Always first-class results: Power Devices from Mitsubishi Electric
Power Modules for Electric and Hybrid Vehicles

This article presents 2 new Mitsubishi Electric power module series for Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV) power-train inverter and converter applications.

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The J1-Series

First a new 6-in-1 IGBT module (“J1-series”) with integrated water cooled Al-fin and Direct Lead Bond (DLB) structure is described [1]. Compared to conventional products, the adoption of these innovative technologies has led to an improved thermal performance of 30%, has reduced the cooling stack's footprint by 40% and its weight by 76%.

Introduction

The market for EV/HEV is growing by increasing global environment protection awareness. The power semiconductor module has become an important part to determine vehicle performance. Having pioneered the first mass production of dedicated automotive power semiconductor modules in 1997 already, the products of Mitsubishi Electric have been used in various mass-produced EV/HEV ever since.

The evolution of EV/HEV has been remarkable in this time frame and the power semiconductor module has become the key part for EV/HEV applications providing the required high performance, small size and light weight. In addition, a wide variety of EV and HEV covering various sizes and power requirements have been developed and power semiconductor modules were required with matching wide product line-up responding to these market requirements.

The J1-Series

Under these circumstances a family of new automotive power semiconductor modules “J1 Series” has been developed based on the concept of “high performance” and “compact size and light-weight” (Figure 1).

The J1 series modules are using a 6-in-1 topology (see Figure 2).

All IGBT-chips have integrated current sense emitters and integrated temperature sense diodes.

The module ratings and package dimensions are given in Table 1. The excellent Vce(sat)-values are the result of using the latest CSTBT chip technology.

<table>
<thead>
<tr>
<th>Type name</th>
<th>Ratings (Ic/Vces)</th>
<th>Vce(sat) Typ. @Ic, 25°C</th>
<th>Package Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT600CJ1A060</td>
<td>600A/650V</td>
<td>1.4V</td>
<td>120x115.2x31</td>
</tr>
<tr>
<td>CT400CJ1A090</td>
<td>400A/900V</td>
<td>1.7V</td>
<td>120x115.2x30</td>
</tr>
</tbody>
</table>

Table 1: J1-Series Power Module Line-up

Package structure

J1-Series modules are employing a built-in Aluminium cooling-fin. A cross sectional drawing is shown in Figure 3.

The directly water cooled module base plate allows to eliminate the thermal contact resistance between module base plate and external heat sink that is unavoidable for inverter designs with conventional modules. In this way a remarkable reduction of total Rth(j-w) compared to conventional designs is possible to achieve. For utilizing this benefit a reliable water cooling system must be designed for fitting the J1-module into the direct water cooling.

Direct Lead Bonding

The new J1-Series is using a highly reliable Direct Lead Bonding (DLB) structure [3] instead of conventional Al wire-bonding (W/B) technology. The principle difference between both technologies can be seen in Figure 4.
The DLB structure provides increased chip surface contact area greatly improving the power module current carrying capability. Compared to W/B packages, by utilizing the DLB structure, the package’s internal lead resistance and the parasitic internal package inductance can be reduced by more than 50% [4].

One further important advantage of the increased chip surface contact area is the uniform temperature distribution across the chip surface reducing the peak temperature value, and hence, resulting in lower stress for the emitter side chip contacting system. In other words, the DLB structure addresses the power-cycling stress issues usually encountered in conventional WB packages.

**Compact cooling stack design**

In comparison with more conventionally packaged products (J-Series T-PM [2], see Figure 5), the new J1-Series reduces the footprint of a 3-phase cooling stack by 40% (Figure 6).

Despite the fact that aluminium cooling-fins have lower thermal conductivity compared to copper cooling-fin structures, this selection provides several advantages to EV/HEV applications. Among these advantages the most prominent one is durability when Aluminium is exposed directly to coolants and its light weight. As shown in Figure 7 and 8, as much as 76% weight reduction and 30% thermal performance improvement was achieved when comparing 6-in-1 power module inverter solutions. The two solutions compared in Figure 7 are based on same module current and voltage ratings (600A/650V) for three-phase EV/HEV motor drives.

**Evaluation Kit**

Since the package size is not differing for several voltage and current classes, the test and evaluation of new J1-Series modules can be facilitated by a unique test environment that provides a DC-link capacitor, a simple and efficient cooling system (water jacket) and an interface circuitry with dedicated ICs controlling the state-of-the-art chip technology comprising an on-chip-diode for temperature sensing as well as the proven mirror emitter technology to detect over current situations before the IGBT de-saturates naturally.
The evaluation kit (gate drive board, DC-link capacitor, water jacket) is available for the evaluation of this new J1-Series IGBT module family (Figure 9 and 10). The comprised drive and protection circuit for short circuit (SC), over temperature (OT) and under voltage (UV) along with a switching mode power supply is optimized for the J1-Series. It is simply mounted on top of the J1-Series IGBT module and provides a comprehensive interface to a superimposed system control unit.

Experimental results
The new J1-Series’ power handling capability in conjunction with the performance of the thermal interface construction was experimentally verified under the following test conditions: main battery voltage = 350V; PWM switching frequency (fc) = 5kHz, 10kHz; coolant temperature (Tw) = 65°C; coolant flow-rate = 10 l/min. The proposed evaluation kit for J1-Series IGBT modules (Figure 9) has been used to carry out this investigation. Under these conditions the inverter output current can exceed 420Arms (corresponding to more than 80kW output power) at a maximum junction temperature of below 150°C as graphically presented in Figure 11.

J1-Series summary
A new series of automotive power semiconductor modules “J1-Series” has been developed to meet the requirements of the evolving EV/HEV market. The J1-Series achieves high performance, compact size and light weight and contributes to the evolution of automotive inverter system by providing state-of-the-art chip technology employing on-chip temperature sensing and mirror Emitter current sensing technology paired with proven high reliability core packaging technologies like Direct Lead Bonding (DLB) and Aluminum cooling fin.
Simplifying the testing of this new technology, an optimized evaluation kit comprising a water-cooling jacket and a driver board with dedicated drive and protection circuitry has been developed for this new family of automotive 6-in-1 IGBT modules.

Intelligent Power Modules (IPM) have been widely used in motor control applications in industry and in High Voltage (HV) traction applications. A dedicated series of IPMs ("J-Series IPM" [2]) has been designed for automotive applications for providing both high functionality and high reliability. The "J-Series IPM" lineup has been extended by 2 new modules, the so called "+B types" [2] with increased current handling capability. The target for this new development was to offer a "ready-to-use" solution to heavy electrical or heavy hybrid electrical vehicles designers. The "+B type" module ratings are given in Table 2.

Table 2: J-Series Intelligent Power Modules “+B type”

<table>
<thead>
<tr>
<th>Type name</th>
<th>Vce-rating</th>
<th>Ic-rating</th>
<th>Package Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM800CJGG060G</td>
<td>650V</td>
<td>800A</td>
<td>165x144.2x32 (6-in-1)</td>
</tr>
<tr>
<td>PM500CJGG120G</td>
<td>1200V</td>
<td>500A</td>
<td></td>
</tr>
</tbody>
</table>

Both "+B" IPM types are configured as "6-in-1" and are using the package outline shown in Figure 12:

Integrated functions
The integrated functionality is given in the block diagram in Figure 13. The power block consists of 6 freewheeling diodes and 6 IGBTs with integrated current sense emitters and temperature sense diodes. The protection block covers the following functions:

- IGBT chip over temperature protection
- Short circuit current protection
- Power supply under voltage protection
- DC-link voltage detection (optional)
- Analogue chip temperature detection circuit

The control block consists of the IGBT drivers and a fault output logic responsible for generating a single fault output signal Fo in case one of the protection functions had operated. The isolation block is using automotive grade high speed opto couplers for signal isolation. The power supply & I/O block contains a built-in switch mode power supply for feeding all IGBT drivers from a single +12V external power source as well as I/O processing circuits.

Input signals are: a) the PWM input from the Control MCU and b) the mandatory for automotive applications “ready” state monitoring signal.

Output signals are: a) the fault output signal Fo; b) the analogue chip temperature signal Tout and c) the analogue DC-link voltage signal VDC out (optional).

The second part of this article presents the extension of Mitsubishi’s 6-in-1 Intelligent Power Module Series for EV and HEV applications [2]. The newly developed "+B" J-IPM series is offering enhanced power ratings in a more compact package design, an integrated switching mode power supply (SMPS) and an improved thermal cycling capability. All dedicated functions for controlling IGBTs safely under EV/HEV application conditions (driving, protection and sensing) are integrated into the J-IPM.

Figure 12: J-Series IPM “+B” package outline

Figure 13: J-Series IPM type +B Block diagram

Figure 14: Three-Dimensional (3D) view of the "+B" IPM’s construction
Module structure and robustness against vibration
A 3D-view of the ‘+B’ type IPM is shown in Figure 14. A shielding plate is inserted between the power part and control PCB to prevent IGBTs and FWDs radiated noise to interfere with the IPM’s control board and disturb the overall control of the inverter.

Lead-free solder has been employed to comply with the “End of Life Vehicles” (ELV) directive.

For ensuring a reliable electrical connection to the superimposed control system a dedicated automotive grade connector has been used to facilitate the needed simplicity of assembly on one hand and robustness against vibration on the other hand. Furthermore, the entire IPM structure has been analytically modeled and simulated under vibration stress. The outcome of this investigation has influenced the outer and inner construction of the IPM resulting in robustness of the case and especially the sensitive control board against mechanical stress. Finally the mechanical ruggedness has been confirmed by actual vibration tests under the following conditions: acceleration > 10G, frequency = 100 ~ 1000Hz, direction = X, Y, and Z Axis.

Short circuit protection
One highlight of J-Series IPM is the over-current protection, employed by a fast response on-chip current sensor. This mirror Emitter sensing function shown in Figure 15 along with the soft shutdown approach provides a comparatively low current and voltage stress to the IGBT throughout the entire short circuit event that in turn provides a higher reliability than conventional de-saturation based detection methods. Figure 16 shows the typical short circuit turn-off behavior of a J-Series IPM.

Enhanced input / output functions
The “RDY” input terminal acts as an added input fail-safe protection measure. In case of an error situation the superimposed control system can directly shut down the IPM by sending a corresponding logic signal to this terminal.

The employed IGBT temperature monitoring function provides an analogue output signal Tout indicating the IGBT chip actual surface temperature through the utilization of a built-in temperature sensor located at the center of the chip. Compared to conventional temperature monitoring with thermistors located on the base plate, this approach provides higher accuracy and a linear output over a wide temperature range as indicated in Figure 17.

The J-IPM type ‘+B’ comprises a new function, e.g. a Tout output selection. This new feature selects automatically the hottest chip and routes the temperature information to the Tout terminal. Especially under locked rotor mode condition or at low output frequency operation at high load current the system control has the advantage to always look at the most stressed chip. This information, besides the efficient protection against chip over temperature, creates the possibility to adjust the inverter output power, the switching frequency or early warning messages and contributes to the reliability of the entire drive system.

The DC-link voltage monitoring function (optionally available) provides an analogue output signal (VDC out) indicating the voltage across the IPM’s main P and N terminals, giving valuable information to battery management functions.

Reliability
The optimization of the base plate’s and the substrate’s match of linear expansion coefficients (CTEs) as well as the interconnection between chip and substrate and the bonding technology itself have a great impact on the module’s reliability [5]. The J-Series IPM type ‘+B’ employs a “low linear expansion coefficient” base plate resulting in a substantial improvement of the T/C capability by about 5–10 times to that of general industrial power modules.

In line with the high reliability targets of the mechanical construction the integrated control board has been verified specifically for automotive applications by dedicated high-temperature and high-humidity bias stress tests.

J-Series IPM ‘‘+B’’ summary
The new J-IPM ‘+B’ modules provide a complete “easy-to-use” 6-in-1 system solution for high power HEV/EV applications. It allows building compact, robust and reliable propulsion systems for heavy electrical and heavy hybrid electrical vehicles. The use of J-IPM ‘+B’ helps to reduce the propulsion system development time as the implemented IPM functionality is providing ready state-of-the-art answers to all needs of an automotive inverter design.

Literature