4GL-IPU: Power Unit for 2-Motor System

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Mitsubishi Electric Corporation first commercialized Intelligent Power Modules (IPM) for hybrid electric vehicles in 1997. Since then, we have been contributing to the electrification of vehicles by releasing products such as 4GS-Integrated intelligent Power Unit (4GS-IPU) with heat sink and motor control functions as a result of our effort to downsize IPM, increase the output power, and integrate the functions. Our newly developed 4GL-IPU described in this article is for the high-power 2-motor systems, which enables motor-driven travel even in a high-speed region and in full acceleration. (Fig. 1).

1. Characteristics of the 4GL-IPU

4GL-IPU has two high-power inverters: one for the high-power traction motor and the other for the generator motor that supplies high power to the traction motor. It also has a voltage boost-up converter that boosts the voltage of the main battery and an insulated step-down converter that lowers the voltage of the main battery to 12 V for the auxiliary battery (Fig. 2).

To realize 4GL-IPU, four requirements needed to be satisfied at the same time: higher power of the two inverters; higher functionality by integrating the voltage boost-up converter and the step-down converter;

Fig. 1 Evolution of IPU and 4GL-IPU

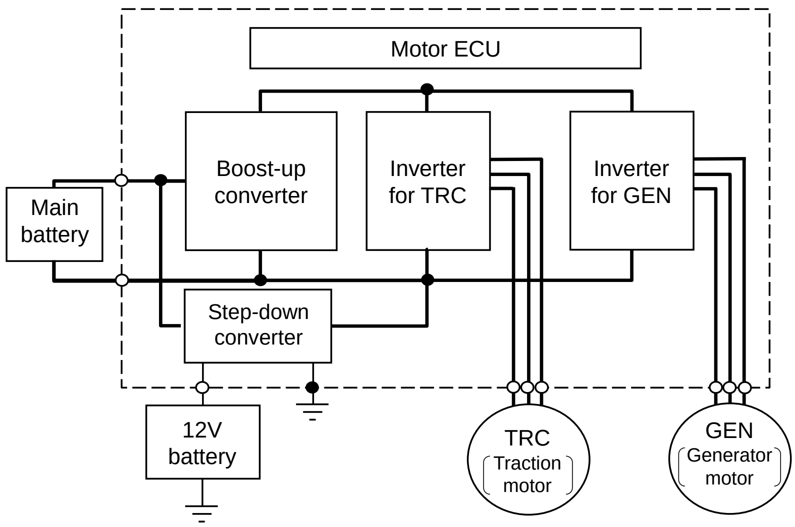

Fig. 2 Block diagram of 4GL-IPU

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downsizing to allow 4GL-IPU to be installed in the engine compartments of various models; and high vibration resistance to allow IPU to be directly mounted in the transmission. To achieve these requirements, the loss in the power devices, which are main heat sources, was reduced and the heat radiation was enhanced. In addition, heat-producing parts, such as the power module and voltage boost-up reactor, were closely mounted on both sides of a highly-rigid water cooling heat sink to shorten the wiring length between the parts while considering their heating (Fig. 3).

2. Technologies Applied to the 4GL-IPU

To effectively achieve the aforementioned higher power, higher functionality, downsizing, and high vibration resistance, various technologies were applied to 4GL-IPU, which include the cutting-edge low-loss power device, low-loss motor control, a new type of power module and heat radiation structure, and a voltage boost-up converter with our unique circuit system.

2.1 Power device and motor control

The power of traction motors driven by 4GL-IPU is approximately five times that of motors for 1-motor hybrid electric vehicles driven by our conventional models (e.g., 4GS-IPU). When the power of the generator motor is included, the total power of 4GL-IPU is approximately ten times that of our conventional model. To reduce the size without sacrificing efficiency, it is particularly important to reduce the loss. The power device adopts the latest seventh-generation Insulated Gate Bipolar Transistor (IGBT) and Relaxed Field of Cathode (RFC) diode to reduce the conduction loss.

However, in the high-power range, the system voltage (applied voltage) increased to approximately four times that of the conventional system due to the boosting. As the switching loss is proportional to the applied voltage and carrier frequency, for reducing the loss, it is essential to reduce the carrier frequency. In addition, the motor rotation speed increased to approximately twice that of the conventional model. At higher rotation speed, the fundamental frequency is higher and the number of switching per cycle of the electric angle decreases, which impairs the controllability. To retain controllability, the carrier frequency needs to be set higher in line with the increased rotation speed in the case of asynchronous Pulse Width Modulation (PWM) used for the conventional models. In other words, it is difficult to increase the motor rotation speed (increase the fundamental frequency) and reduce the switching loss (reduce the carrier frequency) at the same time.

Therefore, synchronous PWM, which was used in our motor control for electric trains, was realized using commercially available general-purpose micro-computers for the first time. In synchronous PWM, even at high rotation speed, the pulse number can be made uniform, thus enhancing controllability. For 4GL-IPU, asynchronous PWM and synchronous PWM coexist and the carrier frequency is finely switched based on the motor rotation speed, which reduces the switching loss by reducing the carrier frequency and realizes controllability to cope with sudden torque changes in the

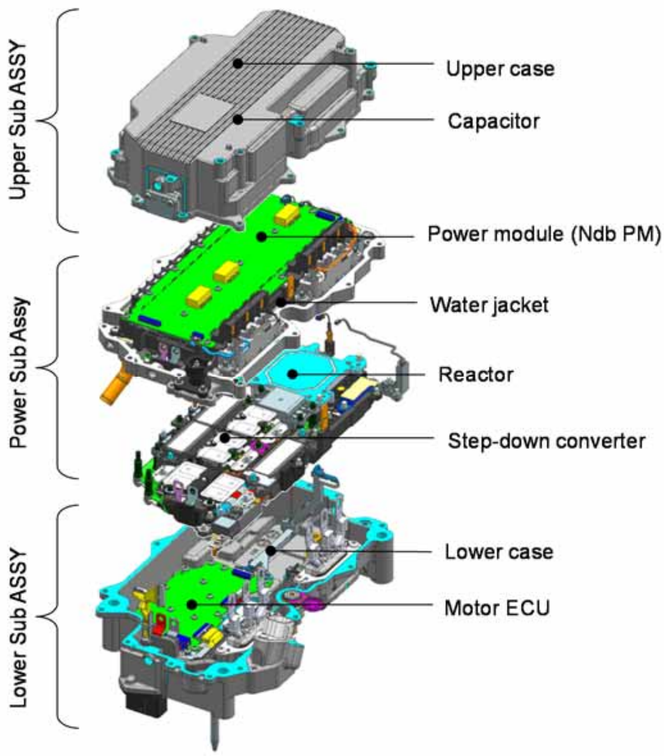

Fig. 3 Parts layout of 4GL-IPU

high-speed range, which is difficult with the conventional method (Fig. 4).

2.2 New heat radiation structure and water sealing structure

To fit the high-power inverters and voltage boost-up converter into a small housing, we developed new Nano sinter die-bonded Power Module (NdbPM) with high heat radiation and highly-rigid heat sinks in a compact water sealing structure.

The Transfer molded-Power Module (T-PM) used for the conventional model was for 1-motor hybrid electric vehicles, where the main task was torque assistance for a short time, and for 2-motor hybrid electric vehicles, for which the output was relatively small. Therefore, the heat radiation structure was designed to reduce the transient thermal resistance in order to supply large currents for a short time. On the other hand, the heat radiation structure of NdbPM is designed to reduce the constant thermal resistance in order to pass large currents continuously. Specifically, the insulating material was changed to ceramic base plates from resin sheets and the die bond of the power device was changed to sinter die-bonding with Ag nano-particles from solder in order to enhance the thermal conductivity of the heat radiation paths, reduce the thickness, and eliminate voids.

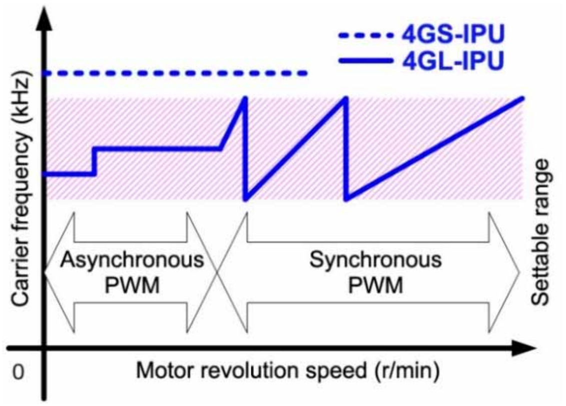

Fig. 4 Comparison of PWM operation mode

In the conventional model, the T-PM is secured to the water cooling heat sink with a spring and screw via thermal grease. In 4GL-IPU, NdbPM is directly soldered to the heat sink to reduce the size by eliminating fixing materials and also to improve the heat radiation. In addition, for the conventional model, the water sealing between the water cooling heat sink and water jacket is realized by using sealing materials (e.g., O-rings) and by fastening with multipoint screws. In 4GL-IPU, the circumference and the center of the water path are connected by Friction Stir Welding (FSW). This method eliminates sealing materials and fastening with screws, and also makes it possible to firmly connect the water cooling heat sink to the thick water jacket, which forms the case, in a line instead of points. Since the water cooling heat sink is the base of various parts, the firm connection of the water jacket and water cooling heat sink by FSW simultaneously solves various issues, including securing high vibration resistance required to install the modules directly onto transmissions, higher reliability of the water sealing thanks to the elimination of sealing materials, and downsizing due to the elimination of O-rings and multipoint screwing, which requires floor area. These improvements have made it possible to install a power module required for two high-power inverters and a voltage boost-up converter on the limited floor area of a heat sink in a simple planar layout (Fig. 5).

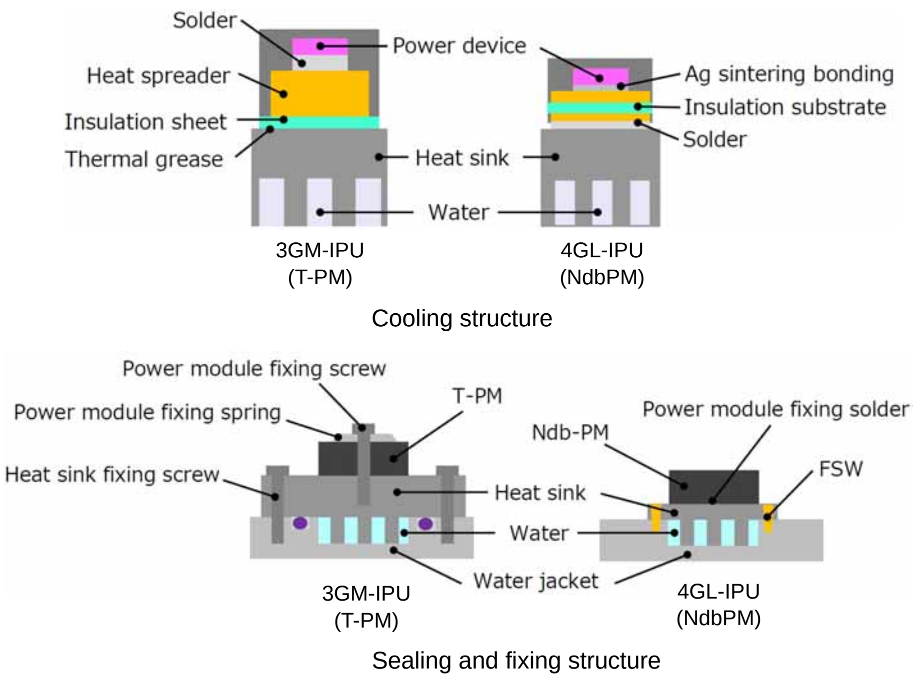

Fig. 5 Comparison of cooling and sealing structure

2.3 Voltage boost-up converter using our unique circuit system

The higher voltage achieved by using the voltage boost-up converter reduces the size thanks to higher efficiency of the motor inverter and smaller currents. However, the voltage boost-up converter requires new parts such as a power module, reactor, and smoothing capacitor.

Generally, a higher switching frequency of a power device enables the reactor to be downsized. On the contrary, the higher the frequency of a power device, the greater the switching loss. To solve this problem, we adopted a new circuit system in place of the common boost chopper method. Our unique circuit system has a flying capacitor (C0) and repeats the four modes shown in Fig. 6 to raise the voltage. This method doubles the reactor frequency without increasing the switching frequency of the power device. The method allowed us to reduce the size of the reactor by approximately 40% compared to the conventional method without increasing the switching loss for the power device.

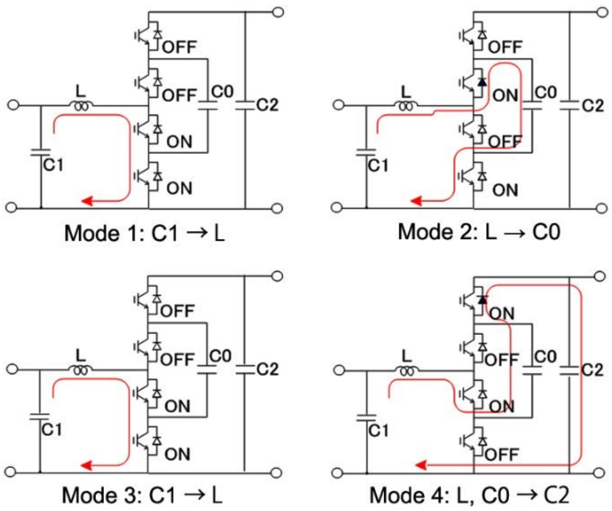

Fig. 6 Operation mode of Mitsubishi's original boost converter

These improvements allowed us to downsize the reactor and install a low-profile step-down converter on the back of the water cooling heat sink. Step-down converters used to be installed in the interior of vehicles. Integrating such converters into 4GL-IPU to be installed in the engine compartment enlarges the space within the vehicle and the luggage compartment.

3. Conclusion

Mitsubishi Electric has been developing smaller and lighter IPU with higher power and integrated functions and putting them on the market since the appearance of electric motor vehicles. Based on the concepts of the existing IPU that are used in many models, small and high-functionality 4GL-IPU with high power were developed by combining the latest inhouse-produced power devices, control methods used in other sectors, new connection techniques, our unique booster circuit system, and other technologies.

4GL-IPU enable vehicles to be driven on high-power motors, thus improving environmental performance, which has become increasingly important in recent years, while making driving more fun. They have also enlarged the space in vehicles by relocating the step-down converters from the interior of the vehicle to the engine compartment. We will continue to develop products that satisfy contradictory market needs for smaller and lighter products and for higher power and functionality, thus contributing to the spread of electric motor vehicles and countermeasures against global warming.

4. References

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