Rectifier-Integrated Printed-Circuit-Board Winding Structure of Secondary-Side Center-Tapped Transformer for Suppressing Parasitic Resonance between Decoupling Capacitors

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***Abstract*--In many practical LLC DC-DC converters, the isolation transformer is commonly designed to have a secondary-side center-tapped configuration with one-turn secondary windings. Conventionally, the rectification circuit is installed outside the transformer. However, the recent LLC converters are designed to operate at increasingly high switching frequencies, which indispensably causes the proximity effect in the rectification circuit as well as the wire that connects this circuit to the transformer secondary windings, resulting in large copper loss generation outside the transformer. The previous paper addressed this problem by proposing a secondary winding structure integrating the rectification circuit, although this structure caused the parasitic resonance inside the rectification circuit and reduced the rectification efficiency. To prevent the reduction in the rectification efficiency, this paper proposes an improved winding structure based on the printed-circuit-board technology for suppressing parasitic resonance. The experiment revealed further improvement in the rectification efficiency compared to the previously-proposed structure, suggesting the effectiveness of the proposed winding structure.**

Index Terms—coil structure, copper loss, forward converter, proximity effect, transformer

I. Introduction

The power consumption of the server computers of the telecommunication infrastructure such as data centers is rapidly increasing due to the recent progress and widespread of information technologies. Because server computers generally require a low voltage power supply, the increasing power consumption results in high current in the power supply cable, which can generate an enormous copper loss in the whole power supply network, particularly of large facilities. To cope with this problem, the recent facilities supply the high voltage dc power to the server computers by installing the isolated high step-down dc-dc converters in the neighbor of the server computers [1][2], as exemplified in Fig. 1. Propelled by the recent increase in the server computers' calculation burden, the power supply is increasingly designed to supply higher dc voltages, which requires the isolated converters to operate at an extremely high step-down ratio [3]–[5].

The converter for this purpose is required to reduce the volume and the power loss simultaneously because of the limited installation space and cooling capacity available for the converter. For effective miniaturization, the converter is commonly designed to operate at high frequencies. However, the high-frequency operation of the converter can result in a large power loss. Particularly, the secondary side of the isolation transformer carries a large ac current and therefore tends to generate large rectification loss and copper loss, which should be solved for the practical design of the high voltage dc power supply system to the server computers.

The LLC converter with a transformer having the secondary-side center-tapped winding configuration [4][6]–[8], as shown in Fig. 2, is a promising converter that can meet this requirement. This converter can easily achieve a high step-down ratio by designing the transformer to have a high turn ratio. In fact, the secondary winding is commonly designed to have only one turn for achieving the high step-down ratio. Furthermore, this converter has attractive features for achieving high efficiency under high-frequency operation. Besides the soft-switching capability of the primary-side switching devices, the rectification loss on the secondary side can be reduced by the secondary-side center-tapped winding

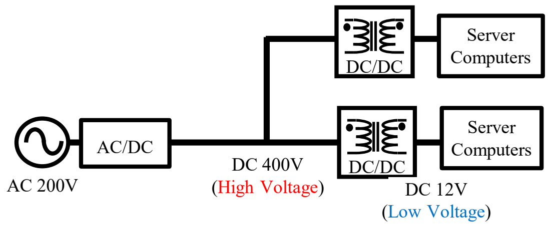

Fig. 1. Typical high voltage dc power supply system of telecommunication infrastructure.

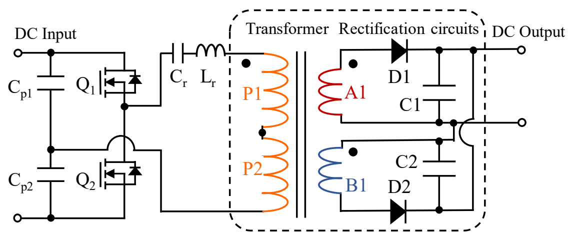

Fig. 2. Circuit schematics of LLC converter.

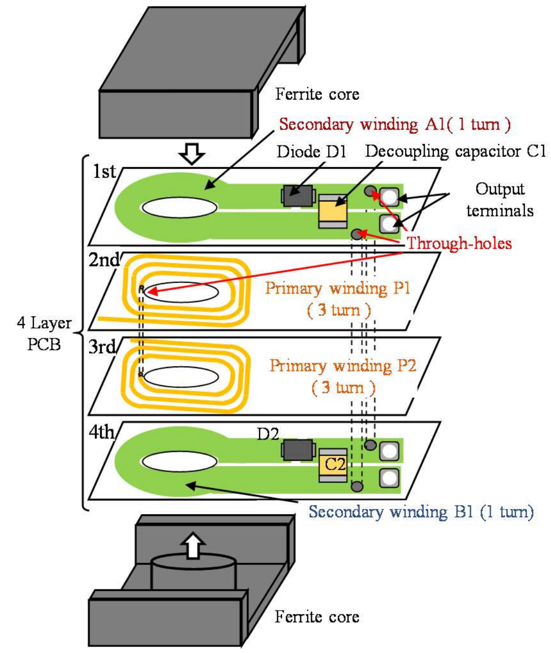

Fig. 3. Conventional transformer winding structure.

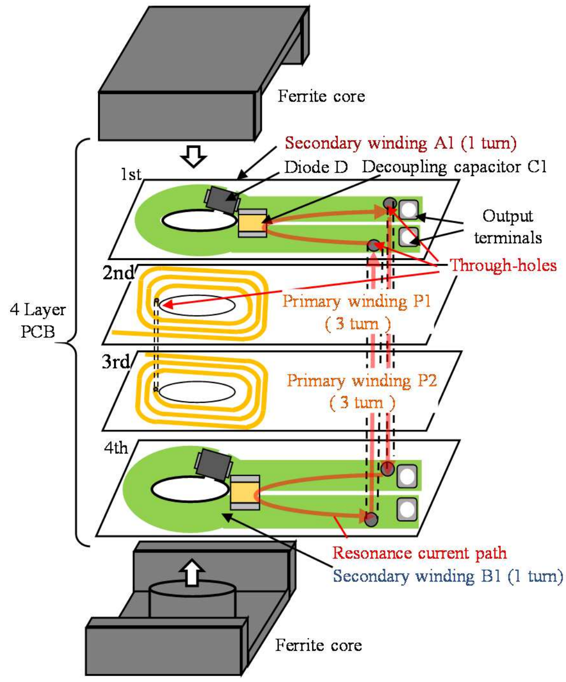

Fig. 4. Previously proposed transformer winding structure.

configuration because the secondary current passes through only a single diode before it flows out from the output terminal.

The secondary winding's copper loss can be further reduced by design optimization of the isolation transformer. The interleaved winding structure, which places the secondary winding layers adjacent to the primary winding layers, as shown in Fig. 3, are known to effectively mitigate the proximity effect in the high-frequency operation and thus reduce the copper loss. The interleaved winding structure has been commonly investigated for the normal transformer winding configuration, which has a single primary winding and a single secondary winding [9]–[12]. However, a recent study has elucidated an optimal interleaved winding structure for the secondary-side center-tapped winding configuration [13].

Adopting these aforementioned technologies can effectively reduce power loss. Nonetheless, a recent research [14] still noticed a remaining major power loss on the secondary side, which is the secondary side copper loss excluding the secondary winding, i.e. the wire connecting the secondary winding to the rectification circuit and the wires constituting the rectification circuit. This research elucidated that the copper loss in these wires can be large enough to apparently deteriorate the power conversion efficiency in high-frequency operation because they are not overlapped with the primary winding.

Reduction of this loss was also sought in this research, which proposed a transformer secondary winding structure integrating the rectification circuit, illustrated in Fig. 4. This structure was designed to have the whole rectification circuit, as well as the secondary windings, overlapped with the primary winding. However, this structure encountered the problem that the difference in the ac current flow between two decoupling capacitors can excite the parasitic resonance to cause a large copper loss. This problem certainly was found to be solved by inserting smoothing inductors between each decoupling capacitor and the output terminal, although this significantly increased the converter size.

The purpose of this paper is to purpose an improved transformer winding structure with two secondary windings integrating the rectification circuit. The proposed structure can prevent the parasitic resonance between two decoupling capacitors without adding the smoothing inductor by a special wire layout that directly connects these two decoupling capacitors with minimum wire length. Unlike the previous study [14], this paper adopts the printed-circuit board (PCB) for implementing the winding, which is recently emerging as a promising winding material for high-frequency transformers. By utilizing the PCB, the proposed structure can be easily manufactured for practical application.

The remainder of this paper comprises four sections. Section II discusses the problems of the previous transformer winding structure based on the electromagnetic theory. Section III presents the proposed winding structure to solve the problem of the previous structure. Section IV shows an experiment to test the performance of the proposed winding structure. Finally, section V gives the conclusions.

II. Previous Winding Structure

This section discusses the problems of the conventional interleaved winding structure as well as the previously proposed winding structure based on Fig. 3 and Fig. 4. These winding structures are constructed as a PCB with four winding layers. Each of the top and bottom layers has a one-turn coil, which corresponds to one of the two secondary windings. The rectification circuits of diode D1 and decoupling capacitor C1 and that of diode D2 and decoupling capacitor C2 are installed on these corresponding secondary winding layers. The output terminals of these secondary windings are therefore connected in parallel via the through holes installed close to these output terminals. Meanwhile, each of the two inner layers has a multiple-turn coil, which accurately overlaps the secondary coils. The coils of these inner layers are connected in series at the coil ends to form the alpha-shaped primary winding.

The difference between the two winding structures, i.e. Fig. 3 and Fig. 4, lies in the installation position of the rectification circuits. The rectification circuits are placed outside the secondary windings in the conventional winding structure. On the other hand, the rectification circuits are placed on the secondary windings so that the series connection of the diode D1(D2) and the decoupling capacitor C1(C2) forms a part of the secondary winding in the previously proposed structure. In both structures, the two terminals of the decoupling capacitors are connected to the output terminals.

As these winding structures are designed for the isolation transformers of the LLC converter, the primary winding carries the sinusoidal current with the same frequency as the switching frequency, which then induces the current in one of the secondary windings. The current of the secondary windings cancels the magnetomotive force in the primary winding because the primary and secondary windings adjacently overlap each other. The magnetomotive force cancelation reduces the ac magnetic field applied to the primary and secondary windings, which mitigates the power loss generated by the eddy current, i.e. the proximity effect loss, inside the windings.

Nonetheless, the secondary-side wires that do not have the overlapping primary counterpart are susceptible to the proximity effect. As a result, such wires of the secondary side tend to generate significant copper loss due to the large eddy current generation in the secondary side. In the conventional winding structure, the wires connecting the secondary windings and the rectifier circuits, as well as the wires forming the rectification circuit, are not overlapped with the primary winding and therefore can generate large copper loss [14].

The previously proposed structure aims at solving this problem. This structure integrates the rectification circuits so that these circuits are entirely overlapped with the primary winding, thereby mitigating the copper loss on the secondary side due to the proximity effect. (Although the wires from the rectification circuit to the dc output are not overlapped with the primary winding, these wires do not cause the proximity effect as they scarcely carry the ac current.) However, the decoupling capacitors are connected each other by the long wires via the output terminal because the two rectifier circuits are installed separately on the two secondary windings. Therefore, this structure includes the parasitic LC resonator comprising the decoupling capacitors and the parasitic inductance of these long wires.

In many PCB designs, the parasitic inductance of these wires is certainly small, ranging from several nH to several tens of nH. However, the decoupling capacitors tend to have large capacitance for decoupling the large ac current

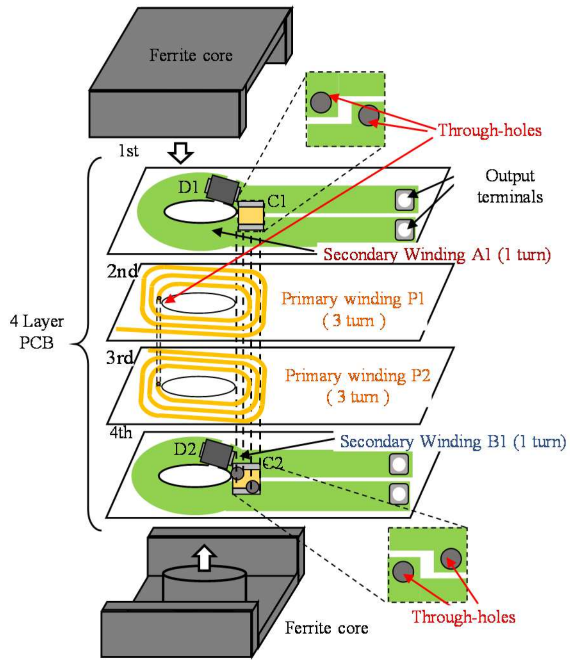

Fig. 5. Proposed transformer winding structure.

on the secondary side. As a result, this parasitic LC resonator can have a resonant frequency close to the switching frequency. In this case, the large resonant current can be excited in the parasitic LC resonator due to the voltage ripples in these decoupling capacitors, which have a 180-degree phase difference. Consequently, this resonant current generates a significant copper loss in these long wires, deteriorating the power conversion efficiency.

III. Proposed Winding Structure

According to the discussion in the previous section, the parasitic inductance of the wires connecting the two decoupling capacitors is the cause of the problems in the previously proposed structure. Therefore, the probable approach to solve this problem may lie in eliminating or minimizing the length of these wires so that these wires have ultimately small parasitic inductance to make the parasitic resonant frequency far higher than the switching frequency. The proposed winding structure was therefore deduced based on this approach.

Figure 5 illustrates the proposed winding structure. Similarly to the previously proposed structure, the proposed structure has the two rectification circuits integrated separately on the two secondary windings to mitigate the proximity effect in the rectification circuits. However, the proposed structure further connects the two decoupling capacitors with minimum length by utilizing through-holes on the PCB. The proposed structure positions the two decoupling capacitors in the different secondary winding layers but at the same horizontal position. However, this results in the fact that the positive voltage terminal of one decoupling capacitor locates at the negative voltage terminal of the other decoupling capacitor and vice versa because of the inverse voltage induction between the two secondary windings. Therefore, the comb-like PCB layouts are implemented just below these

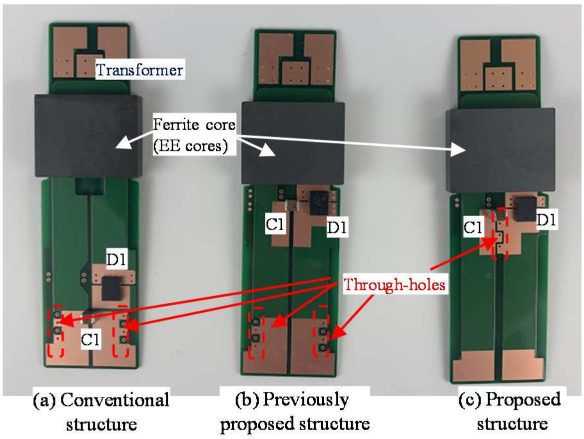

Fig. 6. Photograph of the three prototype transformers.

decoupling capacitors so that the through-holes on this layout can connect the same terminals of these capacitors with minimum length.

Consequently, the proposed winding structure can be expected to reduce the copper loss in the rectifier circuits by integrating them onto the secondary windings and to reduce the copper loss in the wire connecting the decoupling capacitors by avoiding the parasitic resonance between these two decoupling capacitors.

IV. Experiment

Experiments were carried out to evaluate the operation principles of the proposed winding structure. For this purpose, these experiments evaluated and compared the copper loss of the secondary winding including the rectifier circuit, as well as the rectification efficiency, among the transformer prototypes with three different winding structures: 1. The conventional structure, 2. The previously proposed structure, and 3. The proposed structure.

For simplifying the experiments, these prototypes adopted diode rectification. Therefore, the rectification efficiency can scarcely be reflected by the copper loss of the winding and the wires in the rectification circuits because the diode conduction loss is expected to take the major part of the rectification loss. Therefore, the purpose of the rectification efficiency measurement was not weighed on the performance evaluation of the proposed structure, which should be performed with the synchronous rectification circuit. (These experiments will be performed in future research.) Nonetheless, the parasitic resonance between the decoupling capacitors can generate non-negligible power loss even compared to the diode conduction loss. Therefore, the rectification efficiency measurement was aimed at observing the effect of the loss caused by the parasitic resonance.

A. Prototypes

Figure 6 shows the photograph of the three prototype transformers with the rectification circuit. The circuit diagram of these prototypes is the same as that surrounded by the dashed line in Fig. 2. The transformer prototypes are closely coupled transformers with a 6-turn primary winding and two one-turn secondary windings. The rectification circuit was made of diode V30K202HM3/H and 4.7μF ceramic capacitors UMK325B7475KMHP. These prototypes are constructed on the same magnetic cores, i.e. EERS-25J (JFE Corp.). The windings are formed on a 4-layer PCB with a copper thickness of 70μm and a board size of 24mm × 85mm.

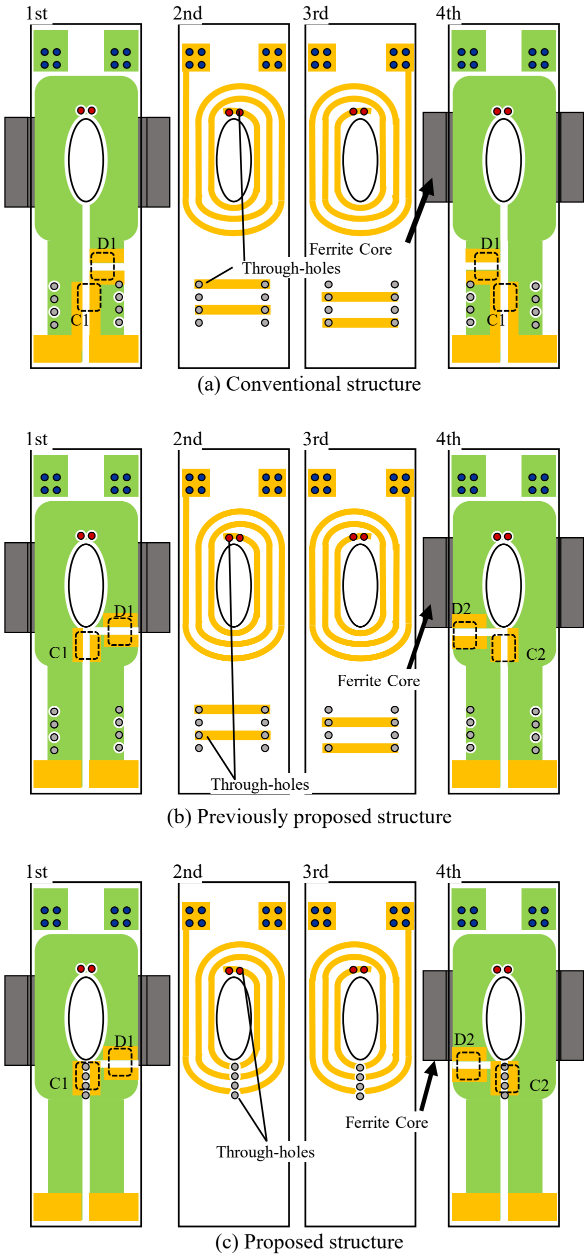

Fig. 7. Printed circuit board layout of prototype transformers.

Figure 7 depicts the PCB layout of the prototype transformers. The layout of the primary winding is the same among the prototypes: the primary winding is the alpha-shaped winding formed as the series connection of the 3-turn coils located in the two inner layers. The only difference among the prototypes lies in the layout for the secondary windings, which are located in the top and bottom layers.

The diodes and decoupling capacitors of the rectification circuits are mounted at the regions surrounded by the dashed lines. The rectification circuits are located

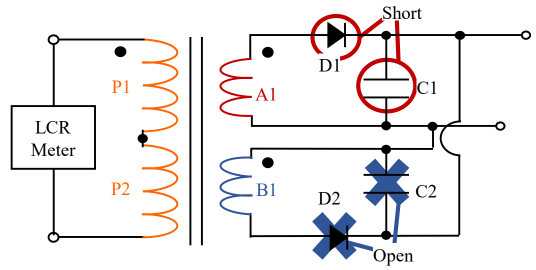

Fig. 8. Experiment circuit for ac resistance measurement.

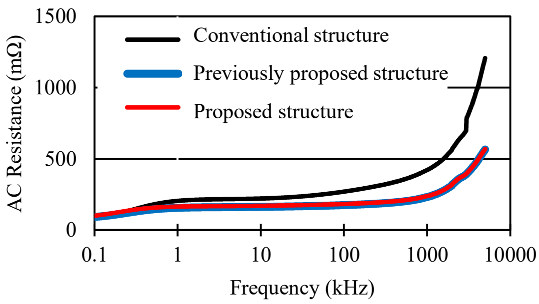

Fig. 9. Measurement result of ac resistance.

outside the regions overlapped with the primary winding in the conventional structure, whereas they are incorporated in the regions in the previously proposed structure and the proposed structure. The difference between the previously proposed structure and the proposed structure lies in the connection of the two decoupling capacitors, located in the two secondary winding layers separately. The decoupling capacitors are connected by long wires that connect these capacitors to the output terminals in the previously proposed structure, whereas they are directly connected by the through-holes with minimum length using the comb-like layout.

B. Evaluation of Copper Loss

Firstly, the experiment evaluated the copper loss of the transformer. For this purpose, Diode D1 and decoupling capacitor C1 on a secondary winding layer are short-circuited, whereas those on the other secondary layer, i.e. D2 and C2, are unmounted and left as open-circuit, as shown in Fig. 8. The output terminals are disconnected from the power load. Then, the ac resistance of the primary winding is measured using an LCR meter ZM2376 (NF Corp.).

Figure 9 shows the measurement results. The three prototypes exhibited similar ac resistance in the frequency region below 20kHz approximately. However, both the previously proposed structure and the proposed structure exhibited smaller ac resistance than the conventional structure in the frequency region above 20kHz. Because the proximity effect is known to appear more prominently than the skin effect in high frequency, the measurement result can be interpreted that the previously proposed structure and the proposed structure suppressed the copper loss due to the proximity effect. This is consistent with the operating principles of the previously proposed structure and the proposed structure, which expect the reduction of the copper loss by suppressing the proximity effect in the

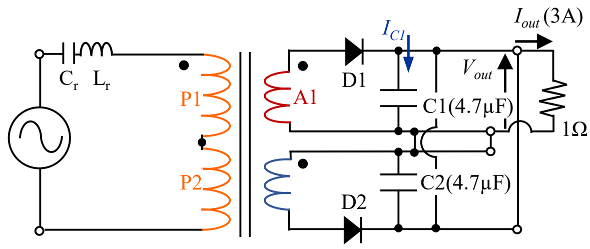

Fig. 10. Experiment circuit for rectification efficiency measurement.

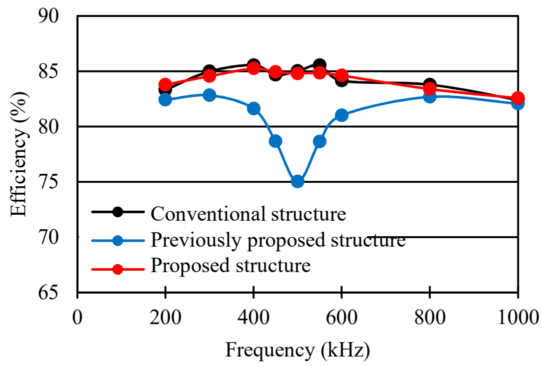

Fig. 11. Measurement result of rectification efficiency.

rectification circuit, i.e. the eddy current generation in the magnetic field at the rectification circuit.

C. Evaluation of Rectification Efficiency

Secondly, the rectification efficiency was evaluated for the three prototype transformers. In this experiment, the bipolar power amplifier 4025 (NF Corp.) was connected to the primary winding for supplying the ac sinusoidal current to the prototype transformers; a 1Ω resistor was attached to the output terminals for consuming the output dc power. The schematic of the experimental setup is shown in Fig. 10. The amplitude of the sinusoidal current was adjusted so that the dc current flowing in the load was kept at 3A. Then, the rectification efficiency was measured as the ratio of the dc output power to the ac input power.

Fig.10 Circuit schematics of evaluating rectification efficiency

Figure 11 shows the measurement results. The difference in the ac resistance, i.e. the copper loss, is expected to be far smaller than the diode conduction loss and therefore scarcely affected the rectification efficiency. Nonetheless, the rectification efficiency was significantly reduced in the prototype of the previously proposed structure, particularly in the frequency region close to 500kHz.

For elucidating the reason for this efficiency deterioration, the ac current of the decoupling capacitor C1 was also measured at two frequencies, i.e. 500kHz and 1MHz. The result is shown in Fig. 12. As can be seen in the figure, the previously proposed structure experienced far greater ac current in the decoupling capacitors, particularly at 500kHz, whereas the conventional structure and the proposed structure succeeded to have a small decoupling capacitor current. Furthermore, the parasitic

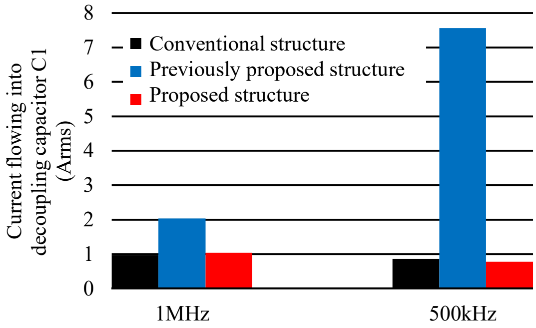

Fig. 12. RMS values of decoupling capacitor C1 current.

resonant frequency between the decoupling capacitors was measured to be close to 500kHz in the previously proposed structure.

This evidence can consistently explain the rectification efficiency deterioration observed in the previously proposed structure: The loss caused by the parasitic resonance between the decoupling capacitors reduced the rectification efficiency. However, this loss was successfully reduced in the proposed structure, which resulted in better rectification efficiency than that of the previously proposed structure.

Fig.12 Results of RMS values of the currents flowing into decoupling capacitor C1

Consequently, the evaluation results of the ac copper loss and the rectification efficiency supported that the proposed structure can effectively reduce the copper loss in the rectification circuit and further suppress the parasitic resonance between the decoupling capacitors, as expected by the operating principles of the proposed structure.

V. Conclusions

The copper loss due to the proximity effect in the rectification circuits, as well as the wires connecting the rectification circuits to the secondary windings, has been one of the prominent causes of the power loss in secondary-side center-tapped transformer with one-turn secondary windings, which is widely utilized for the high-frequency transformer of isolated dc-dc converters. The previously proposed structure addressed this problem to mitigate the proximity effect, although this structure suffered from an additional power loss caused by the resonance current in the parasitic resonator formed by connecting the two decoupling capacitors.

For avoiding the resonance, this paper proposed a novel winding structure. This structure integrates the rectification circuits on the secondary windings to reduce the copper loss, similarly to the previously proposed structure. Furthermore, the proposed structure implements a special PCB layout to directly connect the two decoupling capacitors, which are separately installed on the secondary winding layers, via through-holes with minimum wire length. Thereby, this structure can further suppress excitation of the parasitic resonance

Two experiments were conducted to evaluate the ac resistance and the rectification efficiency. The ac resistance measurement supported the effective reduction of the copper loss due to the proximity effect in the rectification circuits, as well as the wires connecting the rectification circuits to the secondary windings. Furthermore, the rectification efficiency measurement also suggested suppression of the parasitic resonance between the decoupling capacitors. Consequently, the proposed structure was found to be a promising winding structure for the secondary-side center-tapped transformer with one-turn secondary windings. Future studies will evaluate the proposed structure with the synchronous rectification circuits to prove an apparent improvement in the rectification efficiency.

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