Investigation for High Output of 2.5MHz Power Supply Constructed from Multi-Core Transformers and a Multi-Phase Inverter and Application for Wireless Power Transfer

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Abstract— **This paper discusses a development for high output of 2.5 MHz inverter without fast-switching semiconductor switches. This inverter consists of a multi-phase inverter using conventional silicon semiconductor switches and multiple core transformers. In this paper, a principle of drop in inverter output voltage which reduces the inverter output voltage due to a relationship between dead-time and a leakage inductance of a transformer is clarified. In addition, two methods which are bifilar wound transformers and a LC series resonance are applied to the proposed circuit in order to achieve higher output power. The validity of two methods for higher output power is confirmed by experiments. Finally, the proposed circuit is applied to a wireless power transfer when a lamb bulb is used as a load.**

I. INTRODUCTION

Recently, wireless power transmission systems are increasingly received attentions for the application of EV chargers [1-7]. In wireless power transmission, there are two kinds of method, which are an electromagnetic induction method and a magnetic resonance method. In the electromagnetic induction method, low frequency such as several tens kHz is used for power transmission. As a result, the power transmission distance which can achieve high-efficiency is only several centimeters. Also, the efficiency is drastically decreased when the position of a receiving coil is changed. Therefore, the correspondence of the receiving coil becomes a problem when the electromagnetic induction method is applied for a battery charger of EV. On the other hand, in the magnetic resonance method which has high quality factor for resonance, it is possible to achieve the high-efficiency power transmission even though the coupling coefficient is low. Therefore, the magnetic resonance method

is proper the battery charger of EV which requires the larger power and middle-large power transmission distance. In addition, Industry-Science-Medial (ISM) frequency band such as around 13.56 MHz is one of candidate for this application in respecting to the standard of the magnetic coupling from the view point of a radio law and the downsizing of coils. Therefore, power supplies which output MHz band are required.

Conventional high-frequency power supply systems use vacuum tube and high frequency FET, which is categorized in class C linear amplifier. A drawback of this method is low efficiency. Furthermore, the size of the systems is large because a cooling system which includes a heat sink and a fan becomes large.

By the recent technology in semiconductor devices, wide gap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) are used widely due to fast-switching and low conduction loss under a high-temperature operation [8-9]. However, power consumption of a gate drive circuit becomes large in order to drive wide gap semiconductor [10]. In addition, it is difficult to control a gate signal of each switch due to low gate threshold voltage of SiC and GaN. Due to the switching noise, the self turn-on phenomenon sometimes occurs. Therefore, power converters using wide gap semiconductors have some problems in order to output high frequency and large power. Moreover, wide gap semiconductors are still expensive compared to the conventional semiconductors.

The authors have been proposed frequency multiplying circuit, which utilizes the neutral point voltage fluctuation of the multi-phase voltage-type inverter and can use conventional low-switching semiconductor switches. The proposed

converter can output high frequency voltage depending on the number of the phase in the inverter. There is no problems have mentioned previous paragraph in the proposed circuit. So far, the fundamental operation of the proposed circuit have confirmed by simulations and experiments [11].

In this paper, two methods are investigated in order to achieve higher output power of the proposed converter. First, the principle of the proposed frequency multiplying method is described. Next, problems which result in the decreasing of the inverter output voltage and output power in the proposed circuit is introduced. Thirdly, the design of the leakage inductance of the multi-core transformer and the series-resonance are applied to the proposed circuit in order to overcome the problems of the proposed circuit. Finally, fundamental experiments and experiments for wireless power transfer using spiral antennas are shown.

II. PROPOSED CIRCUIT

A. Principle of the multiplying method

Fig. 1 shows the proposed circuit in a five-phase inverter model. The primary side of the transformer is connected in parallel, and the secondary side is connected in series. As a result, the multi-phase inverter can output high frequency over the switching frequency.

Fig. 2 shows the principle of the proposed frequency multiplying method. In the proposed method, the variation of neutral point voltage in a voltage-type inverter is focused. In the five phase voltage-type inverter, each of the voltage phases is shifted by 72 degree and operated with square wave modulation. As a result, the output frequency f_{out} is obtained by Eq. (1) using the switching frequency f_{sw}. The output voltage with N times frequency as larger as the switching frequency of the inverter is achieved.

$$f_{out} = N \cdot f_{sw} \qquad (1)$$

Here, it is noted that any parasitic resistances and leakage inductances are not considered. On the other hand, the amplitude of output voltage is determined by turn ratio of the multi-core transformer.

B. Multicore Transformer

Fig. 3 shows the diagram of multi-core transformers [12, 13]. In Fig. 3(a), secondary winding is wired through each core in order to reduce a wire length and copper losses. However, a leakage inductance becomes large due to low degree of coupling in this method. In this paper, a bifilar wound transformer is applied to the proposed circuit in order to reduce a leakage inductance. In a bifilar wound transformer, a primary winding and a secondary winding ware twisted.

Fig. 4 shows the photograph of the multicore transformers. Toroidal cores are used for the multicore transformers. In a general bifilar wound, the turn ratio of the winding is 1:1. In this paper, in order to achieve the output voltage which has same amplitude to the input voltage, the number of the secondary winding turn is two. As a result, the turn ratio of the winding becomes 1:2.
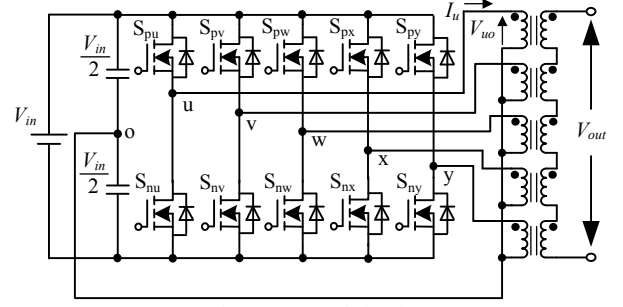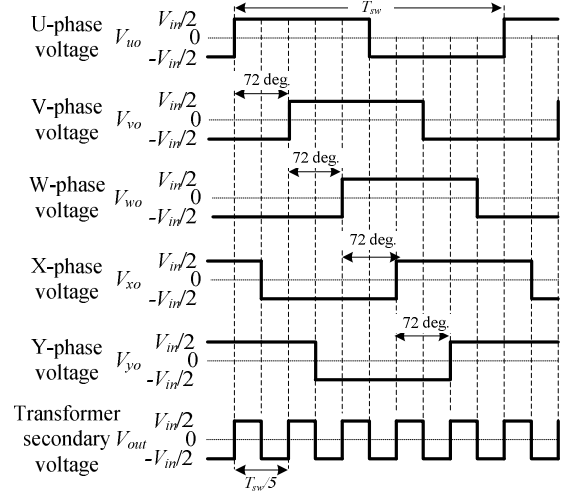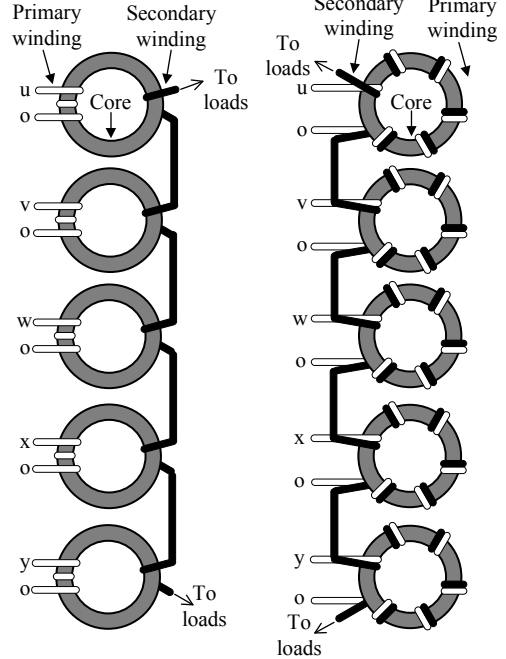

Fig. 1. Proposed circuit.

Fig. 2. Principle of the proposed circuit (Turn ratio=1:1).

(a) Secondary wiring through cores. (b) Bifilar wound transformer.
Fig. 3. Multi-core transformer per a core.

III. DROP IN INVERTER OUTPUT VOLTAGE

Fig. 5 shows the experimental circuit and the single-phase equivalent circuit. L is inductance components transformed to the primary side of the transformer, which includes a leakage

inductance. R is resistance components transformed to the primary side of the transformer, which includes a wire resistance. C_p is parasitic capacitances of MOSFETs.

Fig. 6 shows the operation patterns of the equivalent circuit shown in Fig. 5. In Fig. 6, the switch S_p is changed from off-state to on-state. Fig. 6 (b) and (c) show the period of dead-time during both of switches of S_p and S_n are off. When the drop in the inverter output voltage occurs, the operation pattern is changed according to Fig. 6 (a), (b), (c) and (d). On the other hand, when the drop in the inverter output voltage does not occur, the operation pattern is changed according to Fig. 6 (a), (b) and (d).

First, after the operation pattern is changed from Fig. 6(a) to (b), the current of L flows to the input voltage side through the free wheel diode of the upper switch S_p. During dead-time, when the current of L keeps to flow, the drop in the inverter output voltage does not occur and keep $V_{in}/2$. As a result, after the period of dead-time, the operation pattern is changed to (c). On the other hand, during dead-time, when the current of L becomes zero, the operation pattern is changed to Fig. 6(c). As a result, the resonance occurs between the L and parasitic capacitances of MOSFETs C_p. Therefore, the drop in the inverter output voltage occurs and cannot keep $V_{in}/2$.

The condition that the drop in the inverter output voltage does not occur is obtained by (2) using the single-phase equivalent circuit shown in Fig. 5(b).

$$T_d < \tau \ln \left(\frac{2}{1 + e^{-\frac{T_{sw}}{2N\tau}}} \right) \qquad (2)$$

where $\tau = L/R$ is time constant, $T_{sw} = 1/f_{sw}$ is switching period and N is the number of the phase.

When the leakage inductance is small, time constant becomes small. As a result, the drop in the inverter output voltage occurs. On the other hand, when the leakage inductance is large, the drop in the inverter output voltage does not occur. However, if the leakage inductance is too large, the operation of the proposed circuit becomes a constant current source. As a result, the output voltage cannot be controlled constant according to the load. Therefore, it is important to design a suitable leakage inductance which does not cause the drop in the inverter output voltage and can control the output voltage according to the load in order to output desired output voltage. Moreover, the high output of the proposed circuit with LC resonance using the leakage inductance actively, is also investigated.

IV. PRINCIPLE OF HIGH OUTPUT USING LC RESONANCE

Fig. 7 shows the experimental circuit and the equivalent circuit when a resonance capacitor is connected to the secondary side of the transformer shown in Fig. 7(b). Fig. 7(b) is a LC resonant circuit. Therefore, from Fig. 7(b), the resonance capacitance which can realize LC resonance is obtained by (3).
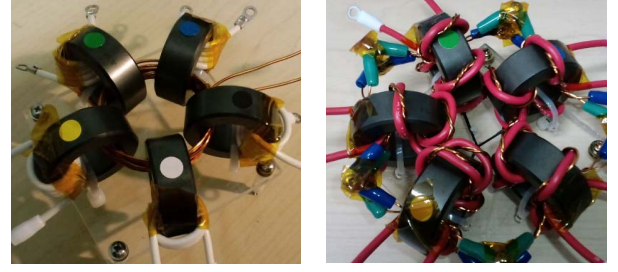
(a) Secondary wiring through cores. (b) Bifilar wound transformer.
Fig. 4. Multi-core transformer.
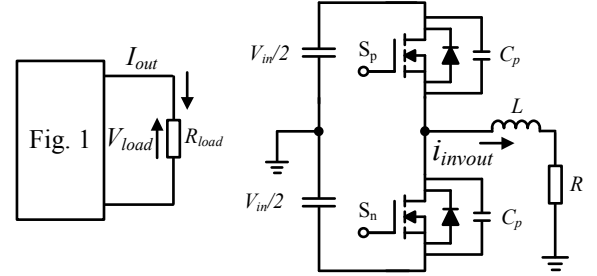
(a) Experimental circuit. (b) Single-phase equivalent circuit.
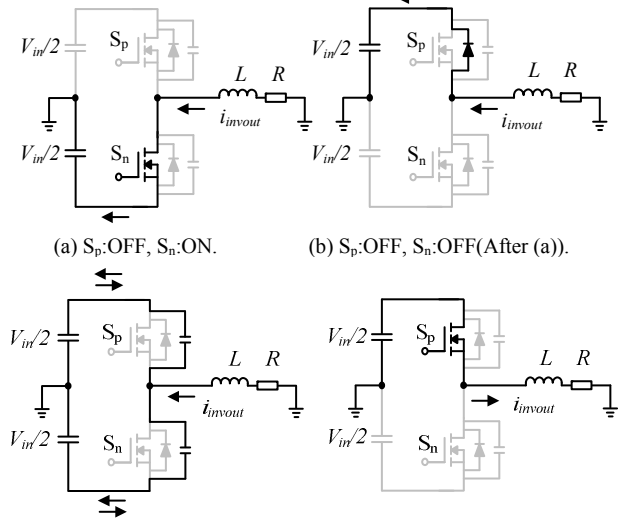Fig. 5. Equivalent circuit.

(a) S_p:OFF, S_n:ON. (b) S_p:OFF, S_n:OFF(After (a)).

(c) S_p:OFF, S_n:OFF(After (b)). (d) S_p:ON, S_n:OFF.
Fig. 6. Operation patterns.

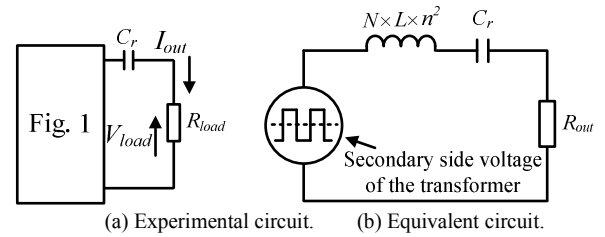(a) Experimental circuit. (b) Equivalent circuit.
Fig. 7. Equivalent circuit when a resonance capacitor is connected to the secondary side of the transformer.

$$C_r = \frac{1}{(2\pi f_r)^2 (Nn^2 L)} \qquad (3)$$

Table 1. Experimental conditions for the prototype circuit.

Parameter	Symbol	Rating	Unit
Output voltage	V_{out}	100	V
Primary number of turn	N_1	5	turns
Secondary number of turn	N_2	10	turns
Switching frequency	f_{sw}	500	kHz
Output frequency	f_{out}	2.5	MHz
Duty cycle	D	0.5	
Flux density	B_m	0.3	T
Cross-sectional area of cores	S	112×10^{-6}	m²

where f_r is a resonance frequency. By the LC resonance, the load voltage can be a sinusoidal waveform and increased even though there is a leakage inductance.

The quality factor for resonance Q is obtained by Eq. (4). From Eq. (4), it is confirmed that Q is decided by the resonance frequency and the time constant shown in Eq. (2). The load voltage becomes the sinusoidal waveform when Q is large.

$$Q = \frac{2\pi f_r L}{R} = 2\pi f_r \tau \qquad (4)$$

V. EXPERIMENTAL RESULTS

Fig. 8 shows experimental waveforms; (a): T_d=85 ns, L=1.8 µH, (b): T_d=160 ns, L=1.8 µH, (c): T_d=85 ns, L=2.6 µH and (d): T_d=85 ns, L=3.1 µH. Table I shows the experimental conditions. Note that the bifilar wound transformer is used. First, comparing (a) and (b), it is confirmed that the period of the drop in the inverter output voltage increases due to the increasing of the dead-time period based on the principle described in pervious chapter. On the other hand, comparing (a), (c) and (d), it is confirmed that the drop in the inverter output voltage does not occur because the inductor current keeps to flow through the body diode of the MOSFET due to the increasing of the leakage inductance. Therefore, it is confirmed that the drop in the inverter output voltage is reduced by designing the leakage inductance properly.

Fig. 9(a) shows experimental waveforms when LC resonance is applied and a resistance of 50 Ω. A resonance capacitance connected to the load in series. From Fig. 9(a), it is confirmed that the load voltage is almost sinusoidal waveform due to LC resonance. Fig. 9(b) shows the variation of the load voltage subjected to the value of the resonance capacitance. The resonance point where maximum voltage occurs in the load exists under the capacitance C_r of 100 pF. However, over the capacitance C_r of 100 pF is used because the withstand voltage of used capacitor is low. From Fig. 9(b), it is confirmed that the load voltage decreases according to the increasing of the resonance capacitance based on the principle of LC capacitance.

Fig. 10 shows the comparison of the load voltage related the input voltage when the secondary winding is wired through each core, the bifilar wound transformer and LC resonance are used. From Fig. 11, when the secondary winding is wired through each core, the load voltage is very low compared with the input voltage even though the turn ration of the transformer is designed in order to achieve the

(a) T_d:85 ns, L:1.8 µH.

(b) T_d:160 ns, L:1.8 µH.

(c) T_d:85 ns, L:2.6 µH.
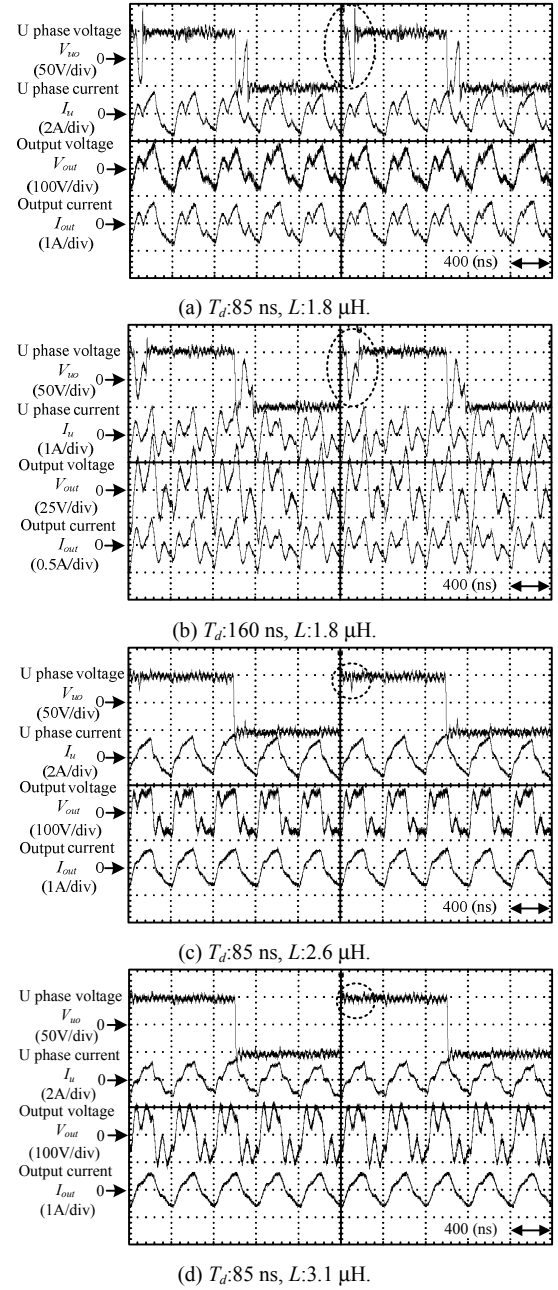
(d) T_d:85 ns, L:3.1 µH.

Fig. 8. Experimental results when inductance component is changed.

same amplitude to the input voltage. This is because the leakage inductance is large. As a result, the proposed circuit is operated as a constant current source. On the other hand, in other two cases, the load voltage is larger because the leakage inductance component is reduced.

Fig. 11 shows the comparison of the output current and the load voltage in three cases. From Fig. 11, the output current is almost same when the secondary winding is wired through each core because of the large leakage inductance even though the load resistance is changed. On the other hand, in other two cases, according to the changing the load resistance, the output current and load voltage is changed. According to the increasing of the load resistance, the output current is decreased. As a result, the voltage drop in the leakage
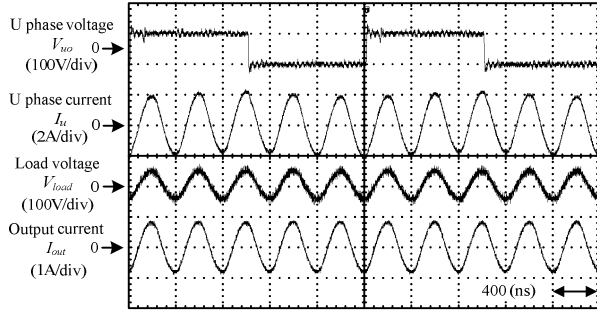
(a) R_{load}: 50 Ω.
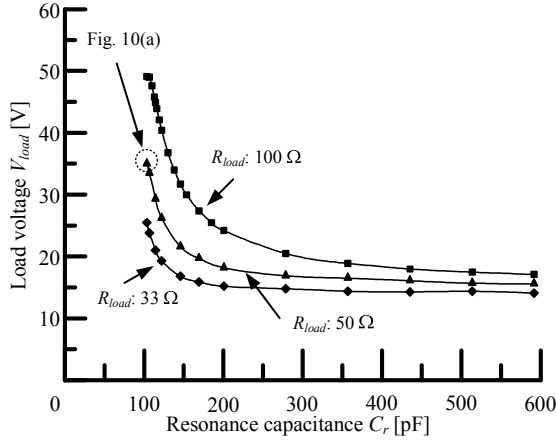
(b) Load voltage related resonance capacitance.
Fig. 9. Experimental results with resonance capacitance.

inductance is decreased and the load voltage is increased.

Fig. 12 shows the load power when the secondary winding is wired through each core, the bifilar wound transformer and LC resonance using the resonance capacitor are used. The condition of the input voltage is 100 V. From Fig. 12, when the secondary winding is wired through each core, it is confirmed that the proposed circuit works as a constant current source because the leakage inductance is very large. On the other hand, in case of the bifilar wound transformer and LC resonance, the load voltage and current becomes higher compared with the condition when the secondary winding is wired through each core. As a result, the validity of two methods for higher output power is confirmed by experiments.

Fig. 13 shows the efficiency characteristics in three conditions. The efficiency of the prototype circuit is calculated from the input and output power measured from the waveforms. Noted that the output power is changed by changing the input voltage 50, 80 and 100V in this experiment. From Fig. 14, using the bifilar wound transformer and the series resonance, the output power and the efficiency are increased. The two methods overcome the problems of the standard multi-core transformers. Especially, in the series resonance method, the maximum efficiency of 84.7 % is obtained by the experiment.

Fig. 14 shows the experimental setup during wireless power transfer using spiral antennas. In order to confirm the wireless power transfer easily, bulb of 60 W is used as a load. In addition, a variable capacitor is added to the spiral antenna
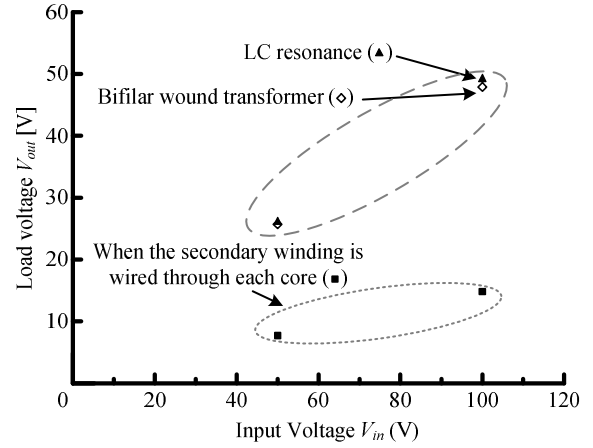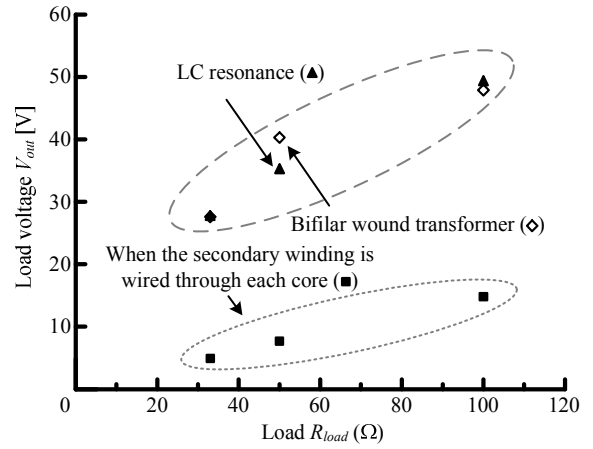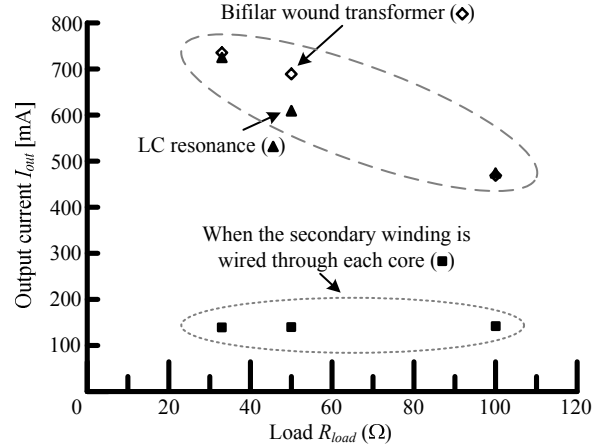

Fig. 10. Comparison of the load voltage related the input voltage.

(a) Load voltage.

(b) Output current.
Fig. 11. Comparison of the output voltage and current related resistance of load.

in series in order to adjust the resonance frequency as 2.5 MHz because the resonance frequency of the spiral antenna is 2 MHz. Note that, the LC resonance is not used and the bifilar wound transformer is used in this experiment. Experimental parameters are shown below; input voltage is 100 V, the capacitance of the variable capacitor is 605 pF.

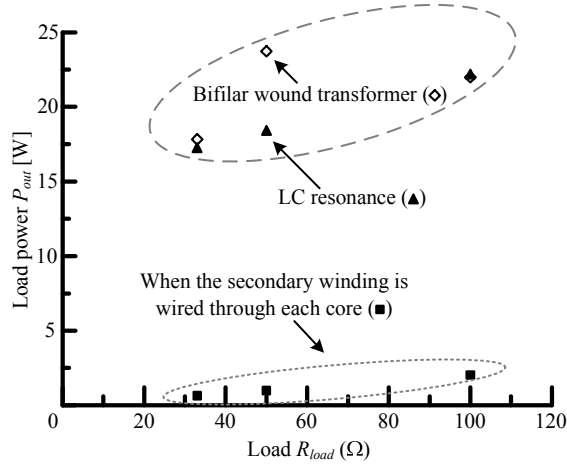Fig. 15 shows experimental waveforms of the output

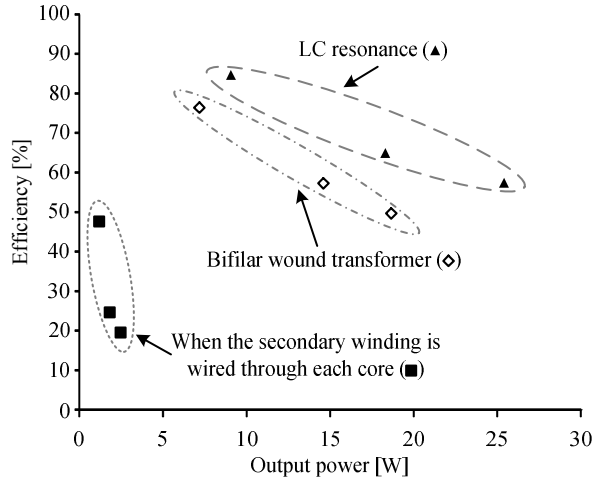Fig. 12. Comparison of output power related resistance of load.

Fig. 13. Efficiency characteristics.

(a) Diagram

(b) Photograph

Fig. 14. Experimental setup of wireless power transfer.
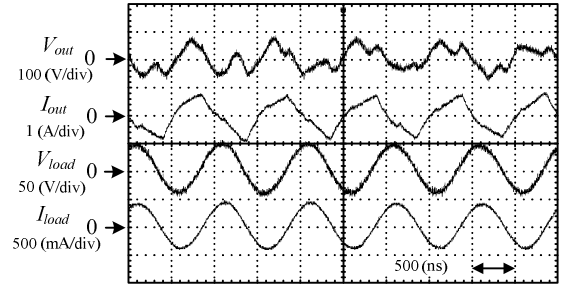
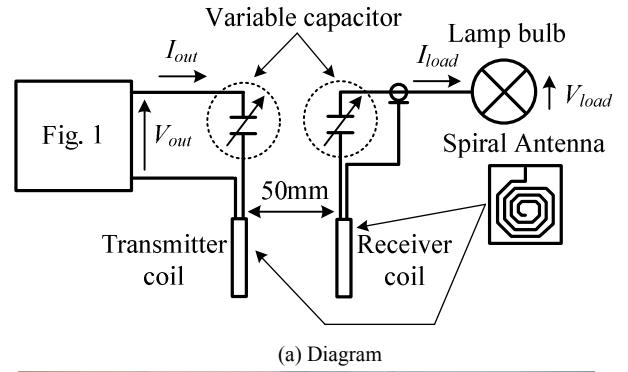Fig. 15. Experimental waveforms of WPT using lamp bulb.

voltage and current of the proposed circuit and the secondary voltage and current of the receiver coil. From Fig. 15, the secondary voltage and current of the receiver coil is almost sinusoidal waveform because the quality factor for resonance Q is high. Therefore, it is confirmed that the proposed circuit can be operated for wireless power transmission.
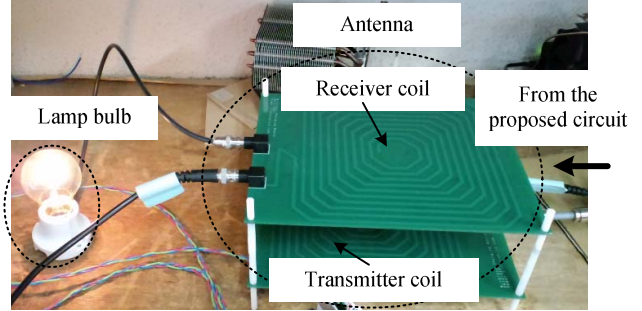
VI. CONCLUSION

This paper discussed the development for high output of 2.5MHz inverter without fast-switching semiconductor switches. In this paper, the principle of drop in inverter output voltage which reduces the inverter output voltage due to a relationship between dead-time and a leakage inductance of the multi-core transformer was clarified. In addition, the experimental results confirmed that two methods which are bifilar wound transformers and the LC series resonance can achieve higher output power of the proposed circuit. Finally, the proposed circuit is applied to a wireless power transfer when a lamb bulb is used as a load.

REFERENCES

[1] Y. Hori, "Future Vehicle Society based on Electric Motor, Capacitor and Wireless Power Supply," Power Electronics Conference (IPEC), pp. 2930-2934 (2010)

[2] K. Kusaka, J. Itoh: "Experimental Verification of Rectifiers with SiC/GaN for Wireless Power Transfer Using a Magnetic Resonance Coupling", IEEE 9th PEDS, pp. 1094-1099 (2011)

[3] U. K. Madawala, D. J.Thrimawithana: "A Bidirectional Inductive Power Interface for Electric Vehicles in V2G Systems", Industrial Electronics, IEEE Transactions on , Vol.58, No.10, pp. 4789-4796, 2011

[4] C-S. Wang, O. H. Stielau and G. A. Covic: "Design Considerations for a Contactless Electric Vehicle Battery Charger", Industrial Electronics, IEEE Transactions on , Vol.52, No.5, pp. 1308-1314, 2005

[5] T. C. Beh, M. Kato, T. Imura, S. Oh and Y. Hori: "Automated Impedance Matching System for Robust Wireless Power Transfer via Magnetic resonance Coupling", Industrial Electronics, IEEE Transactions on , Vol.60, No.9, pp. 3689-3698, 2013

[6] Z. N. Low, R. A. Chinga, R. Tseng and J. Lin: "Design and Test of a High-Power High-Efficiency Loosely Coupled Planar Wireless Power Transfer System", Industrial Electronics, IEEE Transactions on , Vol.56, No.5, pp. 1801-1812, 2009

[7] J. Hirai, T-W. Kim and A. Kawamura: "Study on Intelligent Battery Charging Using Inductive Transmission of Power and Information", Power Electronics, IEEE Transactions on , Vol.15, No.2, pp. 335-345, 2000

[8] J. Wang, X. Zhou, J. Li, T. Zhao, A. Q. Huang, R. Callanan, F. Husna and A. Agarwal: "10-kV SiC MOSFET-Based Boost Converter", Industry Applications , IEEE Transactions on, Vol.45, No.6, pp.2056-2063, 2009

[9] B. Ozpineci, M. S. Chinthavali, L. M. Tolbert, A. S. Kashyap and H. A. Mantooth: "A 55-kW Three-Phase Inverter With Si IGBTs and SiC Schottky Diodes", Industry Applications , IEEE Transactions on, Vol.45, No.1, pp.278-285, 2009

[10] G-T. Zheng, P-T. Liu, M-C. Wu, L-W. Chu and M-C. Yang: "Design of Bidirectional and Low Power Consumption Gate Driver in Amorphous Silicon Technology for TFT-LCD Application", Journal of Display Technology, Vol.9, No.2, pp.91-99, 2013

[11] J. Itoh, Y. Fujita, H. Nishiyama: "Frequency Multiplying Circuit Constructed from a Multi-phase Inverter and Multi-core Transformers", ECCE Asia, Vol. , No. , pp. 807-813 (2012)

[12] E. Herbert, "High frequency matrix transformer," U.S. Patent 4 845 606, Jul. 4, 1989

[13] G. Ortiz, J. Biela, D. Bortis and J. W. Kolar: "1 Megawatt, 20 kHz, Isolated, Bidirectional 12kV to 1.2kV DC-DC Converter for Renewable Energy Applications", The 2010 International Power Electronics Conference, pp. 3212-3219 (2010)