SUMITOMO ELECTRIC TECHNICAL REVIEW

Downsizing of Forced Air-Cooled 150 kW Isolated Bidirectional DC-DC Converter

Masashi OGURA*, Hiroaki MAEJI, Kensuke SHIMIZU, Yuto TAKAYAMA, Nobuhiro KURIO, and Yoshio MATSUBARA

We have successfully developed a forced air-cooled 150 kW isolated bidirectional DC–DC converter, aiming to achieve a power density of 2 kW/L, equivalent to a water-cooled system. This was achieved by improving the cooling performance of the transformer, a major component, integrating the cooler for the power semiconductor and transformer, reducing the switching loss of the power semiconductor, and implementing a novel control system that minimizes the overall loss. These efforts have led to the miniaturization of our converter, comparable to our water-cooled isolated bidirectional DC-DC converter.

Keywords: isolated bidirectional DC-DC converter, downsizing, high-frequency transformer, forced air-cooled, three-level phase-shift control

1. Introduction

To achieve carbon neutrality by 2050, a massive introduction of storage batteries is ongoing in addition to renewable energy systems including solar power generation systems.(1) When connecting storage batteries as a direct current power distribution system, DC-DC converters are required, which should be equipped with a bidirectional power transfer capability required for electrical charging and discharging and an isolation capability intended to prevent local ground faults and other accidents from affecting the overall system. It is also important to downsize the DC-DC converter in light of the need to install storage battery systems in buildings and other facilities with space limitations.

Against this backdrop, expectations are high for the dual active bridge type of isolated bidirectional DC-DC converter (hereinafter referred to as the “DAB converter”) that has both bidirectional power transfer and isolation capabilities. DAB converter circuits are configured to have a transformer in the middle and full bridge-connected power semiconductors on the right and left sides in Fig. 1. Nissin Electric Co., Ltd. developed a DAB converter incorporating a water cooling system (hereinafter referred to as the “water-cooled DAB converter”).(2) This converter is undergoing verification for long-term reliability at the Nissin Academy Training Center of Nissin Electric.(3),(4)

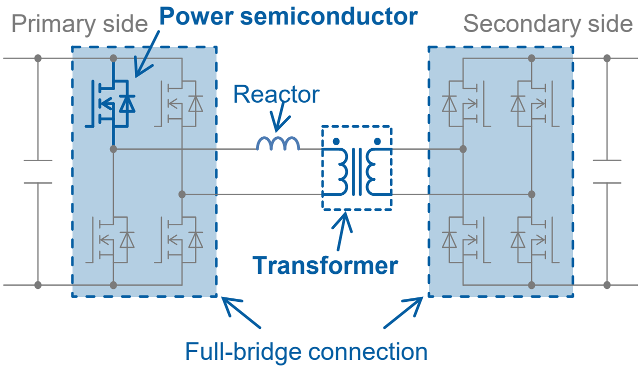


Fig. 1. Circuit configuration of general DAB converters

Recently, we have developed a forced air-cooled DAB converter, demand for which is higher than for water-cooled systems. This paper describes the air-cooled system in detail.

2. Overview of Forced Air-Cooled 150 kW DAB Converter

2-1 Development concept and target

Water-cooled DAB converter systems are known to achieve high cooling performance. However, it is difficult to reduce the size of the entire unit because the water-cooled DAB converter system requires auxiliary equipment such as a refrigerant circulation pump and refrigerant cooling system although the DAB converter itself is small.

In the current development, the concept was set to “downsize forced air-cooled DAB converters” with the downsizing of the entire unit and ease of maintenance in mind. As an indicator of downsizing, power density*1 was used. In light of Nissin Electric’s water-cooled DAB converters having a power density of about 2.0 kW/L (excluding the pump and other auxiliary equipment), the target for the newly developed forced air-cooled DAB converter (including the entire cooling system) was set to a power density of 2.0 kW/L at a level comparable to that of the water-cooled type.

2-2 Exterior and specifications

Photo 1 shows the exterior of the newly developed system. Table 1 presents the specifications. The development target of 2.0 kW/L has been achieved at a rated power of 150 kW and a volume of 75.6 L. The key points in the downsizing of the DAB converter are described below.

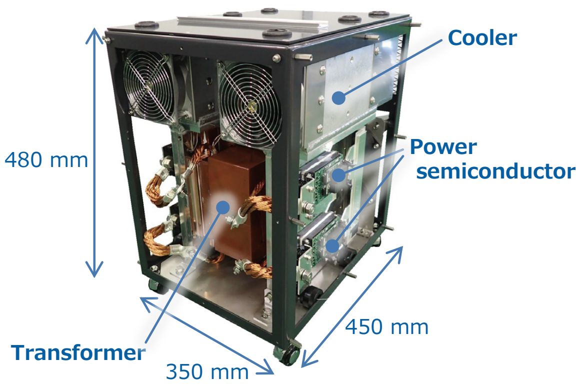


Photo 1. Exterior of forced air-cooled 150 kW DAB converter

Table 1. Specifications for forced air-cooled 150 kW DAB converter

Parameter	Specification
Rated power	150 kW
Rated voltage	750 V : 750 V
Rated current	200 A : 200 A
Switching frequency	15 kHz
Circuit configuration	DAB configuration (high-frequency transformer system)
Cooling system	Forced air-cooled
Outer dimensions (width/depth/height)	350×450×480 mm (excluding caster)
Volume	75.6 L
Power density	2.0 kW/L

3. Key Points in Downsizing the DAB Converter

Our solution to the challenge of downsizing the transformer was to make the DAB converter operate at high frequencies. However, high-frequency operation causes the switching loss*2 in power semiconductors and the iron and winding losses of the transformer to increase. Consequently, to achieve the development target, it was necessary to improve the performance of forced air cooling and reduce the losses. With these in mind, the following downsizing approaches were followed.

3-1 Adoption of two-phase flow circulation coolers

A two-phase flow circulation heatsink was adopted as a cooler. This ensured that the structure is capable of cooling efficiently, utilizing the boiling and condensation of the refrigerant. Taking advantage of the fact that the item provides double-sided cooling, power semiconductors and the transformer were placed on either side of the cooler, enabling shared use of the cooler, as described below (see 3-3).

3-2 Loss minimized by three-level phase-shift control

First, for power semiconductors, silicon carbide (SiC) V-groove trench metal-oxide-semiconductor field-effect transistors (MOSFETs) with excellent fast switching characteristics were selected.(5)

A basic control system used with DAB converters is the two-level phase-shift control. This control is designed to achieve bidirectional power transfer by adjusting the phase difference X between the output voltages from the right and left bridge connections. In this control, what is controlled is only the phase difference X, whose control is simple; however, two output voltage values are involved and the width of the applied voltage is fixed at 180°. The challenge here is that the efficiency decreases during low-power output because the iron loss in the transformer increases or decreases according to the width of the applied voltage, and that the two-level phase-shift control causes iron loss during low-power output at a level comparable to that occurring during operation at the rated power.

As a solution to this challenge, we have developed our original three-level phase-shift control. This is intended to output three voltage values including the 0 V section, by adjusting the phase difference Y between leg 1 and leg 2 and the phase difference Z between leg 3 and leg 4 (Fig. 2). Consequently, this control enables the width of applied voltage to be adjusted although control becomes complex due to the three-phase differences X, Y, and Z to be controlled.

Figure 3 presents a conceptual diagram of loss characteristics versus the width of applied voltage of the transformer and power semiconductors during low-power

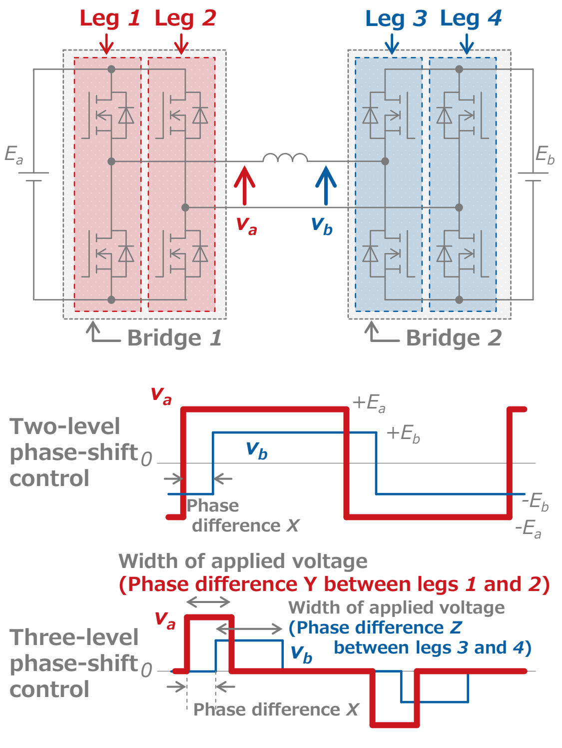


Fig. 2. Equivalent circuits and phase-shift control of DAB converter

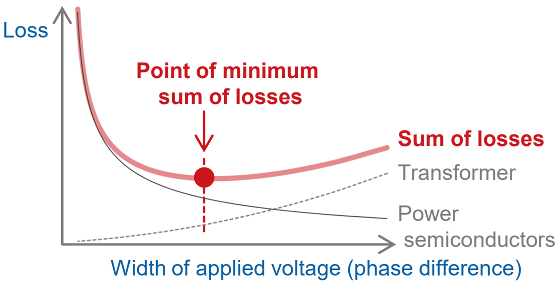


Fig. 3. Loss versus width of applied voltage (phase difference)

output. Output at a smaller width of applied voltage results in a smaller iron loss in the transformer and a greater loss in the power semiconductors, while a larger width of applied voltage results in a greater iron loss in the transformer and a smaller loss in the power semiconductors. In other words, while there is an infinite number of combinations of phase differences X, Y, and Z, an optimum condition exists whereby the sum of losses is at a minimum. For the newly developed three-level phase-shift control, each phase difference value is determined to ensure that the sum of losses is always the smallest.

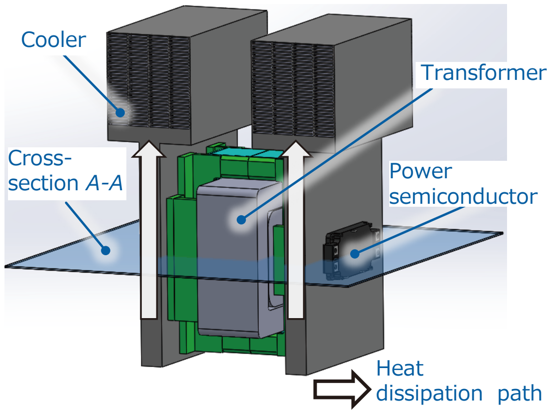
3-3 Development of a forced air-cooled high-frequency transformer

In addition to coolers, wire-wound devices such as a reactor and transformer make up a large portion of DAB converter components. Hence, we worked on the development of a downsized forced air-cooled high-frequency transformer.

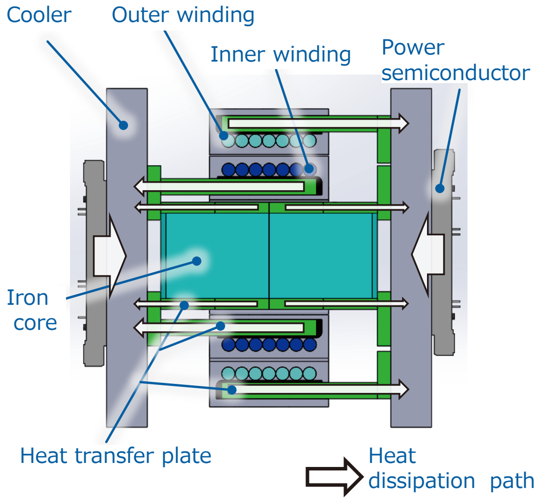
First, an iron core and windings with excellent high-frequency characteristics were adopted to reduce losses, and at the same time, a cooling structure that efficiently releases iron core and winding losses in the form of heat to the outside was developed. Efficient use of space is achieved by allowing the power semiconductors and transformer to share a cooler (Fig. 4). Moreover, the reactor was omitted by using the leakage inductance of the transformer to substitute for the inductance component required for the operation of the DAB converter. Table 2 gives the specifications for the newly developed forced air-cooled high-frequency transformer.

Table 2. Specifications for Forced Air-cooled High-frequency Transformer

Parameter	Specification
Rated capacity	225 kVA
Frequency	15 kHz
Isolation class	F
Rated voltage	750 V : 750 V
Rated current	300 A : 300 A
Cooling system	Forced air-cooled
Outer dimensions (width/depth/height)	262 × 217 × 178 mm
Volume	10 L
Weight	32 kg
Power density	22 kVA/L



(a) General view



(b) Cross-section A-A

Fig. 4. Heat dissipation paths of power semiconductors and transformer

(1) Cooling structure

Figure 4 illustrates the cooling structure and heat dissipation paths of the power semiconductors and transformer. The structure employed for the newly developed transformer is such that heat transfer plates made of a high-thermal-conductivity metal such as copper or aluminum are pressed against the heat-generating parts of the iron core and windings to transfer heat generated in each part to the coolers via the heat transfer plates. The features of this cooling structure are no orientation restrictions, suitability for placement in a closed space, and compatibility with any cooling system (also usable with water-cooled systems).

For losses, heat is dissipated through the paths described below.

(a) Iron loss

For the iron core, a cut core was employed. The cut core is split at the center, with each piece having an individual heat transfer plate affixed to dissipate heat evenly to the right and left coolers.

(b) Winding loss

Heat resulting from inner- and outer-winding loss is separately dissipated to the right and left coolers, as illustrated in Fig. 4 (b).

(2) Electrical isolation and cooling of windings

In pressing a heat transfer plate against windings in a high-voltage block, electrical isolation must be provided between them. Ordinary insulation materials have low thermal conductivity, that is, high thermal resistance. Therefore, this transformer adopted an electrical isolation and cooling structure to ensure compatibility between electrical isolation and cooling by applying a high-thermal-conductivity resin lightly to the heat transfer plates. In addition, reliable electrical isolation was provided by covering the windings and heat transfer plates with an electrically insulating resin in the final step. Figure 5 presents a schematic diagram of the main isolation between the windings and the heat transfer plates. Table 3 lists the transformer isolation specifications. The dielectric strength was specified at 3,000 V dc, referring to JIS C 8980. Because the newly developed converter is used at high frequencies, partial discharges occurring at the rated voltage will accelerate the deterioration of the insulation material, eventually resulting in dielectric breakdown. Therefore, to ensure that no partial discharge occurs during steady-state operation, the DAB converter was designed to be corona-free at 1,500 V dc, which is twice as high as its rated voltage (Table 1).

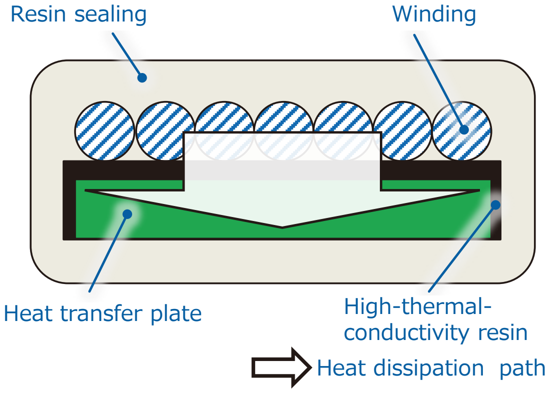


Fig. 5. Main isolation block

Table 3. Electrical Isolation Specifications

Parameter	Criterion
Dielectric strength	3,000 V dc (1 min)
Partial discharge	Corona-free at 1,500 V dc

4. Empirical Testing

Figures 6, 7, and 8 show the test circuits, test waveforms observed when outputting the rated power of 150 kW at the rated voltage of 750 V, and power conversion efficiency, respectively.

The temperatures of each part were measured during continuous operation at the rated power output of 150 kW (power density: 2.0 kW/L). The results were all within the design range, thereby ascertaining problem-free operation.

The power conversion efficiency was 97.7% at the rated power output and 98.0% at the maximum (during 70 kW power output). The output voltage waveforms contained 0 V sections, and the power conversion efficiency at 5% power output reached high values of 90% or more, thus demonstrating the effective application of the proposed three-level phase-shift control for loss minimization. Note that the power conversion efficiency presented here takes into account losses attributed to auxiliary equipment such as control circuits and fans.

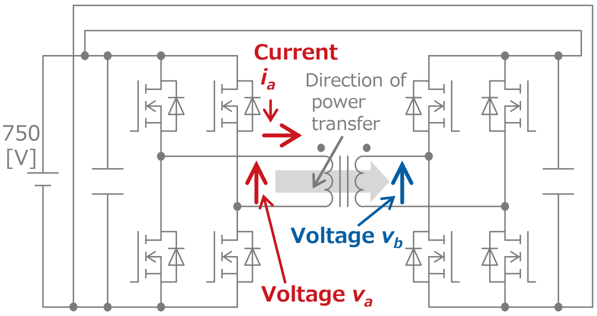


Fig. 6. Test circuits

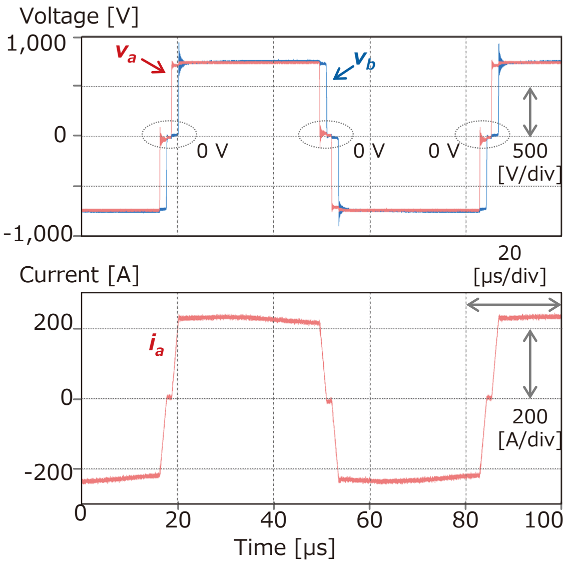


Fig. 7. Test waveforms during power output at rated power of 150 kW

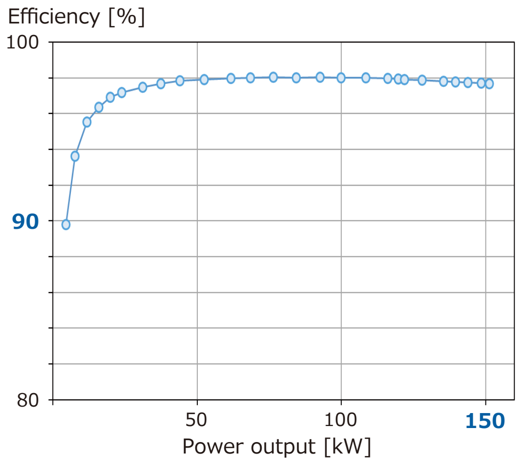


Fig. 8. Power conversion efficiency

Consequently, we have developed a forced air-cooled DAB converter with a power density of 2 kW/L, a level comparable to that of water-cooled systems, and verified the problem-free operation of the converter.

5. Conclusion

A forced air-cooled 150 kW isolated bidirectional DC-DC converter was developed. The converter achieved the rated power output of 150 kW (power density: 2.0 kW/L) in empirical testing, which is an accomplishment of downsizing a forced air-cooled system to a level comparable to water-cooled systems.

One feature of the proposed three-level phase-shift control is high effectiveness in loss reduction in applications subject to considerable output voltage fluctuation as with renewable energy-based power generation and storage batteries. It is considered highly effective DC-DC converter technology for use in direct-current power distribution systems.

Technical Terms

∗1 Power density: Maximum available power per unit volume. Power density = Rated power ÷ Volume. Unit symbols are W/cc and kW/L.

∗2 Switching loss: Loss occurring during the on-off (switching) operation of power semiconductors. Higher switching frequencies result in an increasing number of switching cycles, causing the switching loss to increase.

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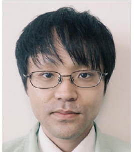
Contributors

The lead author is indicated by an asterisk (∗).

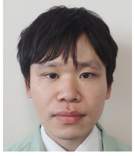
M. OGURA∗
- Chief Research Engineer, Nissin Electric Co., Ltd.

H. MAEJI
- Nissin Electric Co., Ltd.



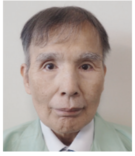
K. SHIMIZU
- Nissin Electric Co., Ltd.

Y. TAKAYAMA
- Doctor of Engineering
  Nissin Electric Co., Ltd.



N. KURIO
- Chief Senior Staff, Nissin Electric Co., Ltd.

Y. MATSUBARA
- Doctor of Engineering
  Technical Executive, Nissin Electric Co., Ltd.



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