13.



Conventional Substrate and Base



New Substrate and Base

Fig. 11. Cross-sectional outline of conventional IGBT module and new IGBT module. High fracture toughness of Si_3N_4 enables copper layer of substrate to be thick. Thick copper layer increases CTE of substrate and decreases CTE difference between substrate and Copper base.

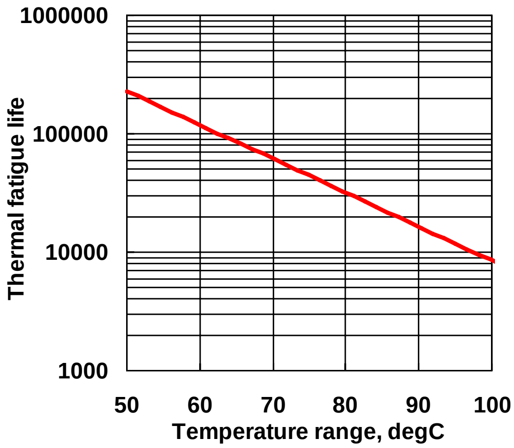


Fig. 12. Thermal cycling diagram of new IGBT module

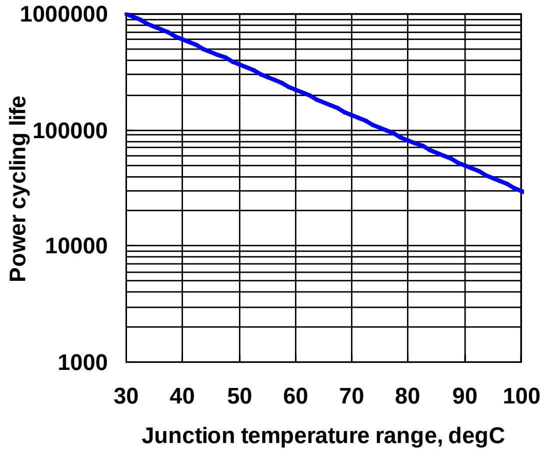


Fig. 13. Power cycling diagram of new IGBT

2.5. Example of Tj estimation by simulation

Junction temperatures under several operating conditions are estimated. In the estimation a 500kW electric power conditioning system with six IGBT modules (two IGBT modules per phase) is considered. Coolant flow rate is set to 8L/minute/channel. Number of flow channels are 3 and a channel is serial for 2 IGBT modules. Total flow rate is 24L/min. Coolant temperature is assumed as 50degC.

Tj estimation results are shown in Fig.14. Estimated results show that, according to its low thermal resistance, the new "direct-liquid-cooling" IGBT module can operate over 5kHz switching frequency with proposed flow channel diagram.

Condi-tion	DC Bus Voltage (V)	RMS Phase Current (A)	PWM Switching frequency (Hz)	Power Factor
1	1100	250	1800	-0.85
2	1100	250	3600	-0.85
3	1100	250	5000	-0.85
4	1100	250	1800	0.85
5	1100	250	3600	0.85
6	1100	250	5000	0.85

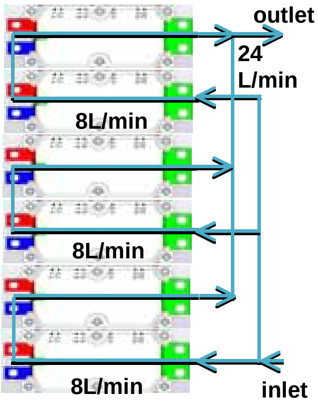
(a) Operating conditions for simulation

Condi-tion	Pressure Drop (kPa)	Coolant Inlet Temp. (degC)	Coolant Inlet Temp. (degC)	Max. IGBT Junction Temp (degC)	Max. Diode Junction Temp (degC)
1	6.5	50	53	70.5	78.6
2	6.5	50	55	84.8	87.7
3	6.5	50	56	95.8	94.8
4	6.5	50	54	82.3	65.7
5	6.5	50	55	96.5	74.8
6	6.5	50	56	107.6	81.9

(b) Simulation results

Assumptions

- **500kW Inverter/Converter**
- **24L/min (8L/min x 3channel)**
- **50% ethylene glycol**
- **6 ECOBLOC**
- **3 parallel channels**



Flow Channel Diagram

Fig. 14. Example of Tj estimation. Tj is calculated considering the effect of temperature increase of coolant outlet. According to its low thermal resistance, the new “direct-liquid-cooling” IGBT module can operate 5kHz switching frequency.

3. Summary

A new “direct-liquid-cooling” IGBT module has been developed. The module uses integrated pin fin base plate to reduce thermal resistance from IGBT chip to coolant without the use of thermal grease. Pin fin layout and channel cover jacket design are optimized by fluid-thermal simulation and experiment. Coolant leakage reliability is also optimally designed by stress simulation and experiment. Si_3N_4 substrate and RoHS bonding technology are developed to achieve high reliability and long lifetime of the IGBT module. Due to its low thermal resistance, approximately 65% of the thermal resistance of conventional “indirect-liquid-cooling” IGBT module, a 500kW power conditioner with 6 IGBT modules can operate.

4. Literature

[1] O. Schilling, M. Wölz, G. Borghoff, Th. Nübel, G. Bräker, Chr. Lübke: Properties of a New PrimePACK™ IGBT Module Concept for Optimized Electrical and Thermal Interconnection to a Modern Converter Environment, PCIM Europe, 2005

[2] C.Göbl, H. Leibold, K. Backhaus, T. Stockmeier, “SKiiP 3”, Proc.PCIM ´01, PC10.6, p. 313 - 318, Nürnberg 2001

[3] K. Horiuchi, A. Nishihara, K. Sasaki, T. Kurosu, “Practical Aspects of Use of Direct-Cooled Power Module”, Proc. IPEC-Sapporo, 2010 (Printing)