“M660” High-Power IGBT Module for Automotive Applications

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ABSTRACT

IGBT modules for automotive applications need to have low power loss to efficiently use battery power. They are also required to achieve small size and lighter weight while having high power. In response to these market demands, Fuji Electric has developed the “M660” direct water-cooled power module. This module adopts a lead frame structure, instead of wire bonding, which was conventionally used for internal wiring. It also employs the cooling structure that integrates a water jacket with reverse-conducting insulated gate bipolar transistors (RC-IGBTs) that have improved characteristics. With these structures, the M660 achieves the rated capacity of 750 V/1,200 A, which is the world’s highest power as a general-purpose 6-in-1 IGBT module.

1. Introduction

Efforts around the world to reduce CO_2 emissions and achieve energy savings have been rapidly increasing. Against this backdrop, automobile manufacturers have been actively promoting the use of electrically powered vehicles such as hybrid electric vehicles (HEV) and electric vehicles (EV) instead of vehicles powered by internal combustion engines that use conventional gasoline and diesel fuel. Insulated gate bipolar transistor (IGBT) modules are used in HEV and EV as one of the key components of the power electronics technology employed in the operation of electric motors. IGBT modules are being required to achieve size reductions and weight savings, as well as realize low power loss in order to facilitate better use of battery power. In addition, they are also required to be larger capacity.

In order to meet these demands, Fuji Electric has developed a direct water-cooled power module. In this paper, we will introduce the features and performance characteristics of the “M660” high-power IGBT module for automotive applications.

2. “M660” Characteristics

Figure 1 shows the external view of the M660, and Table 1, its characteristics.

As can be seen from Table 1, compared with the conventional product, the M660 has reduced collector-emitter saturation voltage $V_{CE(sat)}$ by 22% and thermal resistance $R_{th(j-w)}$ by 31%, while improving power density by 58%. The definitions for power density and motor output used in Table 1 are as follows:

(a) Power density = Used DC voltage × Output current / Module volume

(b) Motor output = Used DC voltage × Output current × Motor efficiency

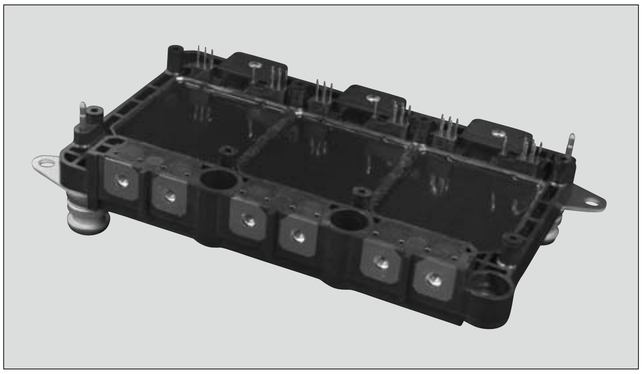

Fig.1 “M660” high-power IGBT module for automotive applications

Table 1 “M660” characteristics

Item	M660	Conventional product
Internal wiring	Lead frame	Wire bonding
Chip	RC-IGBT	RC-IGBT
Collector-emitter voltage	750 V	750 V
Rated current	1,200 A	800 A
Collector-emitter saturation voltage	1.54 V	1.98 V
Thermal resistance	0.09 °C/W	0.13 °C/W
Dimensions (mm)	W178 × D116 × H24	W162 × D116 × H24
Power density	684 kVA/L	433 kVA/L
Motor output	200 kW	150 kW

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3. Technologies Applied to "M660"

3.1 Application of lead frame technology

Fuji Electric has utilized a lead frame for the main circuit wiring of the direct water-cooled power module. In contrast to wire bonding connections, the use of a lead frame structure has the following 2 advantages:

(a) By reducing the size of the direct copper bonding (DCB) substrate, making the product size smaller. Wire bonding connections require larger size of the DCB substrate than lead frame structure because it needs the bonding area of multiple wires.

(b) The lead frame structure has larger contact area with the chip, and this creates more heat dissipation, thus reducing the maximum temperature of the chip.

In addition to the advantages mentioned in (a) and (b), the use of resin as the sealing material has made it possible to reduce stress generated in the solder under the lead frame, thus improves the power cycle capability. Furthermore, in wire bonding connections, it is necessary to make multiple bonding processes for wires. In contrast to this connection, by the lead frame structure, a single lead sheet is laid and connected to DCB substrate, thus providing the IGBT module with excellent productivity.

Figure 2 shows the internal layout of the half bridge circuit of an IGBT module that utilizes wire bonding connections, as well as one that utilizes a lead frame structure.

By employing lead frame technology for the M660, the size of the IGBT module has been reduced by 23% compared with modules that utilize a wire structure.

3.2 RC-IGBT utilization and characteristic improvement

In order to reduce the size of the module, the M660 makes use of a reverse-conducting IGBT (RC-IGBT). The RC-IGBT uses an IGBT with a field stop (FS) structure as the base, while using a structure that arranges stripe-shaped IGBT units and free wheeling diode (FWD) units alternately placed on a single chip. Figure 3 shows the schematic structure of the RC-IGBT.

The use of the single chip made it possible to reduce the size of the region referred to as the guard ring (a region for securing breakdown voltage for the periphery of the chip), thus enabling a smaller chip area than conventional products that employed a structure composed of separate chips for the IGBT and FWD. Moreover, heat is dissipated from the region of the FWD when the IGBT operates, and conversely, from the region of the IGBT when the FWD operates, reducing thermal resistance when either the IGBT or FWD operate.(1)

Fuji Electric has been releasing modules for automotive applications that come equipped with an RC-IGBT.(2) This time, we have undertaken to reduce loss even further for the IGBT module. Reduction of steady-state loss through chip thinning is one method for reducing loss in mounted RC-IGBT chips. Therefore, we developed a cutting-edge thin wafer processing technology that has reduced steady-state loss for the RC-IGBT by thinning the wafer to a thickness sufficient for a breakdown voltage of 750 V. In addition, the surface structures such as trench pitch, channel density and contact were all optimized. Figure 4 shows the $V_{CE(sat)}$-collector current I_{CRM} characteristics for the M660 and a module with the conventional RC-IGBT, and Figure 5 shows the diode forward voltage V_F-diode forward current I_{FRM} characteristics.

Compared with the conventional product, the M660 has reduced $V_{CE(sat)}$ by 22% and V_F by 4.2% at a rated current of 1,200 A by optimizing the cell design of the IGBT.

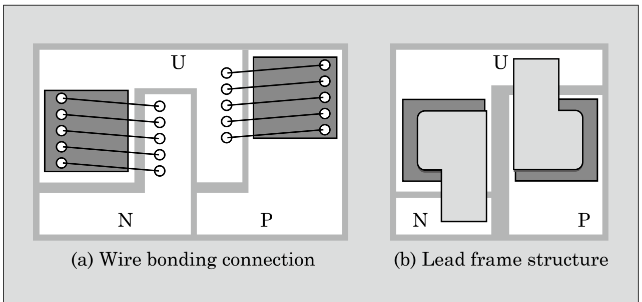

Fig.2 Internal layouts of half bridge circuits

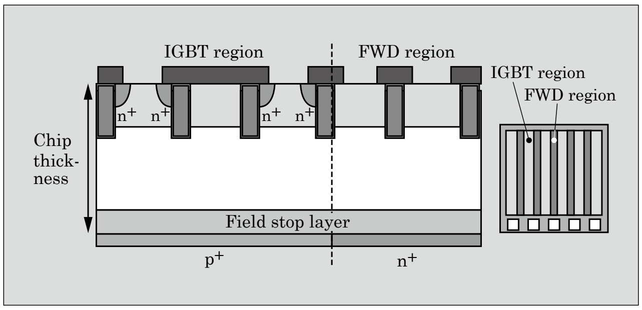

Fig.3 Schematic structure of RC-IGBT

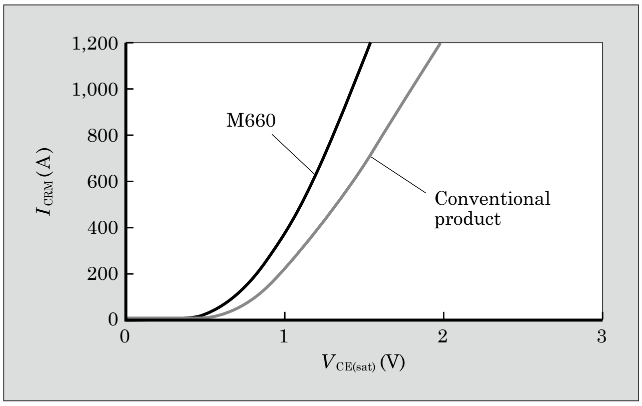

Fig.4 $V_{CE(sat)}$-I_{CRM} characteristics

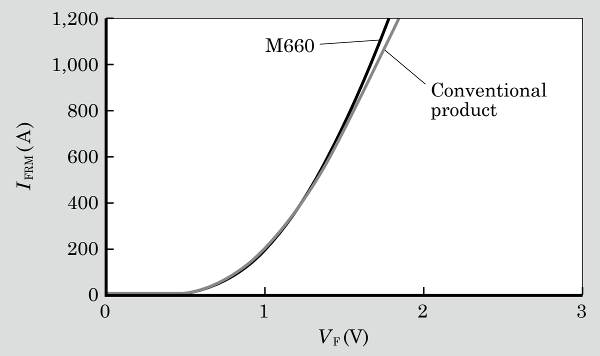

Fig.5 V_F-I_{FRM} characteristics

3.3 I^2t capability

Current squared time I^2t is an indicator that represents the overcurrent withstand capability for the FWD built into the IGBT module. A current from the inverter in its regenerative operation flows through FWD and charges a capacitor. The FWD needs to withstand the regenerative current I^2t without breaking down (see Fig. 6). The main failure modes of the FWD during regeneration relate to device destruction due to large current flow or generated heat destruction of the wire due to heat being generated in the wire.(3)

Figure 7 shows the I^2t capabilities for the M660 and an IGBT module with wire bonded separate chips. It can be seen that the M660 has an I^2t capability of at least 3 times that of the IGBT module with wire bonded separate chips. Temperature rise in the FWD region is suppressed in the RC-IGBT because heat spreads to the IGBT region when current flows through the FWD region. Furthermore, the lead frame structure employed by the M660 widens the contact region for the chip compared with wire bonding connection. Therefore, heat is transferred to the surface of the lead frame and local temperature rise is mitigated.

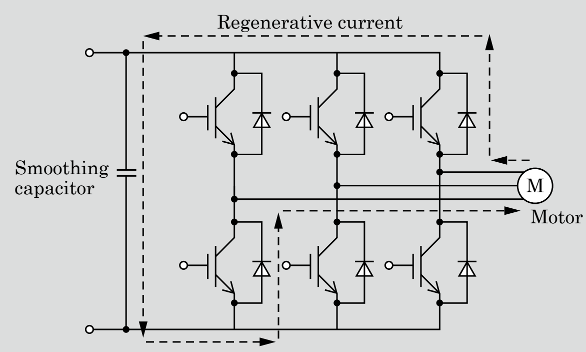

Fig.6 Inverter regenerative operation

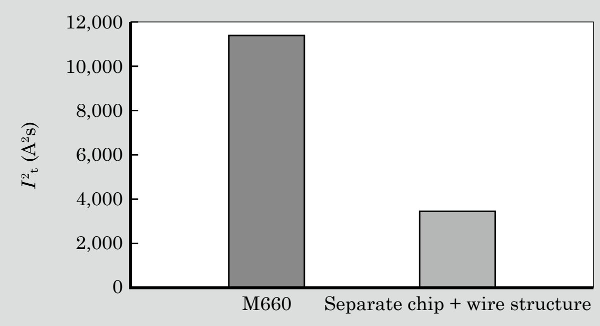

Fig.7 I^2t capability

3.4 Utilization of efficient heat dissipating cooling unit

Fuji Electric has elucidated the fact that space yielded between the water-cooled fins and water jacket causes degradation in thermal resistance, and it has been developing a high-efficiency cooling structure that integrates the heat sinks and water jacket.(4)

To further improve the cooling efficiency brought about by the water jacket integrated cooling structure, the internal structure improvement for the cooling unit is made in the M660.

As a result, the M660 reduced thermal resistance $R_{th(j\text{-}w)}$ to 0.1 °C/W, which is a 23% improvement over the $R_{th(j\text{-}w)}$ value of 0.13 °C/W for the conventional product. However, when implementing a thermal design, it is necessary to use the maximum $R_{th(j\text{-}w)}$ value in the module. Therefore, it was believed that thermal resistance could be reduced even further by reducing in-plane fluctuations for cooling performance. Figure 8 shows the positional relationship for the operation phases of the M660, as well as the in-plane fluctuation for $R_{th(j\text{-}w)}$ before and after optimizing the internal structure for the cooling unit.

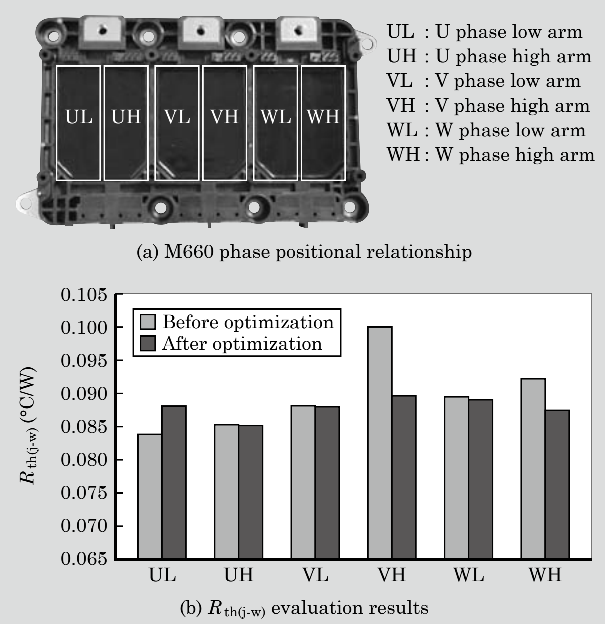

Fig.8 Thermal resistance $R_{th(j\text{-}w)}$ evaluation results before and after cooling unit improvement

As is clear from Fig. 8(b), it was possible to further improve $R_{th(j-w)}$ another 10% to achieve a value of 0.09 °C/W by improving the in-plane distribution for VH phase cooling performance.

4. Operable Current

In order to estimate maximum allowable current, a simulation was implemented with respect to chip temperature T_{vjop} with output current as a parameter in both the M660 and the conventional product (equipped with RC-IGBT with wire bonding).

The simulation conditions included battery voltage V_{DC} = 450 V, PWM switching frequency f_c = 5, 8 and 10 kHz, refrigerant temperature T_w = 65 °C and refrigerant flow rate = 10 L/min. Figure 9 shows the results of the T_{vjop} simulation for the M660, and Figure 10 shows the results of the T_{vjop} simulation for the conventional product.

Please note that Figs. 9 and 10 do not taken into consideration RC-IGBT characteristic fluctuations or changes in thermal resistance due to solder cracking while simulating actual use. At f_c = 10 kHz, the maximum output current for which T_{vjop} remains below 150 °C was improved to 525 Arms for the M660, which is 1.35 times better than the conventional product's value of 390 Arms.

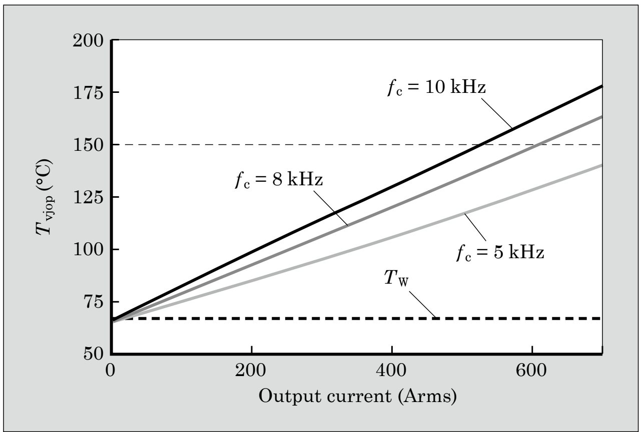

Fig.9 M660's T_{vjop} simulation results

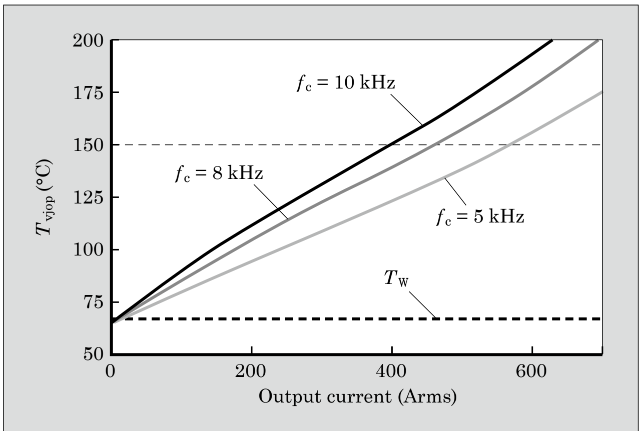

Fig.10 Conventional product's T_{vjop} simulation results

Actual products should have some margin in the characteristics in consideration of characteristic fluctuations in the mounted chip and solder cracking during actual operation. The guaranteed temperature for the RC-IGBT mounted to the M660 is 175 °C. In a worst case scenario that includes margin at f_c = 10 kHz, the M660 will be able to output current up to about 600 Arms.

The M660 reduces loss for the chip and achieves excellent heat dissipation performance through the use of lead frame technology, improved characteristics of RC-IGBT chip and cooling structure that integrates an optimized water jacket. As a result, the M660 is capable of operating in a larger current than conventional products.

5. Postscript

In this paper, we introduced the "M660" high-power IGBT module for automotive applications. The M660 is a general purpose 6-in-1 IGBT module that has achieved the world's largest rated capacity of 750 V/1,200 A through the utilization of a lead frame, characteristic enhanced RC-IGBT and cooling structure that integrates an optimized direct water-cooled water jacket.

We will continue to work to meet the growing demands of the electric vehicle industry so that we can help alleviate global warming.

References

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(4) Gohara, H. et al. "Next-gen IGBT module structure for hybrid vehicle with high cooling performance and high temperature operation", PCIM Europe 2014, p.1187-1194.

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