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Paper

Loss Reduction of Transformer for LLC Resonant Converter Using a Magnetoplated Wire

Tatsuya Yamamoto[*a)] Student Member, Yinggang Bu[*] Member
Tsutomu Mizuno[*] Senior Member, Yutaka Yamaguchi[**] Non-member
Tomoyoshi Kano[**] Non-member

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To improve the power density of a switching power supply, we attempt to reduce the transformer loss using a magnetoplated wire (MPW). Contrary to using a copper wire, the use of an MPW allows for a reduction of the winding loss component due to the proximity effect. In particular, we investigate the 1 MHz LLC resonant converter using an MPW. An 8.8% decrease in the power loss is achieved, giving 33 W at 1 MHz and 1 kW.

Keywords: copper loss, LLC resonant converter, magnetoplated wire, power density

1. Introduction

Stable DC power, in the kW range, is necessary for large PCs, such as servers, to allow for the simultaneous functioning of a CPU, an HDD, and a cooling fan drive. The switched-mode power supply, which is used for servers, requires high-efficiency and high-power density converters. However, the transformer performance is insufficient for improving converter efficiency and power density.

The converter power density increases with the driving frequency [(1)–(4)]. However, a high-frequency drive produces a great switching loss and power loss at the transformer, thus, reducing the efficiency of the converter.

The LLC resonant converter effectively reduces the switching loss [(5)–(8)], enabling soft switching. In addition, the leakage inductance of the transformer can be used as an inductor for resonance. Consequently, reducing the number of circuit elements reduces the size of the converter. SiC and GaN also effectively reduce the switching loss [(3)–(5)(7)–(9)] because the electricity loss is extremely lower than in a device with the conventional Si power semiconductor.

The transformer loss can be classified into iron and copper losses. Reduction of the iron loss can be achieved using core materials with improved properties and by changing the core shape [(10)–(14)]. Copper loss is reduced by changing the wire's shape and winding form. The factors affecting the copper loss are the deflection of the current densities by the skin and proximity effects. Litz wire is used for transformer winding to reduce the AC resistance due to the skin effect. However, the Litz wire causes an increase in the AC resistance due to the proximity effect. Therefore, we propose the use of a magnetoplated wire (MPW) for the transformer coil to reduce copper loss. MPW is composed of a magnetic thin film that is plated onto the circumference of a copper wire (COW). The MPW decreases the AC resistance because of the proximity effect; an alternating magnetic flux flows through the magnetic thin film with greater permeability and resistivity compared to copper [(15)–(17)].

In the present study, the transformer resistances using a Litz wire with a copper wire (LCW) and Litz wire with an MPW (LMW) are measured. Additionally, the power loss characteristics of the transformers in the LLC resonant converters of the LCW and LMW are compared. We discuss the following matters:

1) Impedance characteristics of the transformer.
2) Efficiency and power loss characteristics of the LLC resonant converter.

2. Structure of LLC Resonant Converter using Magnetoplated Wire

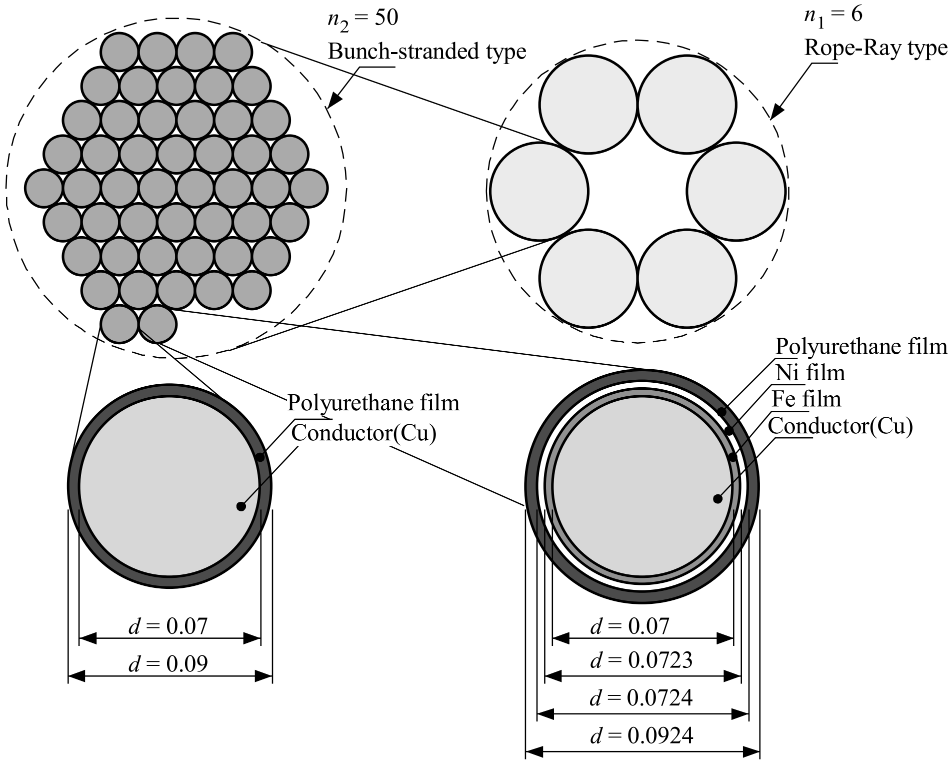
2.1 Structure of Winding Wire Figure 1 shows the winding wire structure for the transformer. The COW with a diameter of 70 μm is plated with a 10-μm-thick insulating film. The LCW is composed of 300 COWs. The LCW sectional area is 1.15 mm^2.

The MPW is a copper wire with a diameter of 70 μm plated on magnetic thin films (Fe and Ni). The Fe and Ni thin films are 1.15 μm and 0.065 μm thick, respectively. The Ni film was plated for ease of soldering. The LMW is composed of 300 MPWs. The LMW sectional area is 1.15 mm^2.

2.2 Structure of Transformer Figure 2 shows the structure of the transformer in the LLC resonant converter. The core of the transformer is made of MC2 materials (JFE), and the shape of the core is EER42D. The core has a gap on the primary side center leg to cause leakage inductance. The gaps of the core in the LCW and the LMW are 1.1 mm wide.

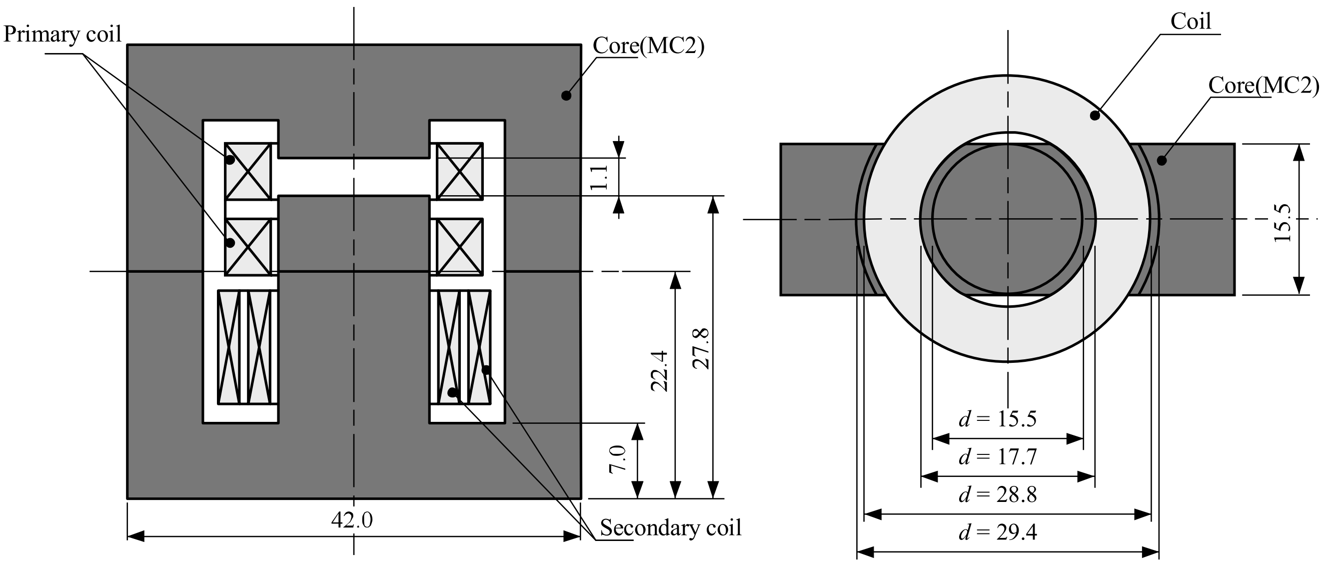
Figure 3 shows the winding structure of the transformer

a) Correspondence to: Tatsuya Yamamoto. E-mail: 16st210c@shinshu-u.ac.jp
[*] Faculty of Engineering, Shinshu University
4-17-1, Wakasato, Nagano 380-8553, Japan
[**] Tabuchi Electric Co., Ltd.
Kinsan Bldg., 3-18-3, Kanda-Nishiki-cho, Chiyoda-ku, Tokyo 101-0054, Japan



(a) Litz wire with copper wires (LCW) (b) Litz wire with magnetoplated wires (LMW)

Fig. 1. Structure of the winding wire for the transformer (unit: mm)



(a) Vertical cross-sectional view (b) Cross-section

Fig. 2. Structure of the transformer for the LLC resonant converter

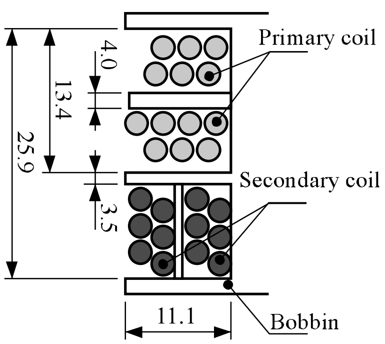


Fig. 3. Winding structure of the transformer for the LLC resonant converter (unit: mm)

in the LLC resonant converter. The primary coil has a gap to increase the leakage inductance, and it has 13 turns with the gap. The secondary side of the transformer is the center tap output. The secondary coil is composed of two coils: S1 (inside coil) and S2 (outside coil). An insulating tape is sandwiched between the two coils. There are six turns in the coil.

2.3 Circuitry of the LLC Resonant Converter

Figure 4 shows the circuit structure of the LLC resonant converter. The inverter part is composed of four FETs that are connected through a full bridge. The diodes between the drain and the source of the FET are parasitism diodes. The FET of the inverter is GaN FET.

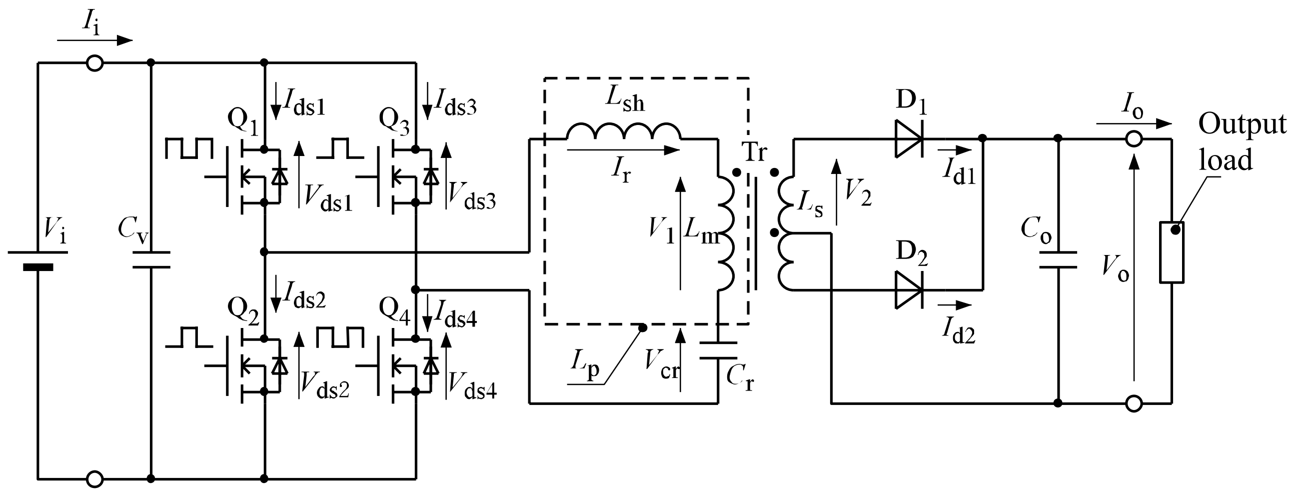
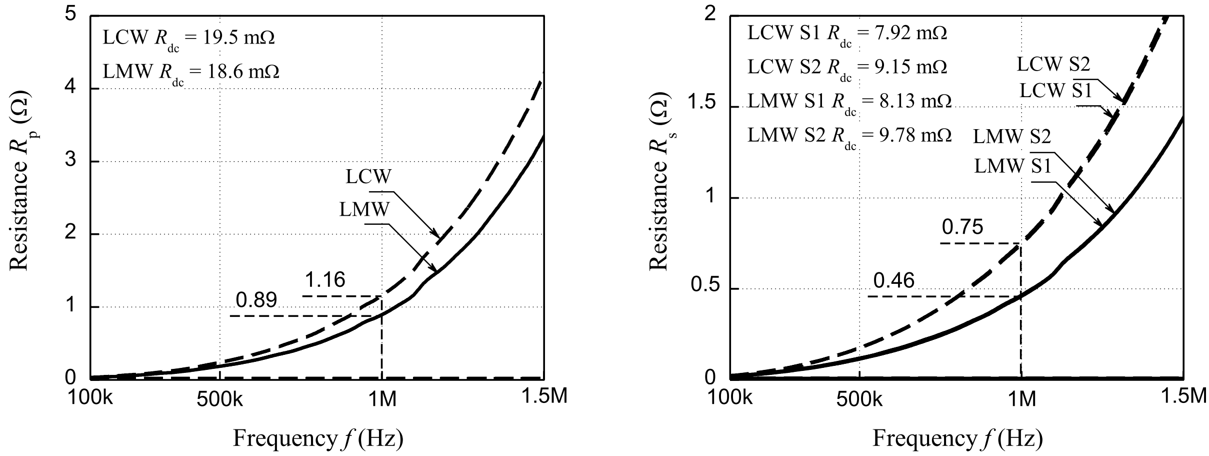


Fig. 4. Circuit structure of the LLC resonant converter



(a) Primary coil

(b) Secondary coil

Fig. 5. Resistance vs. frequency characteristics

The capacitor C_r is a resonance capacitor connected to the primary side of the transformer. The inductance L_{sh} is the leakage inductance of transformer, and it is used for the resonance inductor. L_m is the excitation inductance. C_r, L_{sh}, and L_m are connected in series. The secondary side of the transformer is the center tap output, and it is connected with rectifier diodes. The diode for the rectifier is SiC diode.

3. Impedance Characteristics of the Transformer for the LLC Resonant Converter

3.1 Resistance vs. Frequency Characteristics The impedance characteristics of the transformer for the LLC resonant converter were measured using an impedance analyzer (Agilent, 4294A).

Figure 5 shows the resistance versus the frequency characteristics of the transformer. At frequency 1 MHz, the resistance of the primary coil using LCW was 1.16 Ω, and using LMW, it was 0.89 Ω. Thus, the LMW resistance was lower by 23.2% compared to that of the LCW. At the same frequency, the resistance of the secondary coil using LCW was 0.75 Ω, whereas it was 0.46 Ω using LMW. Therefore, the LMW resistance was decreased by 38.7% compared to the LCW resistance.

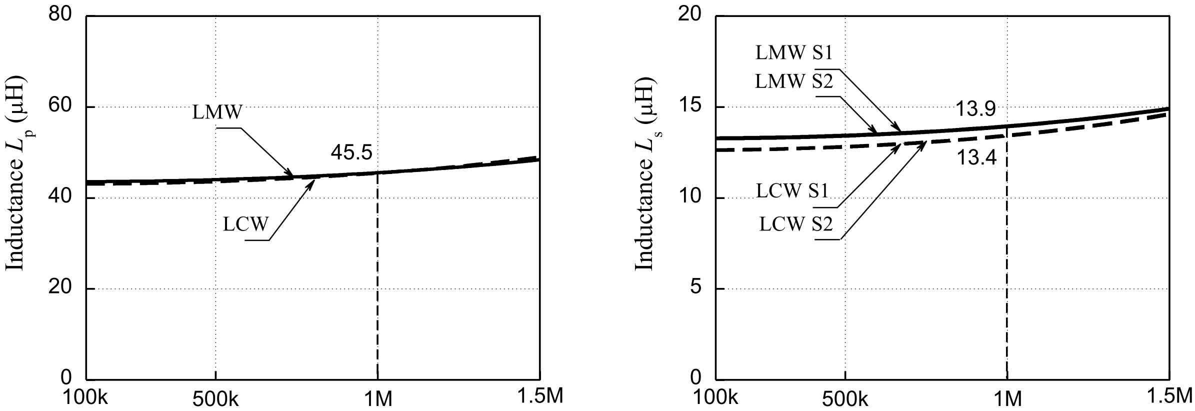
The skin depth of copper wire is 66 μm at frequency 1 MHz. Since the diameter of the strand in the LCW and the LMW is less than twice the skin depth, AC resistance due to the skin effect does not affect. The factor of reducing the resistance of the transformer was reduction of AC resistance due to the proximity effect by using LMW.

3.2 Inductance vs. Frequency Characteristics

Figure 6 shows the inductance versus the frequency characteristics of the transformer. At a frequency of 1 MHz, the inductance of the primary coil using LCW and LMW were 45.5 μH. At a 1 MHz driving frequency, we produced the transformer so that the inductance of the primary side was equaled. At 1 MHz, the inductance of the secondary coil using LCW was 13.4 μH, and it was 13.9 μH using LMW. Therefore, the LMW inductance was increased by 3.7% compared to the LCW inductance. This is because the magnetic energy is stored in a magnetic thin film.

3.3 Short Circuit Inductance and the Coupling Coefficient Figure 7 shows the short circuit inductance versus the frequency characteristics of the transformer. As a condition of measurement, the secondary side of the transformer was short circuited.

At 1 MHz, the short circuit inductance of the coil using LCW was 12.1 μH, and 13.5 μH using LMW. Thus, the short circuit inductance of LMW was 11.6 % higher than that of



(a) Primary coil

(b) Secondary coil

Fig. 6. Inductance vs. frequency characteristics

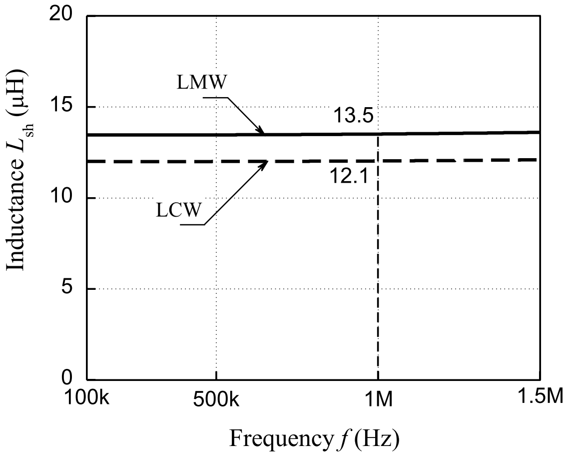


Fig. 7. Short circuit inductance vs. frequency characteristics

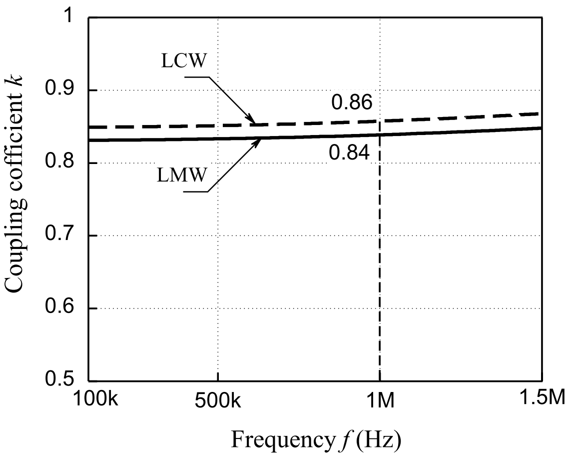


Fig. 8. Coupling coefficient vs. frequency characteristics

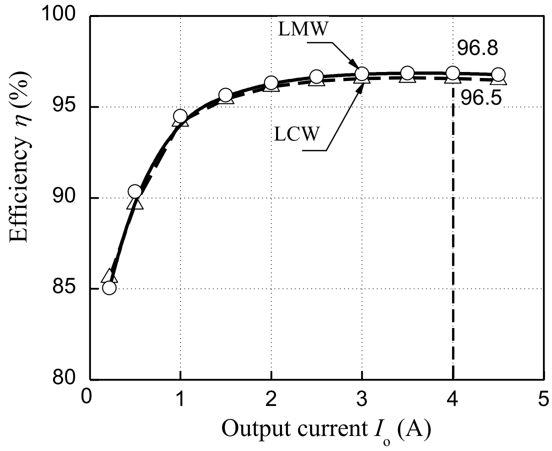


Fig. 9. Efficiency vs. output current characteristics

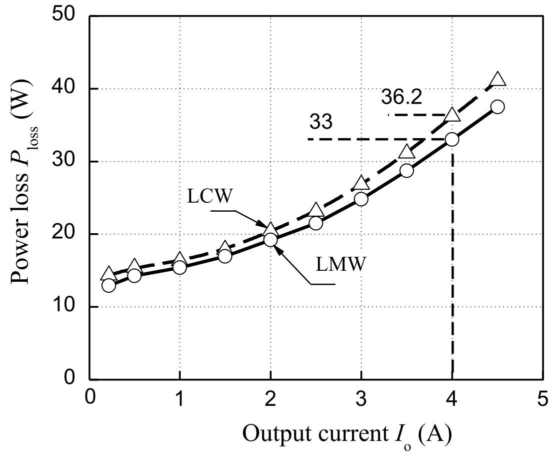


Fig. 10. Power loss vs. output current characteristics

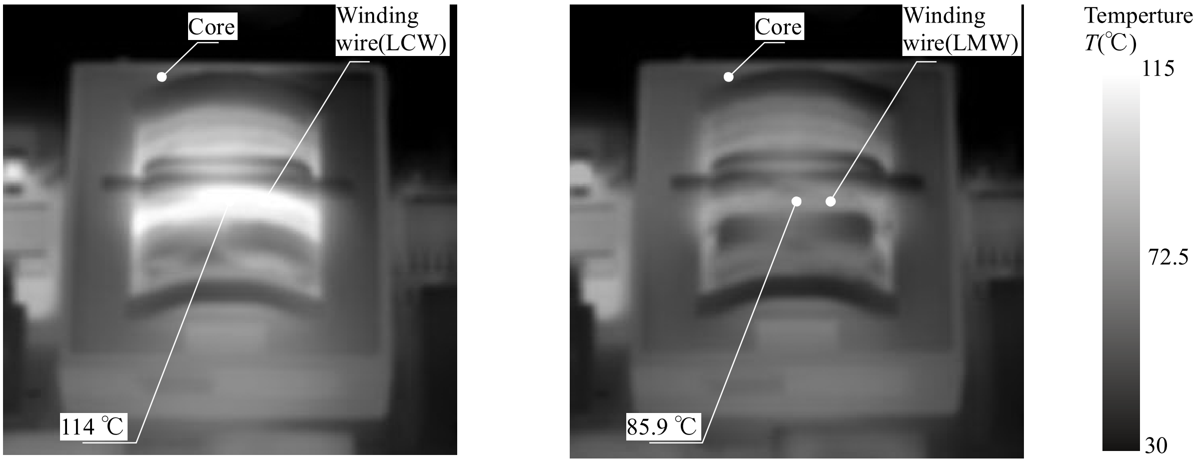
LCW. This is because the magnetic energy is stored in a magnetic thin film, and the interlinkage flux of secondary coil decreases.

Figure 8 shows the coupling coefficient versus the frequency characteristics of the transformer. The coupling coefficients were calculated by substituting the values of the measured primary inductance L_p and short circuit inductance L_{sh} into the following equation.

$$k = \sqrt{1 - \frac{L_{sh}}{L_p}} \cdots\cdots\cdots (1)$$

where k is the coupling coefficient.

At 1 MHz, the coupling coefficient of the transformer was 0.86, using LCW, and 0.84, using LMW. This is attributed to the increase of the short circuit inductance when LMW was used.



(a) LCW (b) LMW

Fig. 11. Comparison of heat generated by the transformers (f = 1 MHz, V_i = 380 V, I_o = 4 A, room temperature: 27°C)

4. Efficiency and Power Loss of LLC Resonant Converter

4.1 Efficiency and Power loss Characteristics The switching frequency of the converter was 1 MHz. The input power P_i and the output power P_o were measured with an electronic load (Keisokugiken, LN-1000C-G7) by changing the load R_L. The input power and the output power were measured with a power meter (Yokogawa, WT1800).

Figure 9 shows the efficiency η versus the output current I_o of the LLC resonant converter using the LCW and LMW transformers. At the output current of 4 A, the efficiencies of LCW and LMW were 96.5% and 96.8%, respectively; thus, the efficiency of the LMW was improved by 0.3%.

Figure 10 shows the power loss P_{loss} versus the output current I_o of the LLC resonant converter using the LCW and LMW transformers. At the output current of 4 A, the power losses of LCW and LMW were 36.2 W and 33 W, respectively; the power loss of LMW was decreased by 8.8% compared to that of LCW. These reason is the reduction of the resistance due to the proximity effect, when LMW is used.

4.2 Temperature Increase in the Transformer

Figure 11 shows the distribution of the surface temperature of the transformers winding using LCW and LMW. The temperature inside the winding wire is difficult to measure; therefore, we measured the surface temperature. The surface temperatures of LCW and LMW at the output current of I_o = 4 A were 114°C and 85.9°C, respectively; thus, the temperature of LMW was 28.1°C less than that of LCW. This result contributes to miniaturization of the cooling fan of the converter and downsizing of the switching power supply.

This lower increase results from the greater ability of LMW to reduce AC resistance compared to LCW.

4.3 Power Density of the LLC Resonant Converter

The volume of the LLC resonant converter is 338.7 cm^3, and the power density is 2.95 W/cm^3 for an output power of 1 kW.

5. Conclusions

The main contributions of this study are as follows.

1) Impedance characteristics of the transformer.

At the frequency of 1 MHz, the resistance of the primary coil was 1.16 Ω, using LCW, and 0.89 Ω, using LMW. Therefore, the resistance of the LMW was 23.2% lower by than that of LCW, and this is attributed to the restraint of the proximity effect.

2) Efficiency and power loss characteristics of the LLC resonant converter.

At the output current of 4 A and output power of 1 kW, the efficiencies of LCW and LMW were 96.5% and 96.8%, respectively; thus, the efficiency of LMW was higher by 0.3%. Moreover, the power losses of LCW and LMW were 36.2 W and 33 W, respectively; therefore, the power loss of LMW was 8.8% lower. This is attributed to the reduction of the resistance due to the proximity effect when LMW is used.

Based on the present results, it is possible to reduce the resistance by using LMW in MHz drive converter. However, the size of the transformer is still bigger than that of the other circuit elements. We are currently examining further loss reduction and downsizing of the transformer.

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Tatsuya Yamamoto (Student Member) received his B.S. and M.S. degrees in electrical and electronic engineering from Shinshu University in 2014 and 2016. He is currently pursuing his Ph.D. degree in electrical and electronic engineering at Shinshu University. He has focused on DC-DC converters.

Yinggang Bu (Member) received his M.S. and Ph.D. degrees in Electrical and Electronic Engineering from the Shinshu University, Japan, in 2006 and 2009, respectively. He is currently an assistant professor in the Department of Engineering in Shinshu University, Japan. His research interests include linear motor, electromagnetic actuators, and power electronics field. He is a member of the IEEE and IEEJ.

Tsutomu Mizuno (Senior Member) received his B.S., M.S. and Ph.D. degrees from Shinshu University, Nagano, Japan, in 1981, 1983 and 1994, respectively. He joined Amada Co., Isehara, Japan, in 1983. Since 2010, he has been a part of Shinshu University as a Professor and has engaged in the research and development of magnetic actuators, magnetic sensors and linear motors. He is a member of IEEE, the Magnetic Society of IEEJ.

Yutaka Yamaguchi (Non-member) received his B.S. degree in electrical engineering from Oita University in 1983. He joined Tabuchi Electric Co., Ltd., Tokyo, Japan, in 2011. His research interests include power electronics, power storage system, wireless power transfer.

Tomoyoshi Kano (Non-member) received his B.S. degree in electronic engineering from Tokyo Denki University in 2000. He joined Tabuchi Electric Co., Ltd., Tokyo, Japan, in 2000. His research interests include power electronics, high efficiency power supply system, RF power supply system.