The Building Blocks of Intelligent Power Modules

Fuji Electric

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TECHNICAL ARTICLES

Expanding the IPM Market

An Interview with James Usack of Fuji Electric

EE POWER

James Usack is the Electronic Devices Division General Manager of Fuji Electric. Image courtesy of James Usack.

Summary:
In this interview, James Usack, the Electronic Devices Division General Manager of Fuji Electric, discussed the company's growth in the intelligent power module market. From introducing the V series of IPMs fitted with IGBT chips, Fuji has produced several more series of IGBT-based IPMs. Now, the manufacturer is looking to expand its IPM offering with small and large capacity IPMs fitted with 7th generation IGBT technology.

As electronic systems become more intelligent, Usack said the power behind these electronic must become more intelligent. Because of their simplicity, efficiency, and high-integration, Usack believes the advancement of IPMs from companies like Fuji Electric will help the technology flourish in the power market.

How does Fuji Electric define what an intelligent power module (IPM) is?

Fuji is and has been making IPMs for a number of years. However, our IPMs were primarily in larger package types viewable in our catalog and the dual-in-line package (DIP) IPM, the so-called DIP-IPM, is relatively new to our portfolio.

An IPM is an acronym for Intelligent Power Module. An array of features and functions are integrated into the IPM. In a single package one gets safety, integrated functionality, and savings because of the integration of overcurrent protection, short circuit protection, control power voltage drop protection, and overheating protection, while also outputting alarm signals in one package.

The IPM and specifically the DIP-IPM has gained a lot of market acceptance in applications where size and performance are a design metrics. In a package that's about an inch wide by a little less than two inches long by about a quarter of an inch thick it really greatly reduces the footprint and also with an integrated control IC possessing IGBT drive circuits and protection circuits, it is therefore easy to design peripheral circuits and possible to ensure higher system reliability than you would normally get with a straight up discrete design.

What makes the IGBT IPM a good fit for Fuji Electric?

Basically, there are three primary vertically-integrated suppliers of IGBTs in the world: Fuji, Mitsubishi, and Infineon. We're in the top three; Fuji Electric is the best kept secret. In power electronics an IGBT is fundamentally used as a switch and in an IGBT module, the devices are simply used in a switching function and the IPM provides, like I said, that intelligent power module structure. It's integrated with the drive circuit and the protection functions.

So, to address the question will Fuji offer MOSFET based IPMs? I don't know. I haven't seen MOSFET based IPMs on the development roadmap. But it is possible. The IPM market had got many more players. What the IGBT module is to the former BJT device it's the same as the discrete device and the IPM.

An IGBT is kind of an interesting animal because an IGBT is basically the love child of a MOSFET and a BJT, bipolar junction transistor. The MOSFET is a voltage-controlled and easy to work with, but it didn't have much power. And the BJT had a whole lot of power, but it was current-controlled and not user friendly. So maybe 30-40 years ago, developers combined these devices and you got the ease of operation of the MOSFET with the power of the BJT. The front end of an IGBT is like a MOSFET. It's the best of both worlds.

Fuji Electric's V Series of IPMs has been a staple for quite some time in the intelligent power module space. How have you seen that series really boost Fuji in the power industry?

The V series was our first bona fide entrance into the DIP-IPM space and it really got us in the game. We did a lot of benchmark testing and we performed well against the incumbent IPM providers. The primary incumbent is Mitsubishi Electric; they are the dominant player in the DIP-IPM space. We

benchmarked well against them with the V series which has been around for a number of years.

An IGBT IPM. Image courtesy of Fuji Electric.

The 6th generation V-Series was our first-generation technology in the DIP-IPM space and now we have introduced the 7th generation X series DIP-IPM that is much more exciting because it leverages the experience that we've gained from the V series in the market. Just in general, in terms of our IGBT technology we have made improvements in our efficiency, which is a big metric for power devices. How efficiently the device can switch is key; the faster the device can switch the implications are reducing the overall size of the system because switching is fundamentally tied to any filtering that's required.

What does this X Series IPM bring to the industry that we're not seeing elsewhere?

We have leveraged the knowledge gained in the market to develop a better 7th generation X series IGBT, and also a IPM-based 7th generation DIP-IPM. We have the standard package that we have introduced with the V series which is also available in the X-Series and also expanded our offering in higher power side to what we call our large IPM, and are also planning to expand on the lower power side to a smaller IPM, the three DIP-IPM form factors that are most sought after by the market.

For the last four years, we have been rolling out the 7tth generation product portfolio starting with the sweet spot of the market, which is the 62-millimeter module, Dual.XT modules, and the PIM's or Power Integrated Modules then we added the higher power rated modules and the DIP-IPMs. The majority of our IGBT product offering our modules which are able to operate at a sustained 175C operating junction temperature. We are the only company that can operate at 175C without using a duty cycle which is the device is on for some time and then must be off for some time.

What is Fuji doing to edge out the competition in the IPM space?

Frankly speaking, we're trying to catch up and that is the honest answer. Basically, when you come into the DIP-IPM space later and not the first one in, there is the benefit of learning from what others have done and improving from there. We have certainly done that.

So true to form, we are going in our traditional, very deliberate pace, and in terms of the IPM market there are predominant packages – industry standards - which are the packages that are in our catalog today. We're also making these other variants, a smaller DIP-IPM and a larger DIP-IPM. Basically, we are targeting these three form factors. We have entered with the middle one, which is the high-volume sweet spot of the market. That was with the V series, and now we're improving that with the X-Series and we're also soon to offer the larger capacity version. We're planning on developing a smaller capacity version in the future. So, the plan is to offer these three types. Right now, our DIP-IPMs are 600V based IPMs though we may potentially develop 1200V IPMs.

What does the market look like for Fuji Electric's IPMs over the next five to 10 years?

The DIP-IPM and the small capacity market is part of our long-term strategy. We are very good in the middle part of the market — what we call the middle part of the market — in terms of current and voltage. We realized that in order to grow, we needed to diversify and penetrate the small capacity market – DIP-IPM country – and also the large capacity market which is the high-power module market. We are expanding the DIP-IPM from 15A-35A to 75A and on the high-power side to 2400A.

So that's what we're going to do. We believe that the long game for DIP-IPM is that we can gain market-share as we broaden our portfolio. Like I said previously, we started with the V-Series the industry standard high-volume package which got us in the game, got us known, got us sockets. Now we're going to expand with the higher capacity, the larger DIP-IPM, which will get us into the smaller frames in the drives market This will help us gain market share in these applications. Then with the smaller DIP- IPM that we're planning on developing, we will get us solidly into the consumer space.

You have got to believe, like the innovations like the Roomba vacuum cleaner, this is not like your mom's vacuum; the market is changing with the IOT. The new standard is the appliance got to have something in there that can be controlled by a microcontroller, and a DIP-IPM is perfect for that.

Do you see IPMs becoming an even larger part of the power space and something young engineers need to come into the workforce knowing?

In the old days it used to be discrete, discrete, discrete. I was working on a project long ago where we were trying to get IGBT devices into the bell housing of a motor to integrate the power into the motor frame. But it was really becoming a problem and somebody had the idea, "Well, I saw something about this DIP-IPM technology."

Frankly, when the IGBT came out, no one really knew much about it. If you could spell IGBT, people hired you. Then the technology reached an inflection point and just went to the stars in terms of adoption by engineers. Engineers realized that these things are really easy to work with. You don't need this very elaborate interface to turn the thing on and off. Using the IGBT was as simple as a light switch due to the voltage front end.

So, I think as the internet of things moves forward and more intelligence gets put into appliances in our lives, the IPM will continue to become more important. So, absolutely the IPM is going to proliferate, it's going to become cheaper, and it's going to become higher performing. There's so much integration — it's truly an intelligent power module.

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Introduction to Intelligent Power Module

An Intelligent Power Module (IPM) is a power semiconductor module that integrates into a single package all the circuitry required to operate an IGBT. It includes the required drive circuitry, the protection functions as well as the IGBTs. In this way, the best possible performance can be achieved from an available IGBT technology. Overcurrent, overheating and undervoltage detection are three of the self-protection functions commonly found in an IPM. In this article, we'll look at some of the basic concepts of this technology and see how an IPM can extract the best performance possible from an available IGBT device.

Power BJTs, MOSFETs, and IGBTs

Power BJTs have desirable on-state conduction performance; however, they are current-controlled devices and need complex base drive circuitry. With power MOSFETs being voltage-controlled devices, we need simpler drive circuitry. However, the major challenge with power MOSFETs is that their on-state resistance increases with device breakdown voltage. At voltage ratings above 200 V, MOSFETs exhibit inferior conduction performance as compared to a BJT. An IGBT combines the best of these two worlds to realize a high performance power switch: it offers the ease of drive of a MOSFET with on-state characteristics of a BJT. The main problem with an IGBT is a parasitic PNPN (thyristor) structure that can lead to device failure. Figure 1 illustrates the creation of this parasitic thyristor.

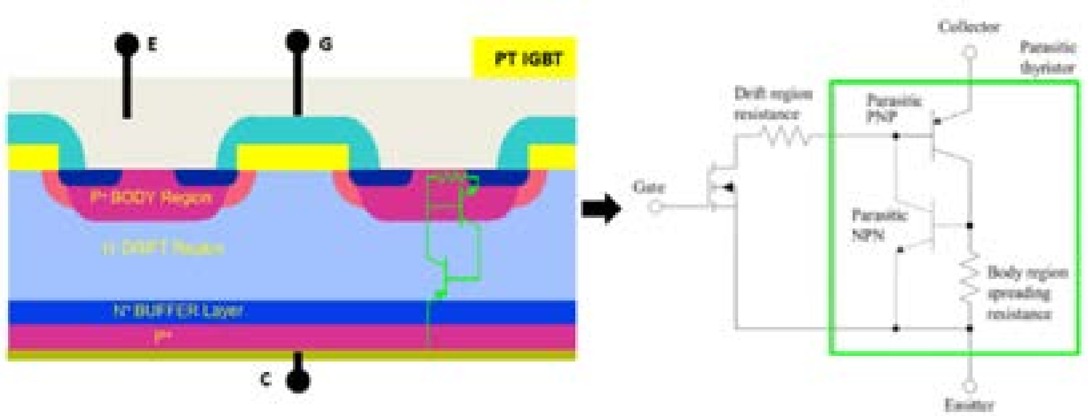


Figure 1: Vertical cross-section and equivalent circuit model of a punch-through (PT) IGBT. Image courtesy of STMicroelectronics.

Depending on the current density and the rate of change of voltage (dv/dt) at the device turn-off, the parasitic thyristor can turn on and cause device failure (latch-up). In this case, the IGBT current is no longer controlled by the gate voltage. The latch-up current is shown in Figure 2.

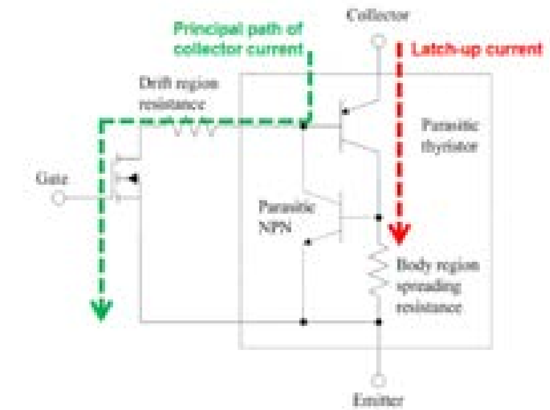


Figure 2: Image courtesy of STMicroelectronics.

Note that the body region resistance and the gain of BJTs are functions of ambient temperature and the device becomes more susceptible to latch-up at elevated temperatures.

The Basic Idea of an Intelligent Power Module (IPM)

Over the years, the IGBT manufacturers have improved the device physics to achieve better power switches that are capable of withstanding relatively larger current densities without experiencing a latch-up failure. Instead of optimizing the device performance, some manufacturers decided to add some control circuitry to the available IGBTs to prevent it from latch-up. This control circuitry, which is integrated with the IGBT, is a feedback loop with current sensing capability. It monitors the device current density to shut the device down when an overcurrent/short-circuit condition occurs. This feedback mechanism leads to an "intelligent" power switch that can protect itself from failure conditions. This basic functionality of an IPM is illustrated in Figure 3.

Current Sensing Methods

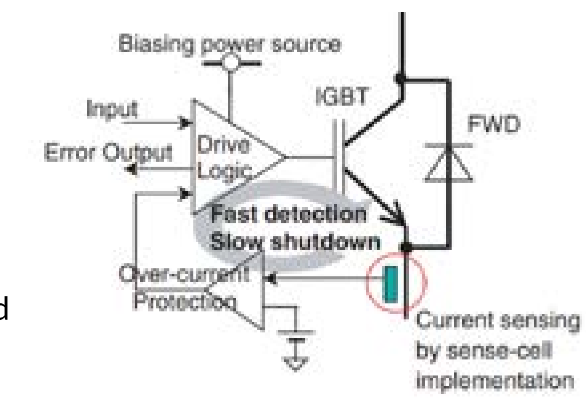


Figure 3: Image courtesy of Wiley Inter-Science.

IPMs employ several different ways of sensing the IGBT current. Some IPMs pass the IGBT current through an external shunt resistor to create a voltage proportional to the device current. The IC compares this voltage with a preset threshold value to detect an overcurrent condition. Figure 4 shows a simplified block diagram of the DIPIPM which is based on a shunt current sensing resistor. In this case, the voltage across R_{SHUNT} is sensed and low-pass filtered before being monitored by the CIN pin of the IC.

Another technique of overcurrent detection is called desaturation detection that is based on monitoring the IGBT collector voltage. During normal operation, the collector-emitter voltage of the IGBT is very low (1 V to 4 V typically). However, in the event of a short-circuit, the IGBT collector-emitter voltage increases. Therefore, this voltage can be used to detect an overcurrent condition. A disadvantage of the desaturation method is that it usually allows a high dissipation in the IGBT while detecting a short circuit condition. This paper presents an IGBT gate driver that uses the desaturation detection method to prevent the device from an overcurrent failure.

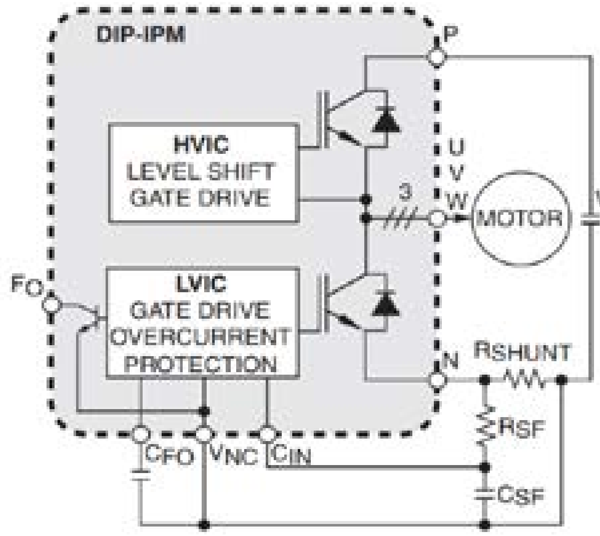


Figure 4: Image courtesy of Powerex.

Soft Shutdown of the IGBT

The feedback loop that monitors the device current should be able to detect the overcurrent condition rapidly; however, it is desired to shutdown the IGBT slowly after overcurrent is detected. Such a soft shutdown is implemented to suppress destructive surge voltages. The paper mentioned above discusses that a soft shutdown can reduce collector-to-emitter peak voltage by 30% when turning off a short-circuit collector current of 260 A.

Other Common Features

IPMs include other self-protection functions in addition to the short-circuit detection discussed above. Over temperature and under voltage protections are two of these functions that are commonly found in IPMs. The under voltage function monitors the power supply of the control circuitry of the IPM for an out-of-tolerance condition. When the supply voltage crosses a preset threshold value, the under voltage function turns off the power devices. This is done to avoid operating the IGBTs in the active (or linear) mode of operation that can be catastrophic. The over temperature function turns off the power devices when the chip temperature goes above a threshold temperature.

Packaging

Advanced packaging is the key to building today's high performance IPMs that need to implement the gate driver, sensing logic, and power semiconductor within the same hybrid IC package. Being notably different from a monolithic IC, a hybrid IC places individual components such as transistors, monolithic ICs, resistors, inductors, and capacitors in a single package. These components are bonded to a substrate or printed circuit board (PCB) inside the package.

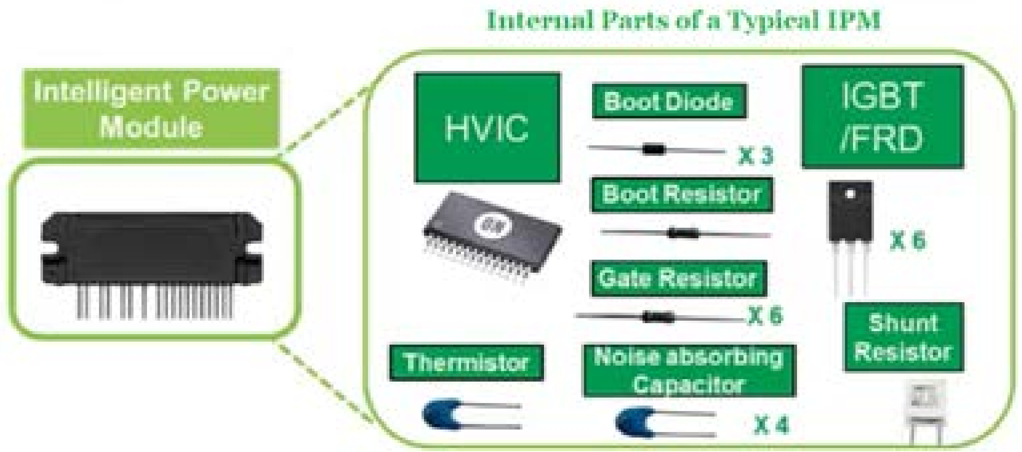


Figure 5: Image courtesy of ON Semiconductor.

IPMs are used for voltage ratings up to 600 V from a current rating as high as 100 A. As the power levels increase, the package heat extraction capability becomes more and more important. The substrate of a power module commonly operates at a temperature of 150-200 °C. Therefore, the substrate should exhibit high thermal conductivity so that we can place high power components in close proximity within a compact package. This is why new materials and advanced packaging technologies can significantly affect size, weight, and performance of the power semiconductor modules.

Conclusion

The IPM IC incorporates a built-in drive circuitry to achieve the best performance possible from available IGBT devices. IPMs have several self-protection functions such as overcurrent, overheating and undervoltage detection. We saw that modern IPMs require high performance power switches, optimized control circuitry and advanced packaging technologies. The following figure summarizes some of the concepts discussed in this article.

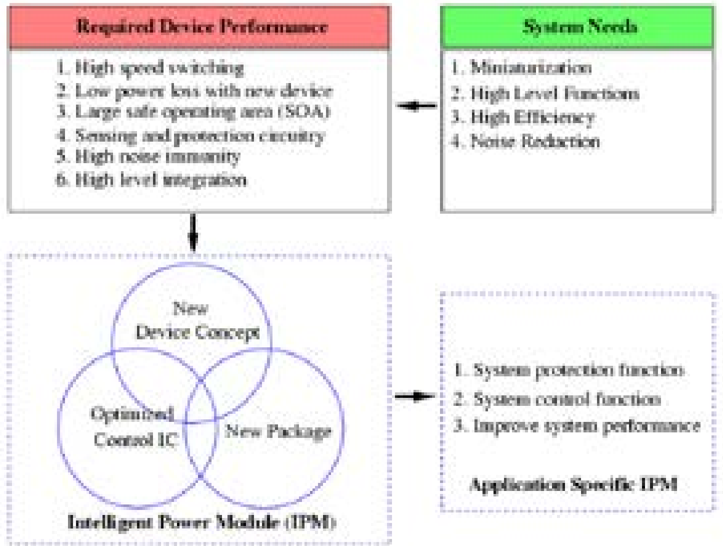


Figure 6: Image courtesy of Jong Mun Park.

TECHNICAL ARTICLES

Intelligent Power Modules (IPMs): Concepts, Features, and Applications

This article provides essential information on IPMs, which offer improved performance and simplified development for high-power switching applications.

What Is an Intelligent Power Module (IPM)?

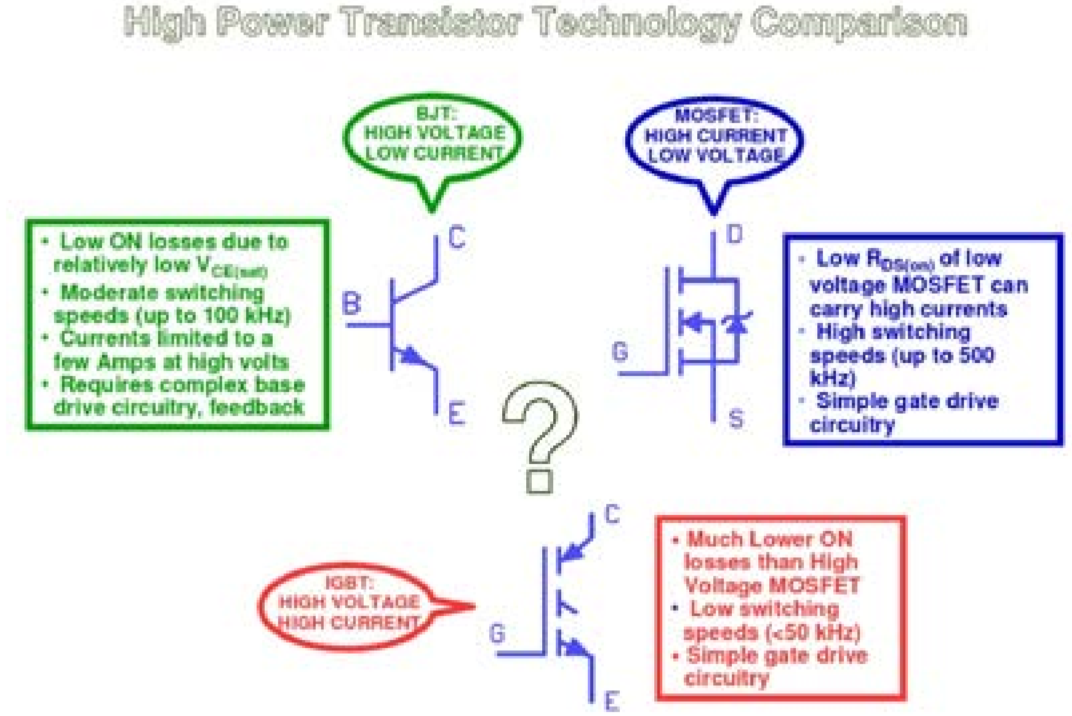
Here's the short answer: "Power module" refers to the presence of a power switching component (usually an IGBT), and the module is "intelligent" because it includes additional control and protection circuitry. The goal is to optimize performance and make the overall solution easier to design and implement.

This terminology might be a bit misleading. When I see the words "intelligent power module," my intuitive interpretation is "power supply module" (such as a DC/DC converter) plus "processor." (In all seriousness, immediately after I wrote this sentence, a marketing e-mail popped up in my inbox: "New Miniature 2W AC/DC Power Modules.")

Basically, I would expect an intelligent power module to be an integrated power supply device that incorporates the digital "intelligence" provided by a microprocessor. I suppose no one can stop me from using the term in this way, because it makes sense, but it's important to recognize that according to standard usage in the industry, an IPM is an advanced, highly integrated solid-state power switch.

IPM Features

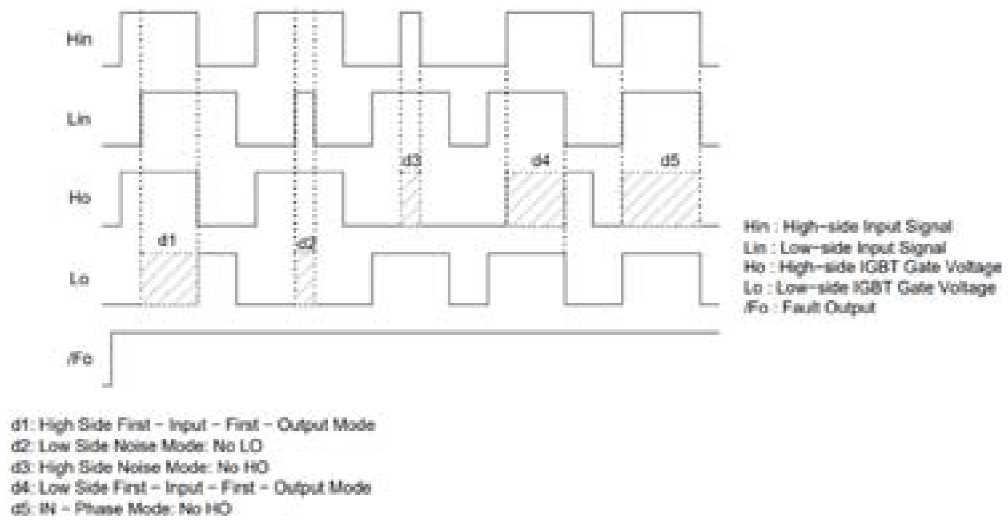
Optimized high-power switching is much more than just turning a FET or IGBT on and off. The following list conveys the features that might be incorporated into a power-switching application, and it also



For an excellent discussion of semiconductor devices used for high-power switching, take a look at FET vs. BJT vs. IGBT: What's the Right Choice for Your Power Stage Design?

conveys the features that we find in intelligent power modules.

- Gate-drive circuitry must apply the proper voltage and supply large amounts of current for fast switching.
- Gate-drive logic can also be designed to prevent high-side and low-side IGBTs from conducting simultaneously. This functionality goes by a few different names: shoot-through protection, cross-conduction prevention, or interlock circuitry.
- Protection circuitry should be able to detect and address overcurrent, overtemperature, short-circuit, and undervoltage conditions. If the system needs to keep records of fault events or operational temperatures, some sort of communication functionality will also be required.
- EMI specifications may necessitate specialized switching behavior.
- Space or cost restrictions might oblige a designer to reduce power losses that occur during switching and on-state conduction, so that a smaller heatsink or enclosure can be used.
- Some applications require power factor correction (PFC).



This diagram illustrates the interlock functionality of the FNB81060T3, a 600 V IPM from ON Semiconductor. Notice how the high-side and low-side gate voltages don't respond to input signals that would lead to cross conduction.

Basically, IPM manufacturers try to integrate any feature or functionality that they can in order to enhance the performance, increase the manufacturability, lower the cost, reduce the size, improve the reliability, simplify the implementation, or accelerate the time to market of a semiconductor-based power-switching circuit.

Voltage Specifications

Intelligent power modules are directed primarily at the high-voltage market. "High" is a relative term; in the parlance of low-voltage engineers such as myself, 50 V might qualify as "high," but that's actually very low in the context of IPMs.

For example, the lowest maximum voltage rating in Infineon's CIPOS Nano family is 40 V. The highest is 600 V, and the Nano line is the smallest, lowest-power option in Infineon's lineup. The Maxi family tolerates voltages up to 1200 V and can dissipate 50 W of power per IGBT.

As another example, Powerex uses the term "low power" to describe IPMs that are specified at 50 A and 600 V. The higher-power modules can handle 75 A.

Form Factor

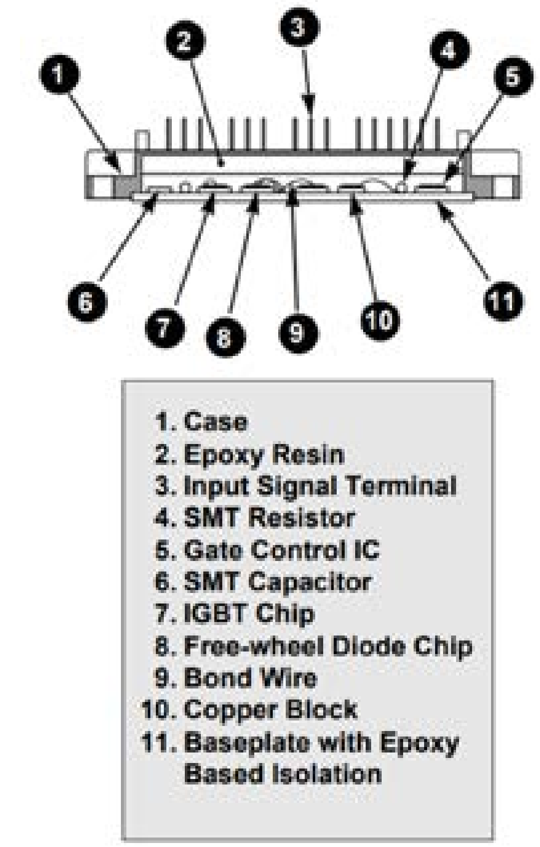
Intelligent power modules tend to come in through-hole packages that I would describe as somewhat nonstandard. Here are some examples:

This is a rendering of the FNB81060T3 (mentioned above).

Applications

Intelligent power modules are most closely associated with motor control, but they're also used in uninterruptible power supplies, inverters, and renewable energy systems. The list below indicates some of the intended applications mentioned by manufacturers.

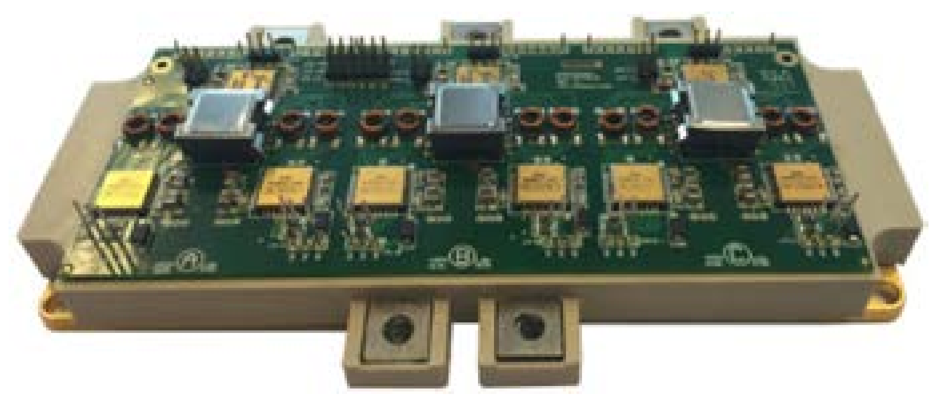
- Home appliances: fans, air purifiers, washing machines, air conditioners, refrigerators, vacuum cleaners
- Industrial: pumps, compressors, HVAC, elevators
- Automotive: AC compressors, oil pumps, on-board charging in electric vehicles



This diagram from Powerex conveys the form factor and internal structure of their lower-power Intellimod IPMs.

Conclusion

Intelligent power modules greatly facilitate the task of developing a reliable, efficient, compact circuit for high-power solid-state switching. These versatile components can find a place in many applications, and they will surely grow in popularity and importance as system requirements and performance expectations become more challenging for designers.



CISSOID developed an aerospace IPM that uses silicon carbide (SiC) MOSFETs instead of IGBTs.

TECHNICAL ARTICLES

2nd-Generation Small IPM Series

Fuji Electric has recently added products with current ratings of 20 and 30 A to our 2nd-generation small IPM series to meet the needs of motor drive devices. Applying the 7th-generation IGBT chip technology as a base and optimizing the lifetime control and drift layer thickness of the FWD, we have significantly reduces the temperature rise while lowering noise and loss. We ran a temperature rise simulation of a package air conditioner that has a standard cooling capacity of 14 kW at the maximum load, which are expected to be actual conditions. It showed 11oC lower temperatures than the 1st-generation small IPM. It can therefore expand the allowable output current of the devices.

Introduction

In recent years, there has been increasing demand for energy-saving in motor drive devices to prevent global warming caused by the increase in greenhouse gases. Among these devices, packaged air conditioners (for commercial use), which consume a relatively large amount of energy, were designated as being subject to the “Top Runner Program” in FY2015, thus requiring a significant improvement in their annual performance factor (APF, indicates year-round efficiency in energy consumption) and higher efficiency in the intermediate load region. Furthermore, compactness and space savings are also being required, as well as improvement of loss under high loads in order to expand the range of operating temperatures in outdoor units.

In addition, there has also been increased demand for high efficiency in industrial-use general-purpose inverters and servo systems, whose housings and frames have been increasingly downsized, in order to correspond to the expansion in output capacity.

Fuji Electric has met these demands with the development of its compact, low-loss and low-noise small-intelligent power module (IPM[1]), which integrates a 3-phase inverter bridge circuit, control circuit and protective circuit, for application in inverter type small-motor drives.

Recently, in order to further improve the energy-saving performance of motor drive devices in packaged air conditioners, general-purpose inverters and servo systems, we have introduced a 20 and 30 A rated current 2nd-generation small IPM[2] equipped with 7th-generation insulated gate bipolar transistor (IGBT) chip technology[3] into our product line-up.

Product Overview

Figure 1 shows the external appearance of the recently developed 2nd-generation small IPM, and Table 1 shows the product line-up and the main characteristics.

The products employ the same compact package as the currently mass produced 10- and 15-A products, the external dimensions of which is 43 × 26 × 3.7 (mm), and the modules contribute to the miniaturization of inverter circuit.
Similar to the 10- and 15-A products, 2 different types of temperature protection functions are available: one type with only analog temperature output, and the other type with analog temperature output and overheat protection.

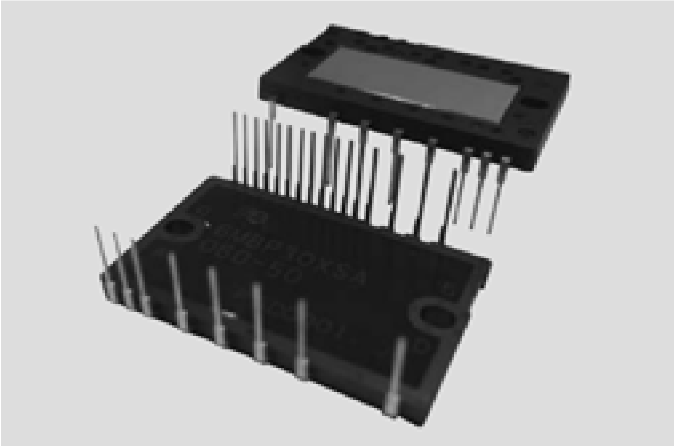


Fig. 1. 2nd-generation small IPM

The recently developed 20- and 30-A products can be used for a variety of devices such as compressor driving units of packaged air conditioners with capacity of 8 to 14 kW, general-purpose inverters with an output of 1.0 to 2.2 kW, and servo amplifiers with 0.4 to 1.0-kW output.

Figure 2 shows the internal equivalent circuit. Similar to the 10- and 15-A products, the modules mount a 3-phase inverter bridge circuit composed of low-loss IGBTs utilizing 7th-generation IGBT chip technology and high-speed freewheeling diodes (FWD) mounted on an aluminum insulating substrate. A single low voltage integrated circuit (LVIC) for operating the low-side IGBTs of the 3-phase inverter

Type name	V_{CE}	I_C	$V_{CE(sat)}$ (typ.)	V_F (typ.)	Temperature protection function
6MBP20XSA060-50	600 V	20 A	1.45 V	1.50 V	Analog temperature output
6MBP20XSC060-50					Analog temperature output + overheat protection
6MBP30XSA060-50		30 A	1.45 V	1.55 V	Analog temperature output
6MBP30XSC060-50					Analog temperature output + overheat protection

Table 1. Product lineup and main characteristics

bridge circuit and 3 high voltage integrated circuits (HVIC) for operating the high-side IGBTs are directly mounted on the lead frame.

In addition, by including the boot-strap-diodes (BSD) with built-in current limiting resistor, the power supply of the high-side drive circuit can be configured with only a small number of components.

Compared with the 1st-generation small IPM, the 2nd-generation small IPM has expanded the permissible output current of the inverter circuit and improved design flexibility by utilizing low-loss devices and expanding the operation-guaranteed temperature $T_{j(ope)}$ from 125 °C to 150 °C.

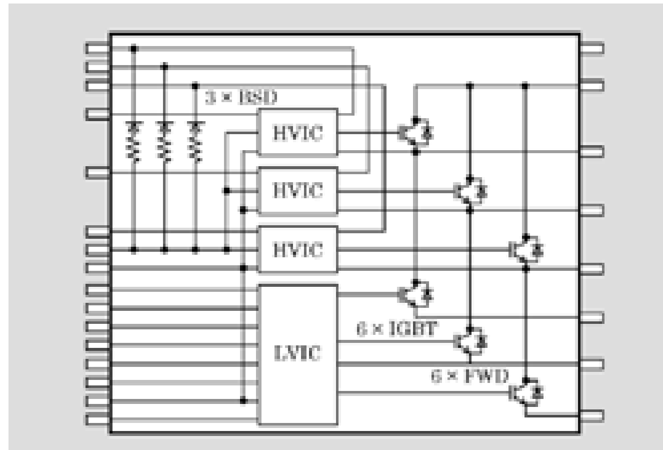


Fig. 2. Internal equivalent circuit

Design

Device design

The expansion of the current capacity brought concern about an increase in the noise generated during switching operation. Thus, as a countermeasure, a low-noise design for improving the trade-off between switching loss and noise has been adopted.

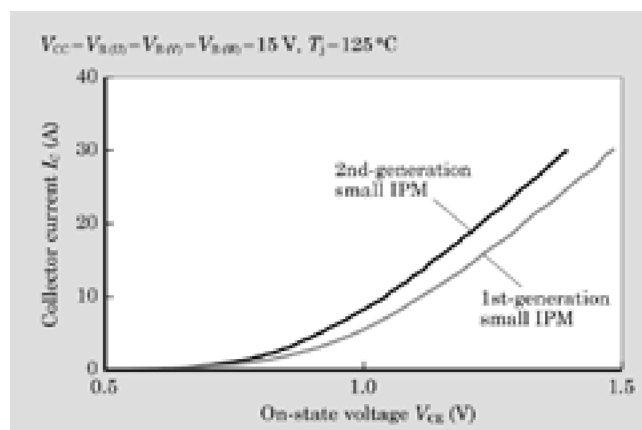


Fig. 3. IGBT on-state voltage and collector current characteristics

(1) Reduction of conduction loss
We have optimized the gate threshold voltage and the cell pitch layout of the trench gate of the IGBT based on the 7th-generation IGBT chip technology to reduce conduction loss.

Figure 3 shows the IGBT on-state voltage and collector current characteristics. Compared with the 1st-generation small IPM, the on-state voltage of the 30-A rated products is reduced by approximately 8% at the rated current, and approximately 7% at the low-current region, which greatly influences APF, that is, an important factor for air conditioning applications.

(2) Reduction of turn-off loss
Though increasing the switching speed is one of the measures to reduce turn-off loss, it may increase generated noise due to the sharp rise in dv/dt.

For the 2nd-generation small IPM, we have suppressed dv/dt to the same level as that of the 1st-generation small IPM to the same level as that of the 1st-generation small IPM while successfully suppressing the tail current generated during IGBT turn-off, and improved the trade-off between noise and turn-off loss. In order to suppress the tail current, we have optimized the thickness of the IGBT drift layer and the amount of carriers injected from the rear-surface pn junction and field stop layer.

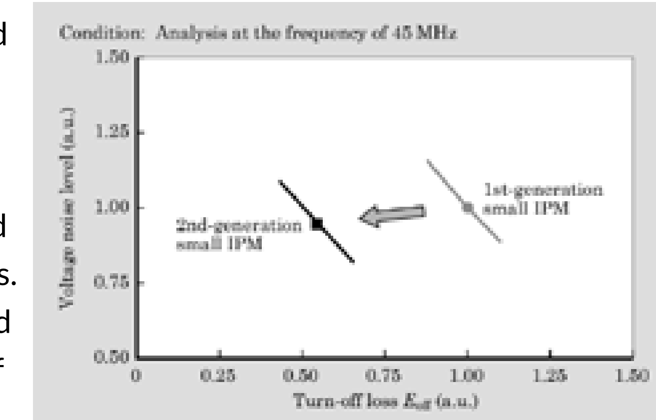


Fig. 4. Trade-off characteristics between IGBT voltage noise level and turn-off loss

Figure 4 shows the trade-off characteristics between turn-off loss and the voltage noise level based on the frequency analysis of the turn-off waveforms of the IGBT. The module has the same voltage noise level as the 1st-generation small IPM at the rated current of 30 A while also significantly reducing the turn-off loss by approximately 50%.

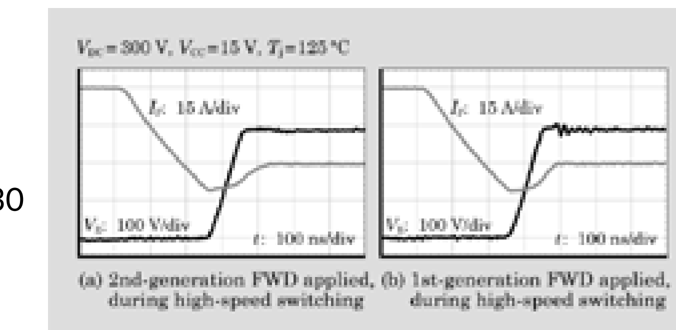


Fig. 5. Switching waveforms during recovery

(3) Reduction of turn-on loss
Figure 5 shows the switching waveforms during recovery. If we use the FWD of the 1st-generation small IPM and increase the switching speed to reduce the switching loss, there would be a large increase in generated noise due to the increase in surge voltage. In order to simultaneously suppress generated noise and reduce turn-on loss, it is necessary to reduce the recovery current and suppress the surge voltage.

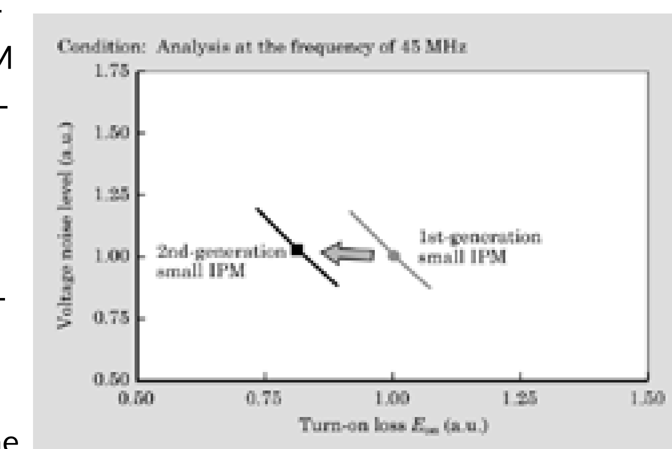


Fig. 6. Trade-off characteristics between FWD voltage noise level and turn-on loss

Figure 6 shows the trade-off characteristic between the turn-on loss and voltage noise level during FWD recovery. We have optimized the recently developed product in terms of the lifetime control and thickness of the WD drift layer and reduced the turn-on loss by approximately 20% compared with the 1st-generation small IPM at a rated current of 30 A while maintaining the same voltage noise level.

Control circuit design

The LVIC overheat protection function needs to ensure that the LVIC junction temperature Tj (LVIC) does not exceed the operation-guaranteed value while also making sure that the protection function is not engaged due to temperature rise during continuous operation of the IGBT.

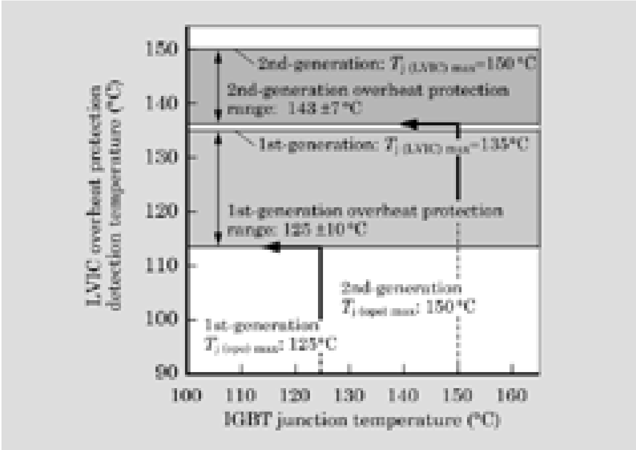


Fig. 7. LVIC overheat protection detection temperature and IGBT junction temperature

The upper limit of the operating temperature range of the LVIC junction temperature Tj (LVIC) in the 2nd-generation small IPM is 150 °C as shown in Fig. 7. Furthermore, when the temperature of IGBT reaches the upper limit of the IGBT operation-guaranteed temperature T_j ($_{ope}$) of 150 °C, the temperature of the adjacent LVIC will rise to 136 °C, and as a result, it is necessary to ensure that overheat protection is not engaged at this temperature or below. Therefore, we have suppressed the variation in detection of LVIC junction temperature and established an overheat protection range of 143 °C ±7 °C. On the other hand, 135 °C is specified for the upper limit of the LVIC junction operating temperature range Tj (LVIC) in the 1st-generation small IPM. Furthermore, when the junction operating temperature reaches the upper limit of the IGBT operation-guaranteed temperature T_j ($_{ope}$) of 125 °C, the temperature of the adjacent LVIC will rise to 115 °C. As a result, the overheat protection range was set at 125 °C ±10 °C. Therefore, the 2nd-generation small IPM not only expands the operating temperature range of the LVIC, but by increasing the precision of the reference power circuit inside the IC to ensure that the detection range is ±7 °C or lower. Consequently, we have expanded the IGBT operation-guaranteed temperature T_j ($_{ope}$) to 25 °C above that of the 1st-generation small IPM, or 150 °C, which allows the expansion of permissible output current. In addition, by maintaining compatibility with the 1st-gener ation small IPM in regard to the characteristic value of the analog temperature output function built into the LVIC, we can support our customers to standardize protection circuit designs.

Package design

The 2nd-generation small IPM has the package structure that the package is directly soldered to the printed circuit board of equipment, such as packaged air conditioners and general-purpose inverters. As the output current of the printed circuit board increases, the temperature of the external lead terminal rises, and as a result, the temperature at the soldered parts also rises.

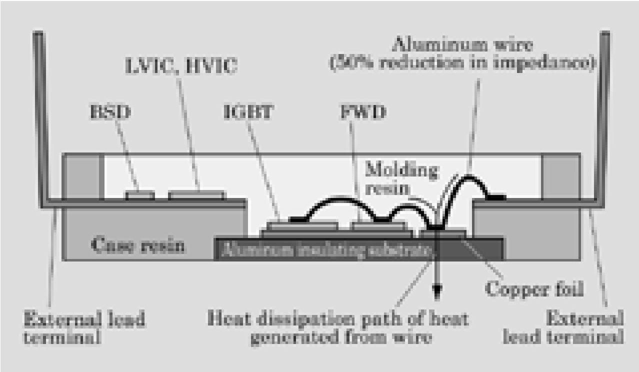


Fig. 8. Package's cross section structure

On the other hand, in order to ensure the reliability of the soldered parts, the temperature at the soldered parts during operation must be kept within 90 °C to 100 °C or below. To achieve this, the output current had to be restricted.

Figure 8 shows the cross section structure of the package. Similar to previous 10- and 15-A products, the recently developed modules have the structure that conducts Joule heat generated by the wire to the aluminum insulating substrate. In addition, according to the expansion of the current capacity, they use 50% lower impedance wires than that of the conventional products to suppress temperature rise at the external lead terminal, thus reducing the Joule heat.

Application Effect

This section provides the application effect of the 600-V/30-A products used for packaged air conditioners and servo amplifiers.

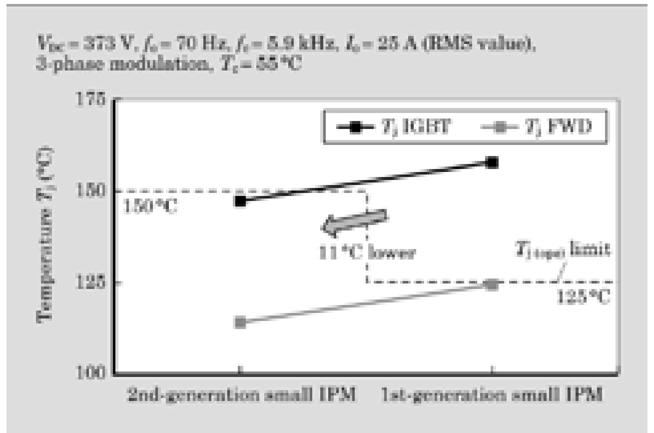


Fig. 9. Results of temperature rise simulation during maximum load in package air conditioner

Figure 9 shows the simulation results of temperature rise at maximum load for a standard 14 kW packaged air conditioner.

A temperature rise at maximum load is lower for the 2nd-generation small IPM than the 1st-generation small IPM by 11 °C because of the loss-reduction effect previously mentioned. In addition, compared with the 1st-generation small IPM, the 2nd-generation small IPM has expanded the operation-guaranteed temperature Tj (ope) from 125 °C to 150 °C, thus enabling operation at the operation-guaranteed temperature T_j ($_{ope}$) or below. As a result, it can be used for the air conditioners, the output current capacity of which require larger rating IPM than the 1st-generation small IPM.

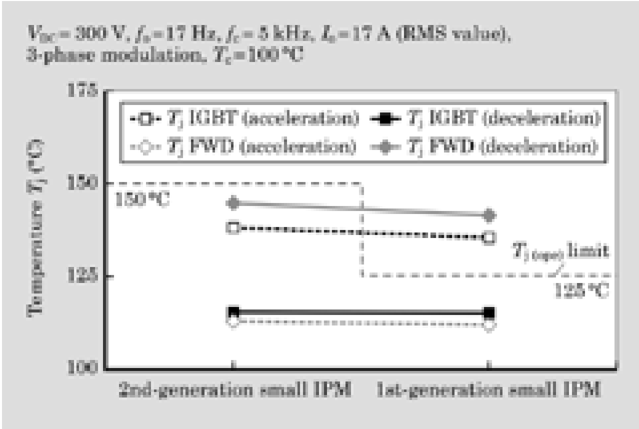


Fig. 10. Results of temperature rise simulation during acceleration/deceleration in servo amplifier

Figure 10 shows the results of the temperature rise simulation during acceleration/deceleration in a servo amplifier with an output of 1.0 kW, and Figure 11 shows the results of the temperature rise simulation during the motor lock operation.

The temperature rise during acceleration and deceleration and the motor lock operation for the 2nd-generation small IPM is nearly identical to that of the 1st-generation small IPM. On the other hand, the 2nd-generation small IPM has an extended operation-guaranteed temperature T_j ($_{ope}$) of 150 °C, which is higher than that of the 1st-generation small IPM, 125 °C, thus enabling operation at the operation-guaranteed temperature T_j ($_{ope}$) or below. As a result, it can be used for the servo amplifiers, the output current capacity of which require larger rating IPM than the 1st-generation small IPM.

Figure 12 shows the measured results of the temperature at the soldered parts of the printed circuit board for a package air conditioner mounted with the 600-V/30-A product operating in an ordinary state under pulse width modulation (PWM). The soldered parts of the 2nd-generation small IPM is lower than that of the 1st generation small IPM by approximately 14 °C because of the lower loss of the device and the suppression effect in the temperature rise of the external lead terminals of the package. Consequently, the ability to suppress the temperature rise in the soldered parts has enabled the expansion of permissible output current by approximately 19%.

Figure 13 shows the evaluation results regarding conduction noise when applying in a servo amplifier with an output of 0.75 kW. The module is compliant with the limit value (QP) prescribed in Category C2 of EN61800-3 and achieved the desired low-noise characteristic in combination with the previously described temperature-rise suppression effect.

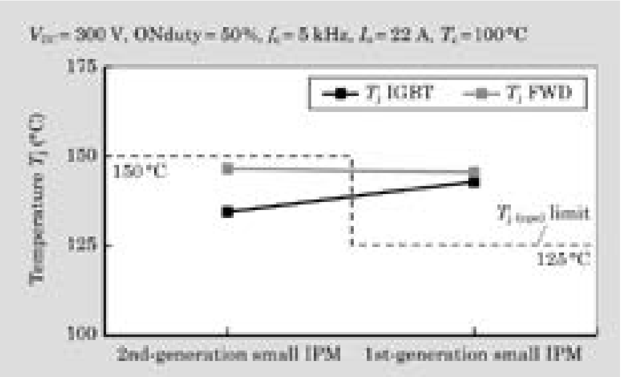


Fig. 11. Results of temperature rise simulation during motor lock operation in servo amplifier

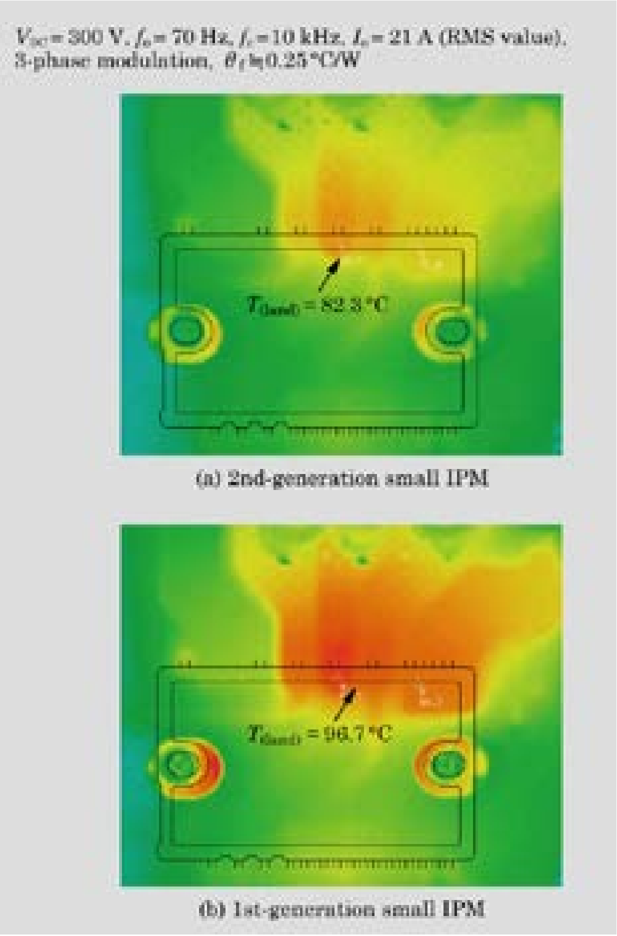


Fig. 12. Results of measuring temperature of soldered components during PWM operation in package air conditioner

Postscript

In this paper, we described the 20- and 30-A products which expanded the current capacity of the 2nd-generation small IPM series. Similar to the currently being mass produced 10- and 15-A products, these products employ optimized low-noise, low-loss devices based on the 7th-generation IGBT chip technology, and they can achieve energy savings in inverter controlled motor drive devices.

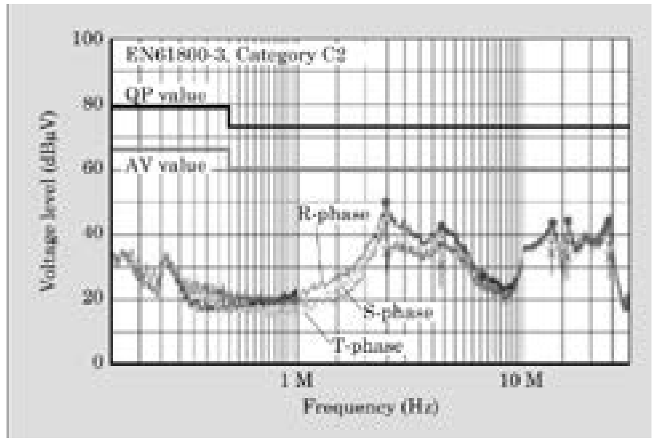


Fig. 13. Results of conduction noise evaluation in servo amplifier

In the future, we plan to continue developing products that contribute to improving the energy-saving performance of motor drive devices.

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TECHNICAL ARTICLES

Line-Up of 2nd-Generation Small IPM with 650 V / 50 A, 75 A

In recent years, to deal with global environmental problems, there has been increasing demand for energy conservation to cope with greenhouse gas emission regulations and size reduction to save on resources. Fuji Electric developed a line-up of 2nd-generation Small-IPM with 650 V / 50 A and 75 A that integrate the power devices and control ICs to compose inverter circuits. The products adopting "X Series" IGBT chip technology reduce their power dissipation compared to conventional products and increase the maximum operating temperature from 125 °C to 150 °C by using a high heat-resistant packaging technology. These enhancements will contribute to saving energy, downsizing of power conversion systems and increasing their output current.

Introduction

In recent years, to deal with global environmental problems, there has been increasing demand for energy conservation to cope with greenhouse gas emission regulations and size reduction to save on resources. Inverter air conditioners, motor drives, and servos amp, which are the target of Small-IPM (intelligent power modules), also need to meet these requirements.

Especially, for the inverter air conditioners in principal countries, energy saving standard is established on the basis of the annual performance factor (APF), which represents the energy consumption efficiency estimated under actual usage.

In addition to an energy saving characteristic, equipment needs to have a low noise characteristic that conforms to standards related to electro magnetic compatibility (EMC) specified by the special committee of IEC, Comité international spécial des perturbations radioélectriques (CISPR).

In order to meet market demands, Fuji Electric has provided Small IPM integrated with power devices and control ICs to compose inverter circuits.[(1)]

The Small IPM includes a 3-phase inverter bridge circuit, a control circuit and a protection circuit on one package, contributing to a size reduction of inverter circuits. The 2nd-generation Small IPM (2G-IPM) with rated values 600 V/10 A to 30 A, which was released in 2015, applies the chip technology[(2)] of the"X-series" insulated gate bipolar transistor (IGBT). The product achieved lower power dissipation compared with the conventional types, further saving energy. Furthermore, this product realized increase of maximum operating temperature T_{vjop} from 125 °C to 150 °C based on the high heat-resistant package technology. In addition, thus, the easiness to design and the expansion of the application area of inverters are achieved by improving the accuracy of the over-current detection and the overheat protection function.

The product series of rated 650 V / 50 A, 75 A, which is developed on the basis of 2G-IPM technology, is added to the product line-up this time. In this paper, the features of 2G-IPM technology are described hereinafter.

Figure 1 and Table 1 show an external view of the product and its main characteristics respectively. The product has outer dimension of 79.0 × 31.0 × 7.8 (mm) and adopts a dual in-line structure. The safety standard of insulation conforms to the UL1557. The rated voltage is 650 V, and the rated currents is 50 A or 75 A. Each type has a line-up with or without the overheat protection function.

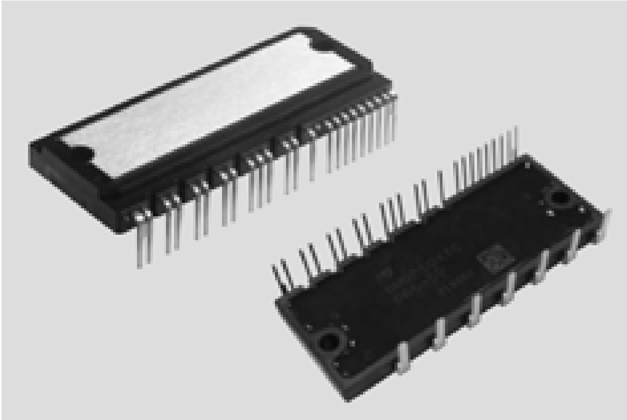

Fig. 1. Product appearance

Figure 2 shows the circuit configuration of the 2G-IPM. The 2G-IPM includes a 3-phase inverter bridge circuit, which consists of 6 pairs of low-loss IGBTs and high-speed free wheeling diodes (FWD). Each low side IGBT has a shunt current sense IGBT*1. The 2G-IPM has a chip of low-voltage integrated circuit (LVIC) for

Voltage	Type name	I_C	I_{CP}	$V_{CE(sat)}$	V_F	Guaranteed operating temperature	Over-temperature protection function
650 V	6MBP50XTA065-50	50 A	100 A	1.30 V (typ.)	1.55 V (typ.)	$T_{vjop} \le 150$ °C	None
	6MBP50XTC065-50						Yes
	6MBP75XTA065-50	75 A	150 A	1.30 V (typ.)	1.80 V (typ.)		None
	6MBP75XTC065-50						Yes

Table 1: Main characteristics of product

*1: Sense IGBT: IGBT with a current sensing function for over-current protection driving the low-side IGBT and 3 chips high-voltage integrated circuits (HVIC) for driving high-side IGBTs. And this 2G-IPM has a 3 chips of the boot-strap diode (BSD) with current limitter resistors. These make it easy to compose high side power supply by only connecting the external capacitors. Therefore, an external insulating power supply is unnecessary, and the space of print circuit boards can be saved.

Product Design

Device design

(1) IGBT

Figure 3 shows the cross section structures of the IGBT chip for 1st-generation Small IPM (1G-IPM) and that for 2G-IPMs. The IGBT chip for 2G-IPMs is based on the X-Series IGBT technology, such as fine cell technology and thinner wafer technology. Those IGBT chips include a newly developed current sensing part, and the IGBT cells for sensing the current are shunted from those of the main current part. Figure 4 shows trade-off relationship between saturated voltage V CE(sat) and turn-off loss E off. The V CE(sat) and turn-off loss of 2G-IPMs are improved by 0.5 V and about 56% respectively compared with 1G-IPMs by optimizing the resistivity and thickness of the drift layer, doping profile of the filed stop (FS) layer and channel density.

(2) FWD

For the improvement of FWD chip characteristics, it is necessary to suppress the dvr/dt during the reverse recovery resulting in noise generation and to reduce the reverse recovery loss.

Figure 5 and Fig. 6 show trade-off relationship be tween dvr/dt and Err, and the comparison of the FFT analysis of reverse recovery voltage waveforms between FWD chips

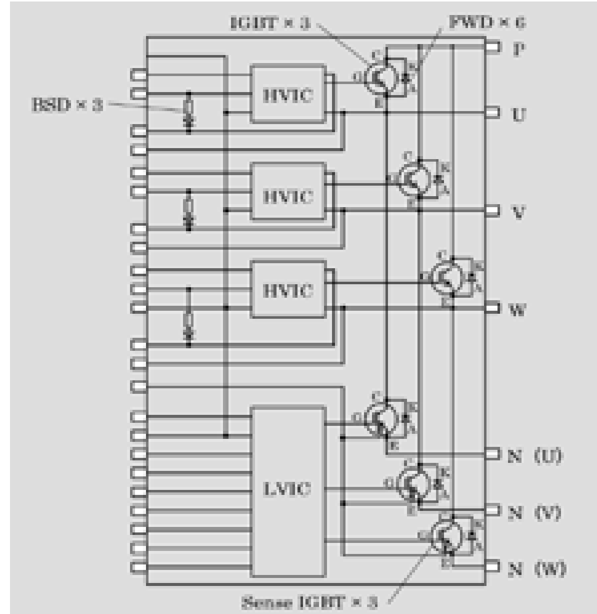

Fig. 2. Internal equivalent circuit

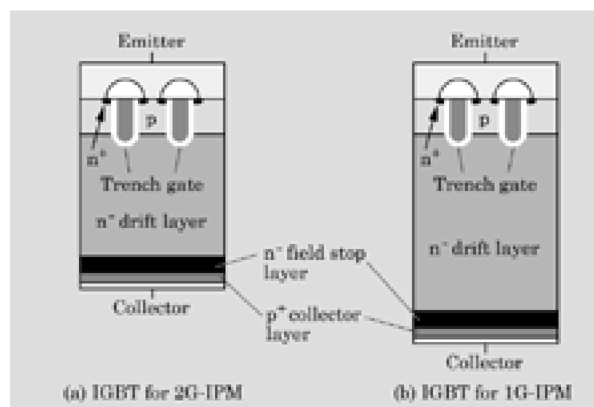

Fig. 3. Comparison of cross section structures of IGBT chips

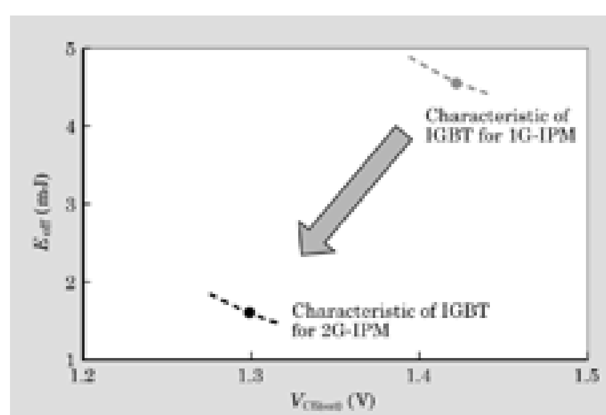

Fig. 4. Trade-off relationship of $V_{CE(sat)}$-E_{off}

for 1G-IPMs and those for 2G-IPMs respectively. The FWD for 2G-IPMs is based on the "X-Series FWD" technology. Furthermore, both of soft recovery waveforms and improvement of the trade-off characteristics have been realized by optimizing the anode diffusion profile and the lifetime control. Thus, 10-dB noise reduction by 15% decrease of the dv_r/d_t and 55% reverse recovery loss reduction are expected compared with 1G-IPM.

Packaging

Figure 7 shows the cross section of the package structure. The package structure of newly developed 2G-IPMs is similar to that of 2G-IPMs in mass-production. This package structure has been realized by using the aluminum IMS (insulated metal substrate) and high adhesive strength with the molding resin. In the case of the 1G-IPMs in the actual operation, chip heat was transferred to the outer leads via wire, and there had been a problem that the outer leads reach high temperature. On the other hand, the temperature rise of the outer leads of 2G-IPMs is reduced with the structure in which the heat of the inter nal wire is dissipated to the aluminum IMS.

Table 2 shows the results of reliability tests. To achieve the high reliability performance that is equivalent to that of the conventional types, the 2G-IPMs with rated values 650 V/50 A and 75 A are designed to suppress the heat

Test items	Test condition	Guaranteed value	Judgment
Thermal cycle test	Low temp.: −40 °C High temp.: 125 °C	100 cycle	No characteristics variation
ΔT_{vj} power cycle test	ΔT_{vj} = 100±5 °C T_{vj} ≤ 150 °C T_C ≤ 125 °C I_C ≥ 50 A	15 kcycle	No characteristics variation
High temperature reverse bias test	T_{vj} = 150°C V_{CC} = 20 V V_{CE} = 510 V	1,000 h	No characteristics variation

Table 2: Result of reliability test (main items)

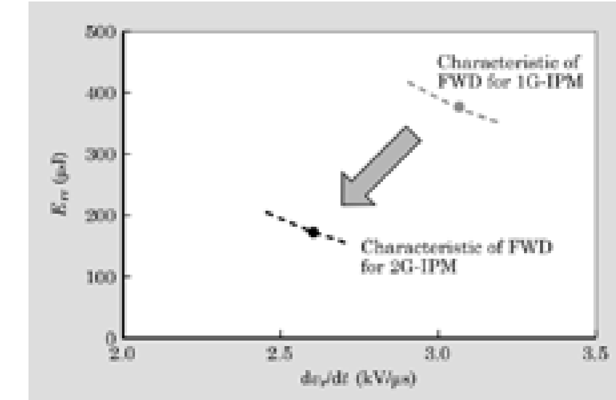

Fig. 5. Trade-off relationship of dv_r/dt-E_{rr}

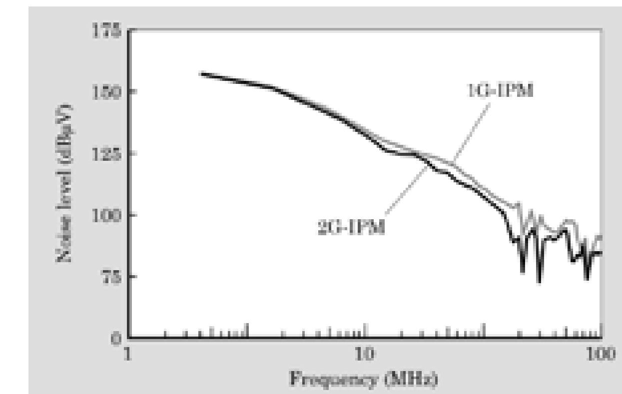

Fig. 6. Result of FFT analysis of reverse recovery voltage waveform

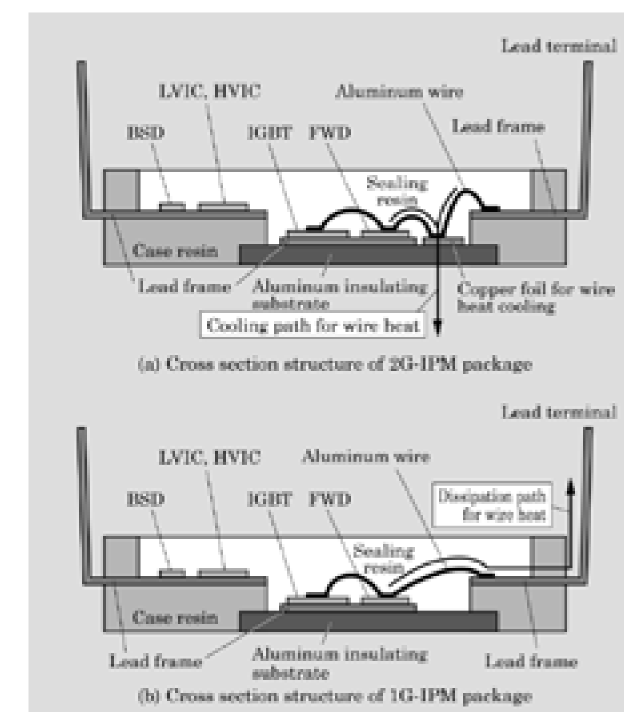

Fig. 7. Cross section of package structure

generation due to the increase in the rated current and to reduce the internal stress of package caused by large package size.

(1) Suppression of heat generation due to increase in rated current

The rated current of 2G-IPM is enhanced to 75 A from the 30 A of the conventional products. Therefore, the heat generated from the IGBT, FWD chip, aluminum wire and copper foil of aluminum IMS increases. To suppress the temperature rise similarly as with that of conventional types, the aluminum wire diameter and the thickness of the copper foil are increased. Thus, the newly developed 2G-IPM achieves the ΔT_{vj} power cycle capability that is equivalent to that of 2G-IPM in mass production.

(2) Optimization of assembly process with rated current increase

The internal residual stress after resin molding increases with enlarging the package size. In this case,ther e is the concern that molding resin is delaminated from chip during the reliability test with heat stress, such as the temperature cycling test, and that leads to the electrical characteristics deteriorating. Thus, the assembly process is optimized to reduce the residual stress inside the package and the stress caused by temperature change, realizing the reliability of newly developed 2G-IPM equivalent to 1G-IPM in mass production.

Protection function

Figure 8 shows the over-current protection circuit. The newly developed 2G-IPM adopts a current detecting method using a sens-IGBT and shunt resistor R_s. In addition, the overcurrent protection and short-circuit protection availability of 2G-IPM is same as 1G-IPM with external shunt resistor method shown in Fig. 8(b). The method of detecting current with the sense IGBT and R_s can reduce the number of components of a filter circuit for current detecting, reducing costs of the total system and saving space of the print circuit board. Figure 9 shows the waveform at the time of

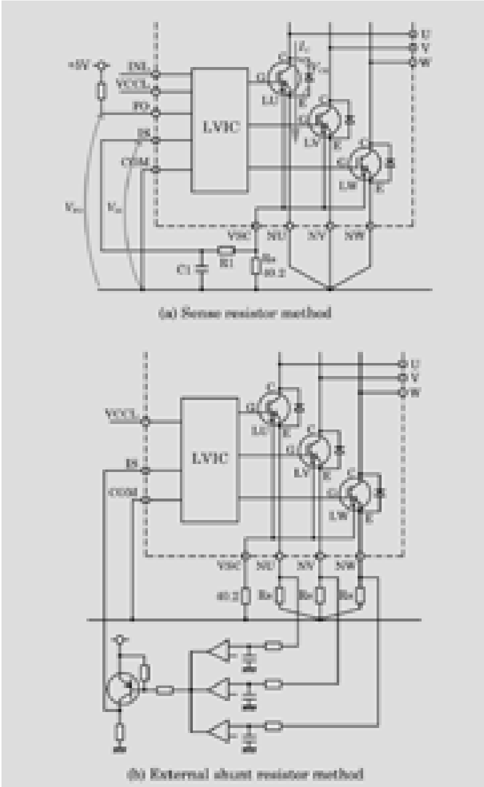

Fig. 8. Over-current protection circuit

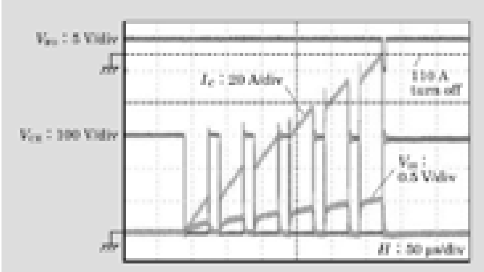

Fig. 9. Waveform at over-current protection

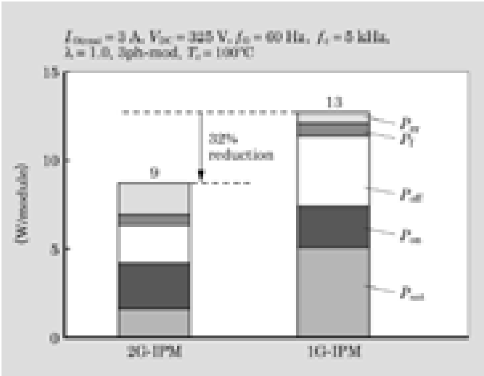

Fig. 10. Calculation result of power dissipation [2G-IPM 650 V / 50A, PAC (10HP) medium load condition]

over-current protection. As shown in Fig. 9, the alarm output signal VFO is output at the threshold level of the current detection, and the low side IGBT cuts off.

Advantage for the Power Conversion System

Figure 10 shows the simulation result of the inverter loss assuming an minimum load of a package air conditioner (PAC) as 10 horse-power unit. The 2G-IPM is expected to exhibit loss of approximately 32% that of 1G-IPM with the same rated current as 75 A of 2G-IPM, improving the APF performance.

Figure 11 shows the simulation result of the inverter loss assuming the maximum load of the same model, and Fig. 12 shows the result of the temperature rise at this time. The 2G-IPM showed low power loss of about 27% that of 1G-IPM with same rated current. The loss reduction of 2G-IPM results in decreasing 20 °C of temperature rise compared with 1G-IPM with same rated current. Furthermore, the rated maximum operating temperature range was increased by 25 °C, and the output current can be expanded and equipment can be downsized.

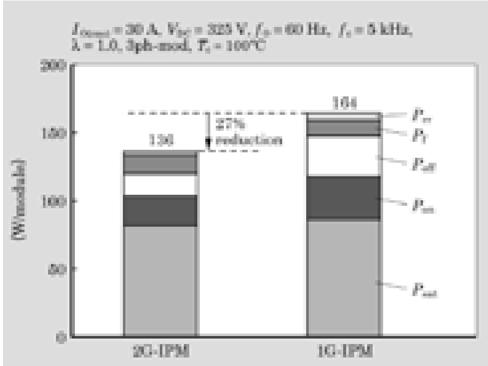

Fig. 11. Calculation result of power dissipation [2G-IPM 650 V/50 A, PAC (10HP) maximum load condition]

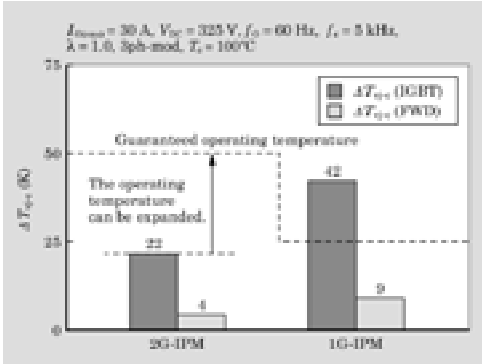

Fig. 12. Calculation result of temperature rise [2G-IPM 650 V/50 A, PAC (10HP) maximum load condition]

Postscript

The series of the 2nd-generation IPM 650 V/50 A and 75 A has been described. This series is a part of the products that meet the requirements of motor drive inverter, servo amp and package air conditioner (PAC), which are expected to increase in demand of world wide. In addition, we are considering of expanding the line-up of 1,200-V series.

Fuji Electric will continuously offer superior products with advanced technologies and will realize many benefits such as downsizing, higher efficacy and reliable performance of power conversion systems.

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