Automotive 48-Volt Converter

Takafumi KAWAKAMI*, Toshiyuki TSUCHIDA, Tatsuya SHIMIZU, Arata NAKASHIMA, Kazuki MASUDA, and Shigeyuki FUJII

In order to meet the CO_2 emission target, the electrification of powertrains is accelerating in each country. The 48-V mild hybrid electric vehicle (HEV) can reduce CO_2 emissions at lower costs than other systems, and therefore it is expected to become popular mainly in Europe. DC/DC converters installed in the mild HEV are required to supply high power with high reliability. We have developed a power control technology and achieved a high efficiency and high response compact converter. This paper introduces the features of the converter.

Keywords: mild HEV, 48-V, DC/DC converter

1. Introduction

To meet the recent tightened global CO_2 emission controls and the revised worldwide harmonized light vehicle test procedure, a globally standardized testing procedure for fuel consumption, vehicle manufacturers have been accelerating the development of electrified powertrains for electric vehicles (EVs), high-voltage plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs), 48-V mild HEVs, and other battery-powered vehicle applications.

Compared to conventional 12-V power systems, mild HEVs can be equipped with higher power generators, making it possible for this type of HEV to reduce CO_2 emissions by improving electric power regeneration efficiency, assisting the engine power when the vehicle starts moving, and using a battery when the vehicle runs at low speeds. Mild HEVs are also expected to enhance their commercial value, since they permit the installation of self-driving systems and other large power-consuming apparatuses.

Mild HEVs have another advantage in that their power-supply voltage of 60-V or less eliminates the need for such high-voltage safety designs that are indispensable for EVs and HEVs, and allows the installation of low cost apparatuses. European countries are currently taking the initiative in the development and widespread use of mild HEVs. The mild HEV market in China will also grow in the future. As a result, mild HEVs are expected to attain the largest share of the electrified vehicle market in 2030.(1)

Sumitomo Electric Industries, Ltd. has developed a 48-V DC/DC converter that is useful for the 48-V dual power supply system of the mild HEV. This paper describes the advantages of the new DC/DC converter.

2. 48-V Power Supply System

An example of the 48-V dual power supply system configuration is shown in Fig. 1. This system is characterized by a lithium ion battery (LIB) that supplies power to the 48-V system and a lead-acid battery that supplies power to the 12-V system. The electricity generator consists of an integrated starter-generator (ISG) and DC/DC converter. The former integrates the engine start-up assist, vehicle start-up assist, electric power regeneration, and electricity generation functions, while the latter supplies power to the 12-V system.

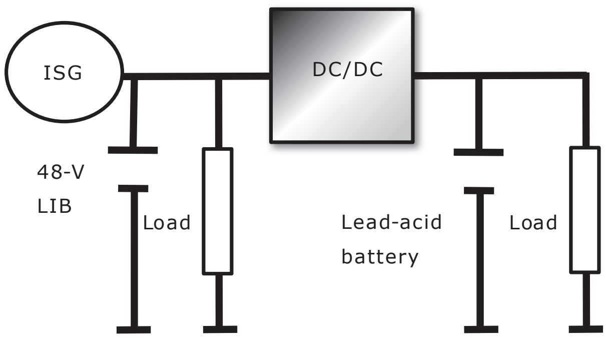

Fig. 1. Example of power supply system for mild HEV

3. Advantage of 48-V DC/DC Converter

3-1 Development concept

The system configuration and principal specifications of the newly developed 48-V DC/DC converter are shown in Fig. 2 and Table 1, respectively. As the power conversion efficiency and volume of the new converter has a maximum output of 3 kW, we set 96% or more and 3 L or less as the respective development targets. We also made efforts to control the converter at high responsivity so that the vehicle can maintain a stable output even if the generated power voltage or load current fluctuate due to a change in the outside environment.

3-2 System configuration

The system configuration is shown in Fig. 2. In addition to a voltage conversion unit and a power supply control unit, the system includes a protector and a controller that were specifically designed to ensure the functional safety of the system by protecting the 12-V system from overvoltage even in the event of converter failure.

For a high-power voltage conversion unit, a multi-phase system reduces the current per phase and enhances the conversion efficiency more effectively than a single-phase system. However, the number of parts increases as the number of phases increases and this results in increases in the cost and size of the converter. For this system, we adopted a 4-phase power conversion circuit that would ensure a good balance between cost and performance such as efficiency and size.

Although the power supply control unit can be composed of analog circuits, they are unsuitable for down-sizing the control unit. For a multi-phase system, in particular, more electronic parts are required for controlling the power coversion unit. Further, additional installation of a fast-response circuit is required to realize a control having excellent power supply tracking performance/response capabilities. Finally, we adopted a highly responsive digital power supply control system with the aim of enhancing power conversion efficiency, downsizing the DC/DC converter, and improving the quality of power supply control.

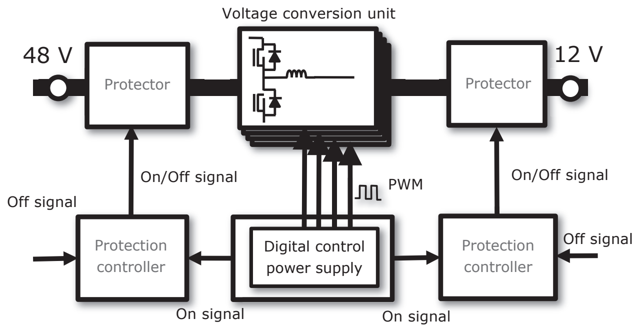

Fig. 2. System configuration

Table 1. Principal specifications

Item	Value
Input voltage	24-60 V
Output voltage	10-16 V
Output power	3 kW

3-3 Efficiency enhancement

The converter loss revealed that the field effect transistors (FETs), which are turned on and off at a high frequency, accounted for the maximum loss or 40% of the total loss. The analysis of the FET loss revealed that the switching loss exceeded 60%. To reduce the switching loss, it is necessary to select parts whose performance is appropriate for the purpose of use and to optimize the substrate pattern design.

In practice, it is most effective to select FETs containing the least number of parasitic elements. Parasitic elements affect the switching characteristics of the converter. However, reducing the number of parasitic elements usually results in an increase in electrical resistance.

In the development of the new 48-V DC/DC converter, we defined the product of electrical resistance and parasitic elements as a parameter that affects the switching loss of the converter. For the high-side FET, which was overwhelmingly responsible for the switching loss of the converter, we selected parts so that they would minimize the parameter. For the low-side FET, whose loss overwhelmingly accounted for the electrical resistance of the converter, we selected parts so that they would minimize the electrical resistance.

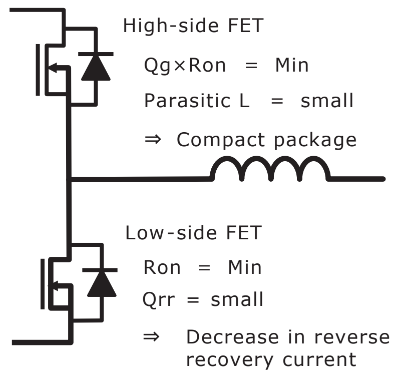

Fig. 3. Design concept for switching unit

In the substrate pattern design, it is important to shorten the switching current-carrying pattern in the FET and capacitor as much as possible. In the substrate pattern design, we conducted electromagnetic field analysis of the pattern to clarify the deviation of the current density distribution on the substrate pattern when the FETs are turned on and off, as well as the on/off transition time, surge voltage, and ringing waveform. Based on the analysis results, we determined the most suitable substrate pattern (Fig. 4). As a result, the switching loss of the finally designed new converter was reduced to 50% that of the initially designed converter.

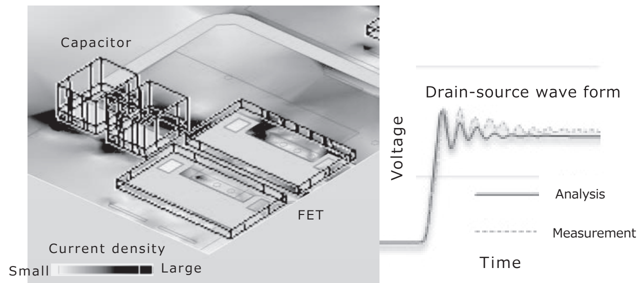

Fig. 4. Electromagnetic field analysis and measurement of printed circuit board pattern

3-4 Enhancement of cooling

To meet a variety of requirements for output and cooling conditions, we designed the new 48-V DC/DC converter so that it can be equipped with either an air- or water-cooling unit. A combination of a purpose-designed cooling unit and a commonly designed conversion unit minimizes the points to be modified for a specific use (Fig. 5).

In the development of both air- and water-cooling units, we conducted a thermal analysis of the cooling unit to quantify its cooling performance and determine the most suitable cooling structure for the new converter.

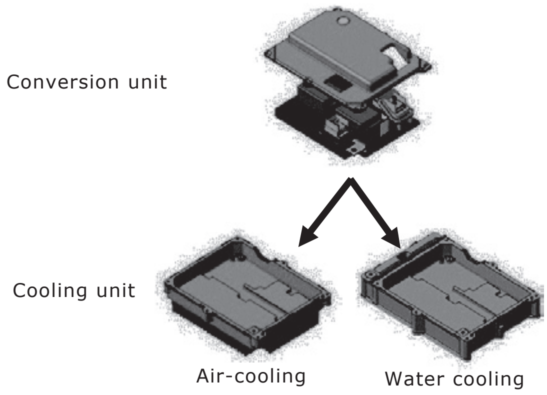

Fig. 5. Construction of converter

For the water-cooling unit, for example, it is necessary to design the water passage after taking into account its pressure loss. The pressure loss depends on the depth of the passage, which affects the size of the converter, and the irregularities formed on the inner wall of the passage due to structural restrictions. In practice, we designed a water passage model and conducted flow analysis for this model. Based on the analysis results, we developed a water passage structure having the most suitable depth and water flow for the new converter (Fig. 6).

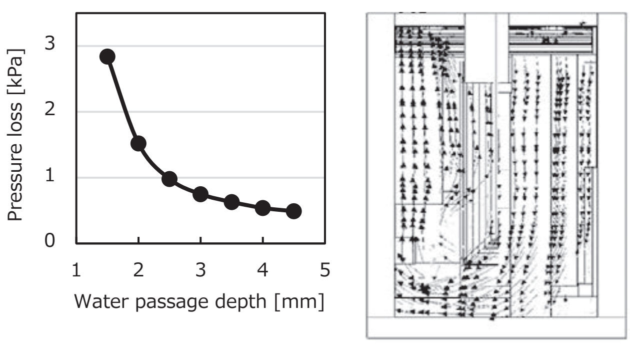

Fig. 6. Flow analysis result

3-5 Coupled coil

The choke coil, which is the largest of all the DC/DC converter components, was a major obstacle to downsizing the converter. We reduced the size of the choke coil by replacing it with a coupled coil.(2)

Coupling two or more coils is a technique for reducing ripple current. In particular, this technique uses a core to couple the magnetic fluxes generated by the coils and makes these fluxes interfere with each other. Use of this technique made it possible for us to reduce the inductance value, thereby maintaining the ripple current below a fixed level (Fig. 7).

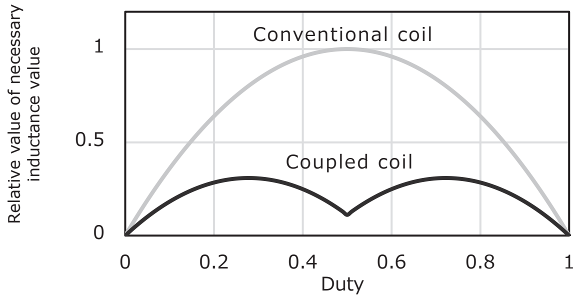

Fig. 7. Relative comparison of necessary inductance values

A coupled coil tends to saturate the magnetism if the current is biased to one of a pair of coils. We determined the distribution of magnetic flux density by conducting an electromagnetic field analysis and, based on the analysis result, devised a magnetic structure that can minimize the magnetic flux caused by a current bias (Fig. 8). Subsequently, we designed a coupled coil consisting of a pair of two-phase coils. Compared to conventional converters, the new DC/DC converter has reduced the volume by 13% while increasing the output by 20% (Photo 1). Thus, the new conversion unit has dramatically improved design flexibility.

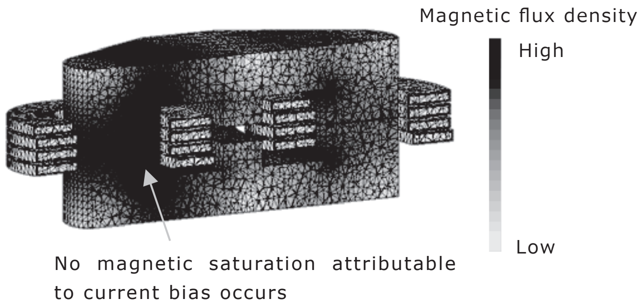

Fig. 8. Simulation of magnetic flux density

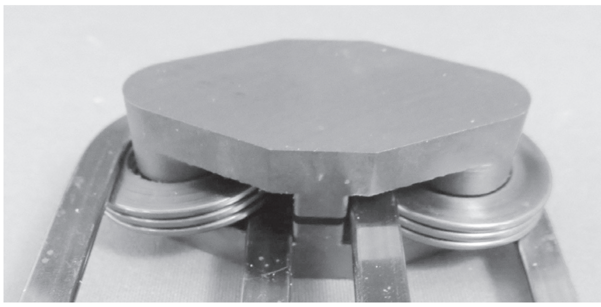

Photo 1. Prototype two-phase coupled coil

3-6 High response characteristics

A microcomputer-based digital control system is more expandable than an analog control system whose control unit is composed of a combination of electronic parts. In particular, a digital control system can flexibly meet the requirements for an increase in the number of phases and phase control of the voltage conversion unit.

A proportional-integral (PI) feedback controller is used regardless of whether its control scheme is analog or digital. A PI control system*[1] is effective for maintaining the load voltage and current with a high degree of accuracy. Even if a 12-V load current fluctuates sharply, this control system responds very quickly to the fluctuation and stably maintains the voltage on the 12-V side. On the other hand, a PI control system cannot tracking the fluctuations of voltage on the 48-V side and allows the voltage on the 12-V side to fluctuate sharply. We newly introduced a feed-forward controller.[(3)] It estimates the effect of the voltage fluctuation on the 48-V side on the voltage on the 12-V side and, based on the estimate, exercises preliminary control of the pulse width modulation (PWM) to suppress the voltage fluctuation (Fig. 9).

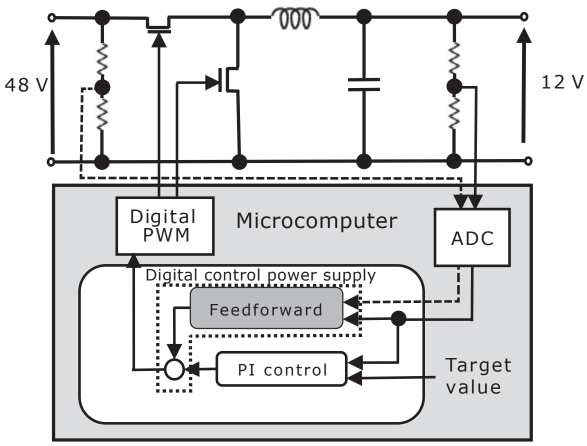

Fig. 9. Digital control of power supply

Figure 10 shows the response performance of the PI plus feedforward control-based digitally controlled power supply to voltage fluctuation on the 48-V side. This figure verifies that the additional feedforward control scheme is effective in suppressing voltage fluctuation. In particular, the voltage fluctuation on the 12-V side was controlled to within 1 V.

It was confirmed that a combination of PI control and feedforward control schemes ensures highly responsive control of the output voltage even if the load on the 12-V and the voltage on the 48-V side fluctuate. It was also confirmed that a digitally controlled power supply achieves stable output characteristics even when it is exposed to the power fluctuation specified in the VDA320, a standard for 48-V power supply.

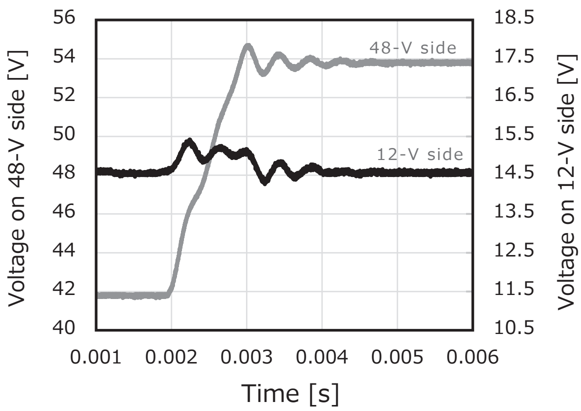

Fig. 10. Comparison of response performances to voltage fluctuation on 48-V side

4. Evaluation Results

The external appearance of the newly developed 48-V DC/DC converter (water-cooled) is shown in Photo 2. The volumes of the water- and air-cooled converters we designed were measured to be 2.0 L and 2.8 L, respectively.

The power conversion efficiency test result for the new converter is shown in Fig. 11. The converter achieved a maximum efficiency of 97.8%. It produced a maximum output of 3 kW with an efficiency of 96.7%.

The temperature rise test result for the converter with a water-cooling unit is shown in Fig. 12. The test result at a water temperature of 70°C verified that the converter stabilizes its temperature at a sufficiently low level.

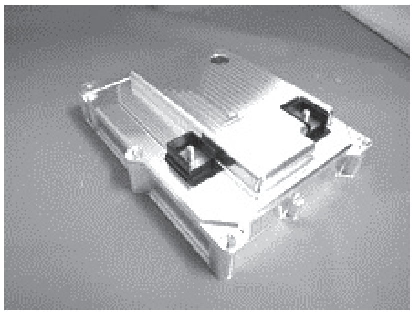

Photo 2. External appearance of newly developed converter (water-cooled)

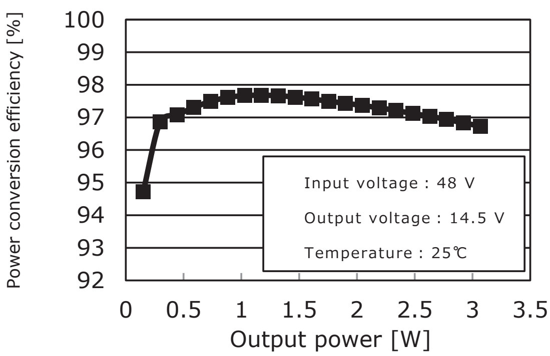

Fig. 11. Power conversion efficiency

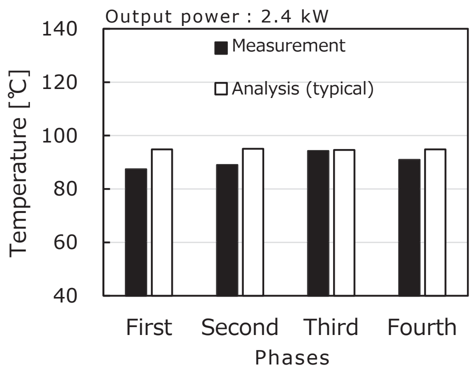

Fig. 12. Comparison between thermal analysis and actual measurement

5. Conclusion

Sumitomo Electric has developed a high-efficiency, compact 48-V DC/DC converter. Its outstanding features are summarized as follows:

1. The new converter ensures high power conversion efficiencies with low switching loss. In particular, a test result showed an efficiency of 96.7% at a maximum output of 3 kW.
2. The volumes of the air- and water-cooled converters we designed were measured to be 2.8 L and 2.0 L, respectively. A temperature rise test result verified that the new converter has high thermal performance.
3. The adoption of a coupled coil has reduced the volume of the coil by 13%.
4. The power response performance of the new converter meets the requirements for the power supply fluctuation test specified in the VDA320, a standard formulated in Germany.

Technical Term

*1 Proportional-integral (PI) control scheme: An algorithm that uses the deviation between an output value and its target value and the integral of the deviation.

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Contributors The lead author is indicated by an asterisk (*).

T. KAWAKAMI*
• AutoNetworks Technologies, Ltd.

T. TSUCHIDA
• Assistant Manager, AutoNetworks Technologies, Ltd.

T. SHIMIZU
• Sumitomo Wiring Systems, Ltd.

A. NAKASHIMA
• AutoNetworks Technologies, Ltd.

K. MASUDA
• AutoNetworks Technologies, Ltd.

S. FUJII
• General Manager, AutoNetworks Technologies, Ltd.