Conducted emission voltage reduction for multi-cell SST with current-type ACC

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***Abstract*— This paper proposes a common mode (CM) noise reduction method for a multi-cell solid-state transformer (SST) using a current-type active common mode noise canceler (ACC). Multi-cell power converters typically have complex noise propagation paths. However, the proposed current-type ACC with Rogowski coil effectively reduces electromagnetic noise in power converters with multiple cells. The effectiveness of this approach is validated through experimental results. The conducted emission voltage of the power converter is reduced by 20.8dBμV when the ACC is connected to the DC voltage part on the primary(high-voltage) side in one cell.**

Keywords*— *Solid-State Transformer; Common mode current; Active common mode noise canceler; Conducted emission voltage

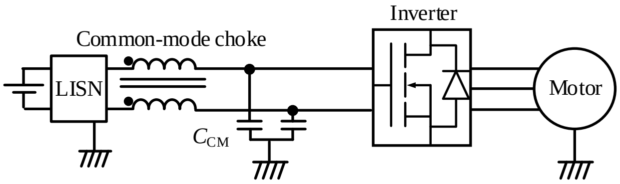
I. INTRODUCTION

In recent years, extensive research has been conducted to enhance the power density in power converters by utilizing wide bandgap devices, such as SiC (silicon carbide) and GaN (gallium nitride) [1-2]. These devices use higher switching frequencies compared to Si devices in order to reduce the volume of passive components of capacitors and inductors. However, high-speed switching leads to a steep voltage variation and a large electromagnetic noise [3]. Wide bandgap semiconductors enable faster-switching speeds and higher switching frequency operation than conventional semiconductors. This results in more minor passive elements, such as inductors and compact cooling systems, due to lower switching device loss. Nevertheless, the increased switching speed results in sharp voltage fluctuations, making the impact of electromagnetic noise more pronounced.

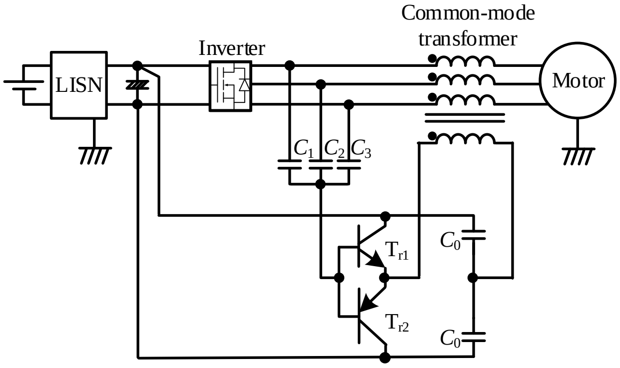
To suppress common-mode (CM) noise, which is the primary source of electromagnetic interference, passive CM filters are commonly used [4]. The passive CM filters attenuate electromagnetic noise in the frequency range above the cutoff frequency, which is determined by the inductance and capacitance of the constituent component. However, the cutoff frequency must be carefully designed to achieve an effective noise reduction across a wide bandwidth. This requirement often leads to more significant passive components in the common-mode filter, reducing the power density.

On the other hand, active common-mode cancellers (ACC) using active components have been actively studied [5-6]. ACCs reduce electromagnetic noise by detecting CM voltage or current and applying an out-of-phase CM voltage or current through an amplifier. Compared to passive filters, which consist only of passive elements, the ACC offers the advantage of a smaller circuit volume in broadband applications. However, in power converters with multiple, it is challenging for ACCs to suppress electromagnetic noise effectively due to complex noise propagation paths.

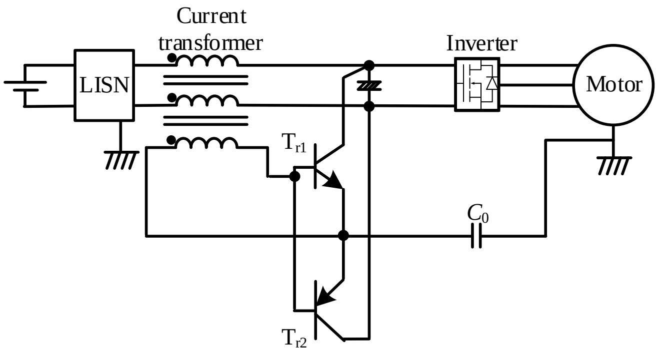
This paper proposes an electromagnetic noise reduction method in a solid-state transformer (SST) in a multi-cell configuration, with the capability of bi-directional power flow, reactive power compensation, and other functions, using the ACC. The current type ACC with Rogowski coils is used to detect the CM current in order to minimize the volume of the current transformer. The advantage of the Rogowski coil is that the primary winding becomes just one turn. Moreover, the Rogowski coil increases the number of secondary side turns. Consequently, the Rogowski coil is smaller than the normal current transformer for CM current detection. The target frequency range of the CM current reduction is from 150 kHz to 30 MHz based on the guidelines of the CISPR standard. In addition, a non-inverting amplifier circuit using a high-performance current feedback operational amplifier increases the ACC bandwidth. The CM current path varies depending on the connection position of the power supply section of the



(a) Inverter circuit with passive filter



(b) Inverter circuit with VSVI



(c) Inverter circuit with CSCI

Fig.1. Conventional CM Filter

amplifier. In the experiment, the conducted emission voltage is reduced by 20.8dBμV when a current-type ACC is connected to the DC voltage part on the primary side in one cell in a three-cell configuration.

II. SYSTEM CONFIGURATION

A. Configuration of Active Common-mode Canceller(ACC)

Figure 1 shows conventional electromagnetic noise suppression methods using a passive CM filter consisting of a common-mode choke and a Y-connection capacitor. The passive CM filters reduce electromagnetic noise in the frequency band above the cutoff frequency, which is determined by the inductance and capacitance of the filter components. However, a low cutoff frequency is required to significantly reduce noise over a wide bandwidth. The passive CM filter with a low cutoff frequency increases the volume of the passive components and reduces the power density.

The current-type ACC comprises a CM current detection unit, an amplifier circuit, a power supply, and a compensation current injection section. This paper investigates the noise reduction effect of a current-type ACC [7] using a Rogowski coil in the CM current sensing section.

Figure 2 shows the current-type ACC block diagram in the common mode equivalent circuit. The detection current-detection voltage ratio of the detection section and the amplifier gain determine the noise reduction effect of the ACC. The higher the gain, the higher the noise reduction effect on the conducted emission voltage.

A Rogowski coil is used in the CM current detection section to achieve a wide bandwidth. Conventional current-type ACC typically uses current transformers (CT) for detection [8-9]. The detectable frequency bandwidth is limited due to increased volume and frequency characteristics caused by increased primary windings. In contrast, the Rogowski coil has a single turn on the primary side, which enables a reduction in volume compared to CT, and a wider frequency bandwidth is achieved by increasing the number of turns on the secondary side, which has a lower current value than the primary side. Additionally, the Rogowski coil provides excellent insulation, making it suitable for circuits handling medium voltage, such as 6.6 kV systems.

In the amplifier circuit, the DC bus voltage is divided by a capacitor and stepped down to 15 V using a regulator. A high-performance, non-inverting amplifier circuit utilizing a current-feedback operational amplifier is implemented.

Figure 3 shows a non-inverting amplifier circuit using a current feedback operational amplifier. The amplifier part of the ACC also needs to operate over a wide range. A high output current feedback amplifier (THS3491 (Texas Instruments)) is used, which operates with a maximum bandwidth of 900 MHz when operating under ideal conditions. The optimum resistor combination for this op-amp to obtain the desired gain is described in the datasheet. This study determined the resistor values to achieve 26dB of the maximum gain shown in the datasheet.

B. Configuration of Solid-State Transformer(SST)

Figure 4 shows the circuit configuration of the SST. The circuit comprises a power factor correction (PFC) stage, which includes a boost chopper circuit and a voltage-source series resonant DC/DC converter in the input stage. The PFC regulates the full-wave rectification of the current flowing through the inductor in the second stage of the diode bridge rectifier and performs PFC using a phase-locked loop (PLL) synchronized to the system voltage. The resonant DC/DC converter operates at the resonant frequency through series resonance with the leakage inductance Ls and capacitor Cr.

III. SIMULATION AND EXPERIMENTAL RESULTS

Figure 5 shows the principle diagram of a Rogowski coil. The coupling between the primary winding (the winding through which the CM current flows) and the secondary winding (the Rogowski coil) does not need to be high when using a Rogowski coil. The CISPR standard defines the

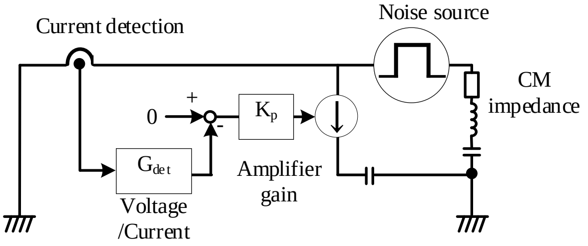


Fig. 2. Equivalent block diagram of ACC in common mode circuit.

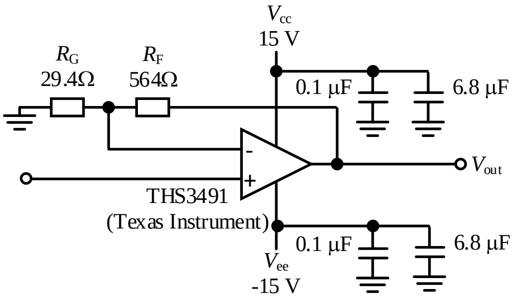


Fig.3. Noninverting amplifier circuit.

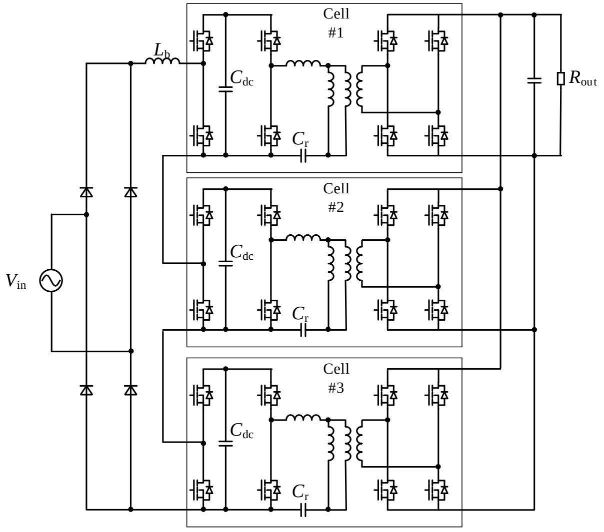


Fig. 4. Circuit configuration of the three-phase SST

allowable conducted emission voltage in the band between 150 kHz and 30 MHz; the evaluation of the characteristics of the detection current to detection voltage ratio at the detection unit is carried out within the frequency range of 150 kHz to 30 MHz the characteristics of the output voltage concerning the detected current of the detection unit are evaluated in the 150 kHz to 30 MHz bands.

The resistance and number of turns are determined as follows.

$$N = \frac{r_R}{\mu_0 S_R} \frac{G_{\mathrm{det}}}{f_{\mathrm{cut}}} \text{ ....(1)}$$

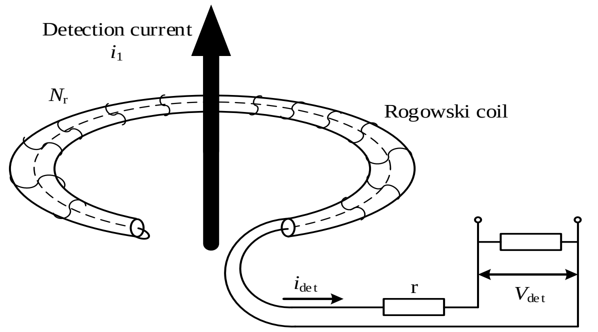


Fig. 5. Rogowski coil conceptual diagram.

$$R = \frac{r_R}{\mu_0 S_R} \frac{\left(G_{\mathrm{det}}\right)^2}{f_{\mathrm{cut}}} \text{ ....(2).}$$

Table 1 shows the simulation and experimental conditions. In this experiment, the SST is configured in three stages with a rated capacity of 100 W. The conducted emission voltage is measured under these conditions.

The Rogowski coil in the current-type ACC has 120 turns. The detection resistance is set to 2.4 kΩ, resulting in a detection current-to-voltage ratio of 20 times (26 dB). The cutoff frequency is 20 kHz. The amplifier gain is also set at 26 dB to measure the noise reduction effect.

A. CM equivalent circuit simulation

Figure 6 shows the SST's common-mode equivalent circuit of the SST in a three-cell configuration. The parasitic components between the heat sink and the device are modeled as an RLC series circuit. In contrast, the parasitic elements of each cell in the multi-stage connection are modeled as parallel connections.

Figure 7 shows the simulated conducted emission voltage results using the common-mode equivalent circuit. The figure shows that when ACC is not operating, a conducted emission voltage of 116dBμV is generated at 2.5 MHz. However, when the ACC is activated, the conducted emission voltage is reduced to 79.5dBμV, achieving a reduction of 36.5dBμV. The simulation results also demonstrate that the conducted emission voltage is consistently reduced by 36.5dBμV across the measurement range of 150 kHz to 30 MHz when the ACC is connected. This verifies the effectiveness of the current-type ACC in reducing conducted emission voltage within the specified frequency range.

B. experimental results

Figure 8 shows the photograph of the created Rogowski coil. Table 2 shows the parameters of the Rogowski coil. The outer dimension of the Rogowski coil, including its windings, is 26 mm. Its weight is 28.6 g. The Rogowski coil in the detection section detects the CM current flowing in the main circuit and converts the current voltage on the secondary side.

Table 1. Circuit parameters.

Parameter	Symbol	Value
Input voltage [V]	V_{in}	300
Output power [W]	P_{out}	100
Switching frequency [kHz]	f_{sw}	30
Boost inductor [mH]	L_b	5.0
Resonant capacitor [ns]	C_r	204
DC link Capacitor [µF]	C_{dc}	1500
Amplifier gain [dB]	-	26
Detective voltage / current [dB]	-	26
Number of turns	N	120
Detection resistance[kΩ]	R	2.4

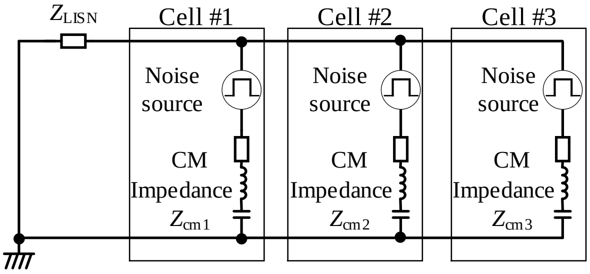


Fig. 6. Equivalent block diagram of SST in common mode circuit

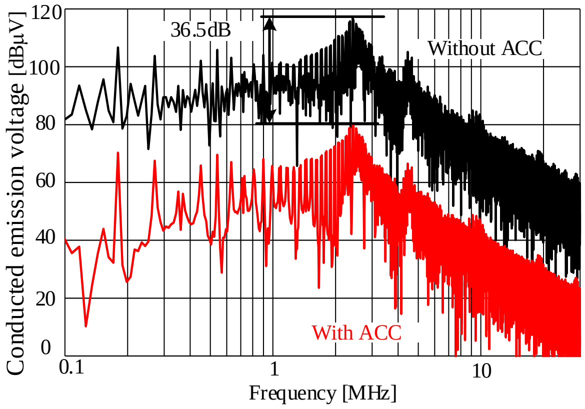


Fig. 7. Conducted emission voltage of the equivalent circuit.

Figure 9 shows the characteristics of the detected current-detected voltage ratio as a function of frequency for the Rogowski coil. The measurement results indicate that the Rogowski coil provides a detection gain 25.6dB. However, a 1.5% error is observed, attributed to changes in magnetic permeability and differences in wiring impedance compared to the design specifications. The cutoff frequency is 20 kHz, significantly lower than 150 kHz. The detection gain remains constant up to 30 MHz, confirming that the designed gain is suitable for use as a CM current detection unit in the noise measurement range from 150 kHz to 30 MHz.

Figure 10 shows a photo of the amplifier circuit created. The elements are compactly arranged to minimize the influence of wiring impedance.

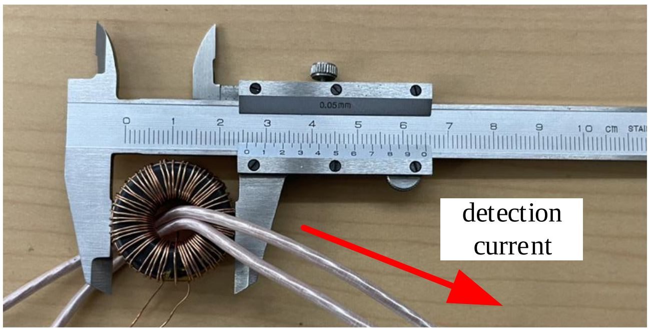


Fig.8. Rogowski coil.

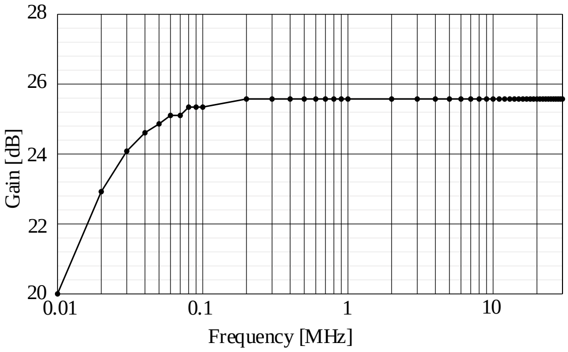


Fig. 9. Rogowski coil frequency characteristics.

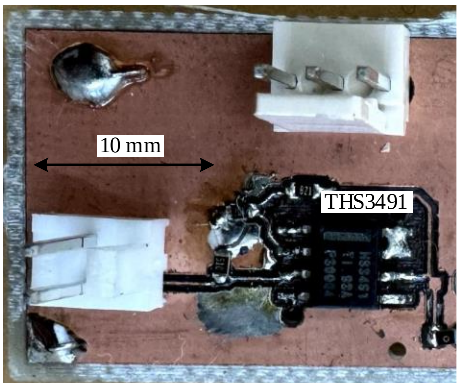


Fig. 10. Amplifier circuit.

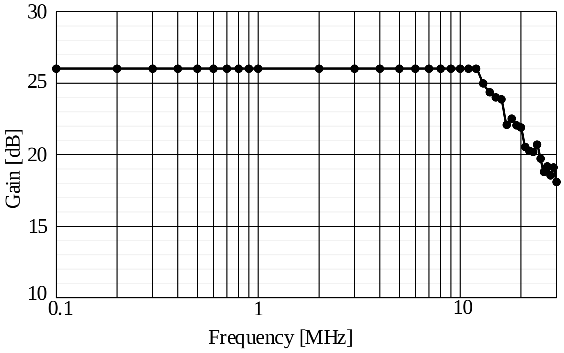


Fig. 11. Amplifier gain characteristics.

Figure 11 shows the measurement results of the amplifier's frequency-gain characteristics. The amplifier operates with the designed gain up to 12MHz, although its gain characteristics decrease at higher frequencies due to the more significant influence of the wiring inductance.

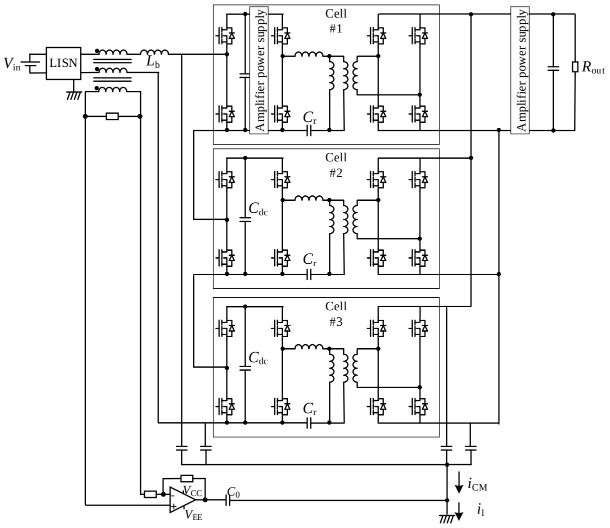


Fig. 12. Circuit configuration of the three-phase SST with ACC.

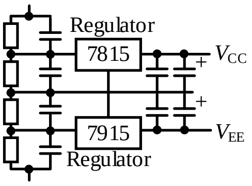


Fig.13. amplifier power supply circuit.

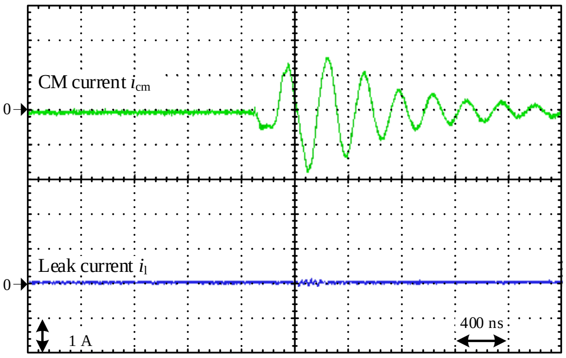
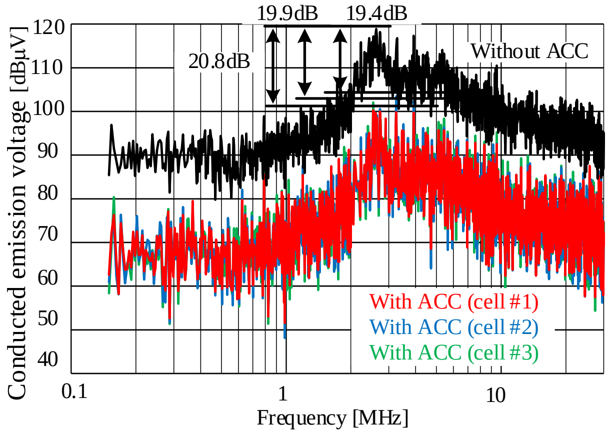
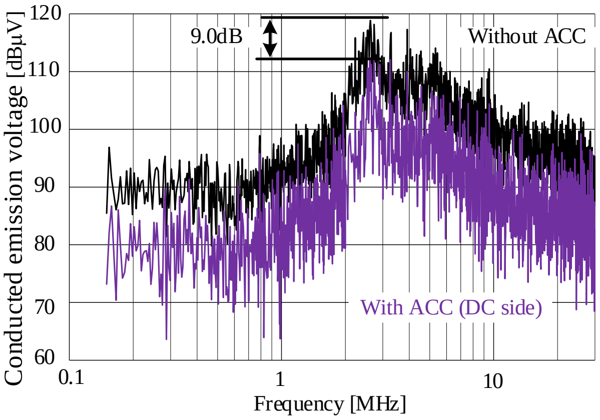


Fig. 14. CM current waveforms.



(a) Connection of the amplifier power supply to AC side



(b) Connection of the amplifier power supply to DC side

Fig. 15. Conducted emission voltage.

Figure 12 shows the circuit diagram when ACC connects to SST. A pseudo power supply network (LISN) measures the conducted emission voltage generated on the power supply side in this circuit. The Rogowski coil, which is the current detection part of the current-type ACC, connects to the rear stage of the LISN to detect the CM current flowing in the circuit. The detected CM current is converted to a voltage on the secondary side of the Rogowski coil and applied to the amplifier circuit. This circuit is used to measure the effect of reducing the conducted emission voltage when the power supply of the amplifier circuit connects to the DC voltage part of cell #1, cell #2, cell #3 and when it connects to the DC side.

Figure 14 shows the measurement results of the CM current flowing to the ground wire connected to the heat sink and the CM current flowing to the LISN compensated by ACC. The figure shows that the motor generates a maximum CM current of 1.4 A, but ACC reduces the CM current flowing to the LISN.

Figure 15(a) shows the measured conducted emission voltage when the amplifier power supply connects to the AC side. The figure shows that when ACC is not operating, a conducted emission voltage of 118.2dBμV generates at 2.5MHz. The peak value is almost consistent with the equivalent circuit simulation. The equivalent circuit model is valid. When the amplifier power supply connects to cell #1, a reduction of 20.8dBμV is obtained at 2.5MHz. Similarly, a decrease of 19.9dBμV is obtained when cell #2 connects. The reduction of 19.4dBμV is obtained when cell #3 connects. From the above, it is seen that the noise reduction effect of ACC is independent of the cell to which the amplifier power supply connects. Figure 15(b) shows the measured conducted emission voltage when the amplifier power supply connects to the DC side. The reason why the noise reduction effect is lower than when the amplifier power supply connects to the AC side is thought to be that the CM current flows through the power supply, switching device, heat sink, power supply, and the DC side does not serve as a path, so the compensation current could not be injected sufficiently. This is thought to be because the CM current path flows through the power supply, switching device, heat sink, power supply, and the DC side does not serve as a path. However, when the current-type ACC connects, the conducted emission voltage is checked to be reduced from 150 kHz to 30 MHz. It is said that the current-type ACC effectively reduces electromagnetic noise in all frequency bands of the measurement range.

IV. CONCLUSION

This paper demonstrated the reduction of conducted emission voltage in a multi-cell SST using a current-type ACC. The experimental results show that when the amplifier power supply connects to the AC side of cell #1, a reduction of 20.8dBμV is achieved at the 2.5 MHz peak frequency. Additionally, noise reduction is observed across all frequency bands from 150 kHz to 30 MHz, as defined by the CISPR standard. The results confirmed that the ACC effectively reduces conducted noise in multi-cell circuits.

In the future, we will analyze the detailed noise propagation paths in multi-cell circuits and design an ACC optimized for further noise reduction in such systems.

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