Frequency Multiplying Circuit Constructed from a Multi-phase Inverter and Multi-core Transformers

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Abstract— **This paper discusses a frequency multiplying circuit, which consists of a multi-phase voltage-source inverter and multiple toroidal core. The principle of the frequency multiplying is to utilize the neutral point voltage fluctuation of the load. A multi-core transformer is used to obtain the voltage fluctuation. This paper discusses the design of the circuit, transformer and loss analysis of the proposed circuit. Besides, this paper clarifies the validity of the proposed converter in terms of simulation and experimental results.**

Keywords-high-frequency power supply, neutral voltage fluctuation, toroidal core, multiple core transformer, leakage inductance

I. INTRODUCTION

Recently, wireless power transmission systems are increasingly received attentions for the application of EV chargers [1]. There are two types of wireless power transmission systems; the first is magnetic coupling with a magnetic core, and the second is magnetic resonance coupling method with high frequency antenna [2-5]. The wireless power transmission using magnetic resonance coupling is more suitable for the EV charger in terms of the accepting wide gap and large position error between primary coil and secondary coil. However, the magnetic resonance coupling system requires high frequency power supply in order to reduce size and achieve light weight. Industry-Science-Medical (ISM) frequency band is one of candidate for this application in respecting to the standard of the magnetic coupling. Therefore, 13.56 MHz and several kW power supply are required for the EV charger.

It is very difficult to realize a high frequency and high power supply in several kW and 13.56MHz [6]. Conventional high-frequency power supply systems use vacuum tube and high frequency FET, which is categorized in class C linear amplifier. The disadvantage of this method is low efficiency. Furthermore, the size of the systems is large because heat sink is large.

Follow the recent technology in semiconductors device, large capacity and low loss are enabled in IGBT and MOSFET for power conversion, especially in the implementation of high frequency inverter such as induction heating [7-8]. However there is a limit in high frequency operation. Because switching speed of each semiconductor device has a limit, especially for the large capacity application [9].

The authors propose frequency multiplying circuit, which utilizes the neutral point voltage fluctuation of the multi-phase inverter. A neutral point voltage of the load in the multi-phase inverter has fluctuation to the neutral point of the DC input voltage. The proposed converter connects a multi-core transformer among the neutral point of the DC input and output terminals. The proposed method uses a five-phase inverter to confirm the principle. Then, the output frequency of five times of the switching frequency is obtained. In this method, the high speed switching device is not needed because the switching frequency for each phase is low.

This paper is organized as follows; firstly, the approach for multiplying operation is introduced. The circuit configuration is described accordingly. Secondly, the operation principle and energy losses are analyzed in simulation. In addition, the design strategy of the prototype is clarified. Finally, some experimental results are given in order to demonstrate the advantages of the proposed circuit.

II. OPERATION PRINCIPLE

In the proposed method, the variation of neutral point voltage in a voltage-type inverter is focused. When an inverter with N phase is driven with square wave operation, the neutral point voltage of the load is potentially fluctuated based on neutral point of DC link voltage, which can be obtained from (1).

$$v_{no} = \frac{1}{N}\sum v_{ko} \tag{1}$$

Where v_{ko} is the output voltage based on neutral point of each phase DC link voltage. Then, the neutral point voltage becomes N times frequency as larger as the switching frequency of inverter. The proposed multiplying circuit uses the spoken principle. In order to pull out the output voltage with N times frequency, a multi-phase transformer is used. As shown in (1), the output voltage becomes 1 / N. Therefore, the proposed circuit uses series connection in secondary side of the multi-phase transformer in order to boost the voltage. It is note that the number of phase N must be an odd number to keep the voltage fluctuation. If N is an even number, then the voltage fluctuation of the load is disclaimed.

Figure 1 shows the proposed circuit in a five-phase inverter model. In the five phase voltage-type inverter, each of the voltage phases is shifted by 72 degree and operated with square wave modulation. The primary side of the transformer is connected in parallel, and the secondary side is connected in series to increase the output voltage.

Figure 2 shows the principle of the proposed frequency multiplying method. The neutral point of load becomes square wave of 36 degree. The output frequency on the secondary side becomes five times of the input frequency of the square waveform.

The proposed method uses a lot of switching devices compared to a conventional circuit using a H-bridge topology. In H-bridge, the fast switching device, which operates at 13 MHz is needed, and therefore, large switching loss occurs. In that case, it is difficult to refrigerate the junction temperature because the thermal resistance is large. In contrast, the proposed circuit can distribute the power loss of each device. The loss of one switching device is smaller than that in the conventional circuit. Therefore, it is easier to reduce the switching device. Besides, the switching frequency is 1/N times lower than the conventional circuits, as a result, low cost power devices can be applied.

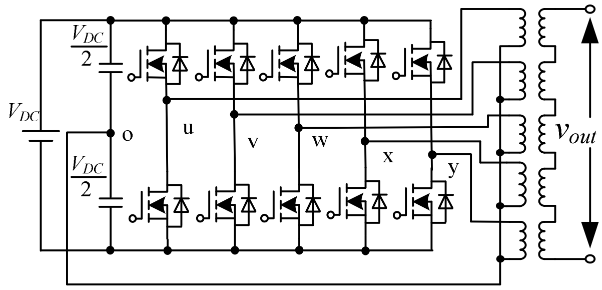


Figure 1. Proposed multiplying freqeuncy circuit using five-phase inverter

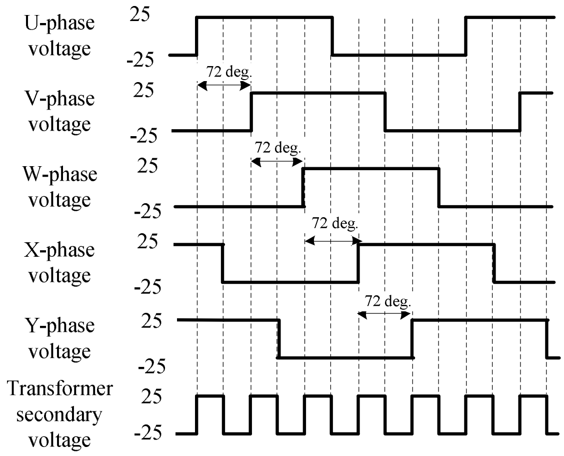


Figure 2. Principle of the proposed circuit

III. CIRCUIT DESIGN

In the proposed circuit, reduction of leakage inductance is important because of using high frequency. Leakage inductance of the transformer causes an increase in rise time of the waveform and a decrease on the amplitude of the output voltage.

Therefore, the toroidal multi-core transformer is chosen in the proposed circuit. Toroidal core has characteristics that the majority of the magnetic flux passes through the core with low leakage of magnetic flux. Therefore, it shows an advantage of good reproducibility because it has lesser interference with adjacent device. In addition, the inductance is obtained in a fewer number of turns. Therefore, it is possible to reduce the leakage inductance of the transformer wiring by devising the structure of the secondary side. In addition, in this paper, ferrite core is used as the toroidal core, because ferrite core is a low loss element in term of high frequency.

The proposed circuit is designed as follows, the output voltage *Vout*=50V, and output frequency *fout*=1.5MHz. When number of transformer is n, frequency of secondly side is related to (2).

$$f_{out} = n \cdot f_1 \tag{2}$$

Therefore in the case of five phase (n=5), output to input ratio of transformer is 1:2. In addition, operation frequency is f_1=300 kHz.

The design of the transformer winding is obtained by (3). The ratio of voltage determines the winding of secondly side N_2. (3)

$$N_1 = \frac{V_{in} D}{\Delta B \cdot S \cdot f_1} \tag{3}$$

B is the magnetic flux density, and S is the effective cross section of core of transformer, and D is the duty ratio per phase.

Table 1 shows the specification of transformer. The primary winding N_1=2 is calculated from this table. Therefore secondly winding N_2=4 is calculated by (4).

$$N_2 = \frac{V_{in}/2}{V_{out}} N_1 \tag{4}$$

Figure 3 shows the diagram of a multi-core transformer for the proposed circuit. In order to reduce the wiring inductance of the circuit, the transformer cores of each phase are placed in the pentagon. Then, the primary-side winding of the transformer is wound concentrated on the each of core. The neutral point is connected to the midpoint of DC capacitor. The secondary-side winding of the transformer is wound with penetrating to the entire core. In addition, the element is located very close to the core, the power lines are placed inside and outside by using a double-sided board. The upper side switch of each arm is implemented in the front side of the Figure 3 (a). The lower side switch of each arm is implemented in the back side of the Figure 3 (a). It aims to reduce the leakage inductance of the transformer and to reduce the wiring inductance of the high frequency part. In addition, the skin effect is bigger on high frequencies above 1MHz. Therefore, it also aims to reduce the losses that occur in the circuit. Using this method, the parameters of multi-core transformer is as shown in table 2.

A. Loss analysis

Loss is analyzed to clarify the loss distribution of the proposed circuit. The proposed method is composed of the multi-core transformer and the voltage inverter. Therefore, the major loss is separated into two parts, the inverter and transformer. The following formula is used to calculate the losses.

The loss of inverter P_{Loss} is obtained by (5). The inverter loss is the sum total of P_{con} conduction loss, P_{Sw} switching loss and P_{Rec} loss of recovery. In addition, the conduction loss P_{con} can be separated into P_{FET} and P_{FWD}, where P_{FET} is the on resistance that occurs regularly, P_{FWD} is the loss of freewheeling diode FET (FWD). This relationship is shown in equation (6).

$$P_{Loss} = P_{Con} + P_{Sw} + P_{Rec} \quad (5)$$

$$P_{Con} = P_{FET} + P_{FWD} \quad (6)$$

B. Steady loss

P_{Con} conduction loss of five phase inverter is obtained by integrating the (7). P_{FET} conduction losses of the FET and PFWD conduction losses of the FWD are obtained from (8),(9).Where I_D is drain current, I_F is current of FWD, R_{ON} is the on resistance.

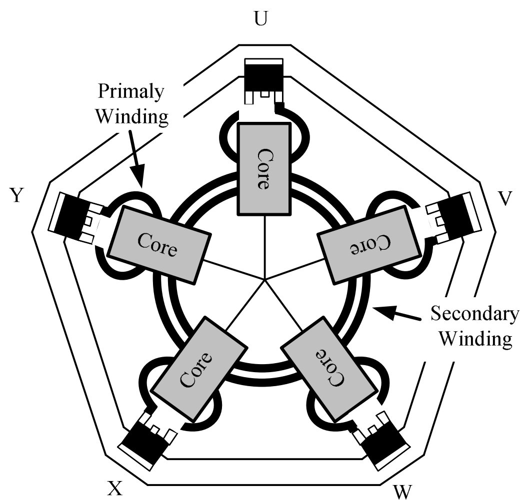
$$P_{Con} = \frac{1}{2\pi}\int_0^{\frac{3}{5}\pi} I_D^2 R_{ON}\, dt + \frac{1}{2\pi}\int_0^{\frac{2}{5}\pi} I_F^2 R_{ON}\, dt \quad (7)$$

$$P_{FET} = \frac{1}{3} I_D^2 R_{ON} \quad (8)$$

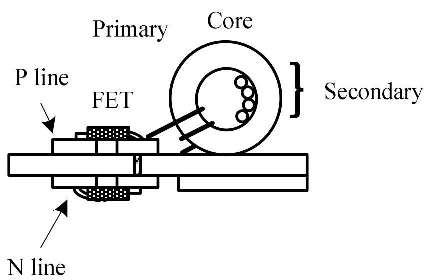
$$P_{FWD} = \frac{1}{6} I_F^2 R_{ON} \quad (9)$$

TABLE I. SPECIFICATIONS OF TRANSFORME

Parameter	Symbol	Rating	Unit
Primary Voltage	V_1	25	V
Secondary Voltage	V_2	50	V
Primary Number of Turn	N_1	2	turns
Secodary Number of Turn	N_2	4	turns
Primary Frequency	f_1	300	kHz
Primary Frequency	f_2	1.5	MHz
Duty cycle	D	0.5	
Flux density	B_m	0.3	T
Cross-sectional area	S	112×10^{-6}	m^2



(a) Top view of the circuit



(b) Side view of the circuit

Figure 3. Implementation of the proposed circuit

TABLE II. SPECIFICATIONS OF TRANSFORME

Parameter	Symbol	Value	Unit
Leakage inductance	l_l	1.54	μH
Exciting inductance	L_m	13.47	μH

C. Switching loss

Equation (10) shows the switching loss P_{Sw}, where P_{On} is the turn on loss, and P_{Off} is the turn off loss, which are obtained in (11) and (12). E_{On} is the on voltage, E_{Off} is the off voltage, and fc is the switching frequency. In addition, the recovery loss P_{Rec} is obtained in (13). Where I_{rr} is the recovery current, V_{cc} is the DC link voltage, and t_{rr} is the recovery time.

$$P_{Sw} = P_{On} + P_{Off} \tag{10}$$

$$P_{On} = E_{On} f_c \frac{1}{\pi} \tag{11}$$

$$P_{Off} = E_{Off} f_c \frac{1}{\pi} \tag{12}$$

$$P_{\mathrm{Rec}} = \frac{1}{8} I_{rr} V_{cc} t_{rr} f_c \tag{13}$$

Figure 4 shows the results of loss analysis that is calculated using the above equations. The analysis conditions are 200V DC voltage, load resistance is 50Ω, and the output frequency is set to 2.079MHz. Comparison of loss is performed with changing the numbers of phase of the inverter. In this case, load is given with a5% inductance.

From the result as shown in Figure 4, the loss is constant even if the numbers of phase of the inverter has increased. This shows that the loss of each device is reduced by increasing the numbers of phase. However, the loss due to change on the numbers of phase is only changed slightly because there are a lot of switching devices. In addition, the conduction loss is expected to increase slightly with an increase in the numbers of phase because excitation current flows in the actual circuit.

IV. Simulation of the Proposed Circuit

Table 2 shows the simulation parameters. These parameters are identical to the experimental parameters. However, an ideal transformer is used in simulation for simplicity. The basic operation of the proposed circuit can be confirmed in the simulation results shown in Figure 5. The result shows that the transformer secondary voltage has a voltage fluctuation that is five times the frequency of the primary side. Figure 6 shows the voltage and current relationship between the primary and secondary sides of the transformer. The result shows that the primary side current is turned on and off repeatedly with the same period to the secondary side current. In addition, the current flows through each switching devices has fluctuation, which is the same to the secondary side of the transformer.

Table 3 shows another simulation parameters. These parameters include magnetizing inductance and leakage

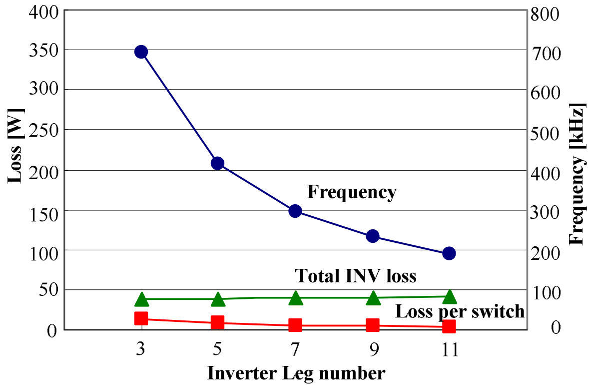


Figure 4. Relation between the number of phase and total loss(semiconductor part)

TABLE III. SIMULATION CONDITIONS.

Parameter	Value	Unit
Input voltage	50	V
Switching frequency	300	kHz
Dead time	100	ns
Load resistance	10	Ω
Load inductance	8.2	μH

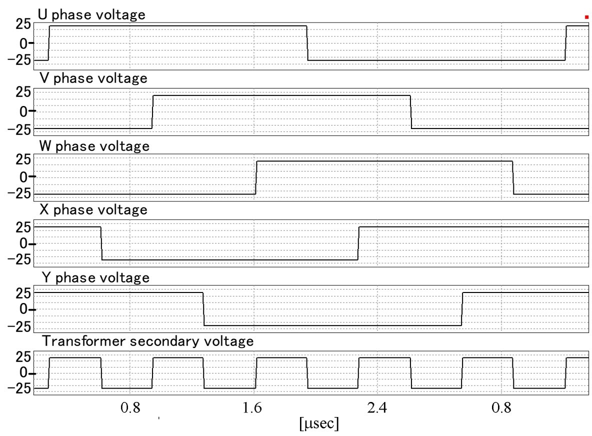


Figure 5. Operation waveforms in Simulation:each phase voltage and output voltage of the transformer.

TABLE IV. SIMULATION CONDITIONS.

Parameter	Value	Unit
Input voltage	50	V
Switching frequency	300	kHz
Load resistance	50	Ω
Magnetization inductance	10~100	μH
Leakage inductance	0.1~50	μH

inductance. The results obtained from this simulation parameter are differed to Figure 6. Figure 7 shows the simulation results, which using ideal transformer and parameter from the magnetizing inductance. In this figure, the current flows through switching device is compared. The current amplitude is larger than that of without magnetizing inductance. In addition, the current amplitude becomes smaller in order to increase the magnetizing inductance.

Figure 8 shows simulation result, which using ideal transformer and parameter from the leakage inductance. As compared to previous result, the current waveform becomes a triangular wave. This is because the leakage inductances are connected in series in the circuit. The current ripple becomes smaller value because impedance becomes larger. Figure 9 shows the current waveform which is given magnetizing inductance and leakage inductance. In addition, it also changes the maximum value of the current flowing through the device by changing the inductance value for each case.

Figure 10 shows a graph that plots the maximum value of the current flowing through the switching devices to change the value of magnetizing inductance while maintaining a constant ratio of the magnetizing inductance and leakage inductance. These show that the breakdown current value of the switching device could be reduced by increasing the magnetizing inductance. Here, increasing the number of turns can increase the magnetizing inductance. However, it is not possible to increase the magnetizing inductance in this circuit. In order to achieve it is necessary to reduce the number of turns of the transformer. In a transformer which has a large number of winding, leakage inductance value is smaller than compared to magnetizing inductance. However, transformer has a small number of winding in this circuit. Therefore, the ratio of leakage inductance versus magnetizing inductance can be predicted to be small. Based on Figure 10, the ratio of leakage inductance versus magnetizing inductance is desirable larger than 1:10. In addition, the ratio must be a practical value. Therefore, as shown in Table 2, actual parameter of the transformer is suitable to apply in this experiment.

V. EXPERIMENTAL RESULT

The prototype is created to confirm the effectiveness of the proposed circuit. Table 2 shows the experimental conditions. MOSFET (manufactured by IR, IRFR3911) is used as the switching device of main circuit. The DC voltage for inverter is 50V, and the switching frequency is 300 kHz. In addition, phase number of the multi core transformer is five which is based on the design described in section 3. The primary winding is 2T and the secondary winding is 4T.

A. Characteristics of no-load test

Figure 11 shows the experimental result in a no-load operation. From the result, the output waveform is a square wave that has peak voltage 50V. This value is consistent with the input voltage. In addition, frequency of the secondary side is 1.5 MHz which is five times of switching frequency.

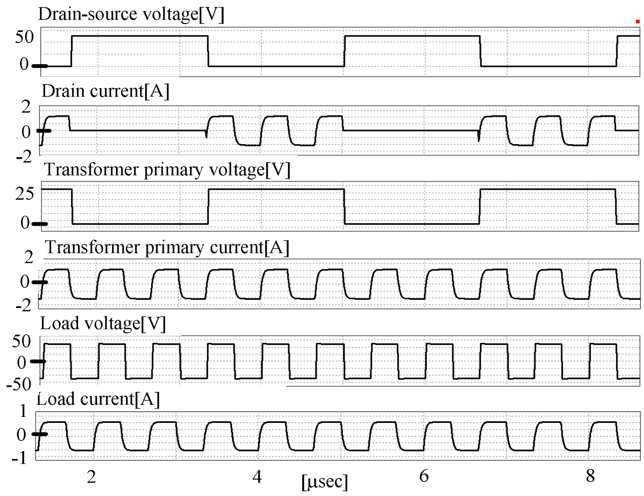


Figure 6. Operation wavefoms in simulation:voltage and current in switching device and transformer.

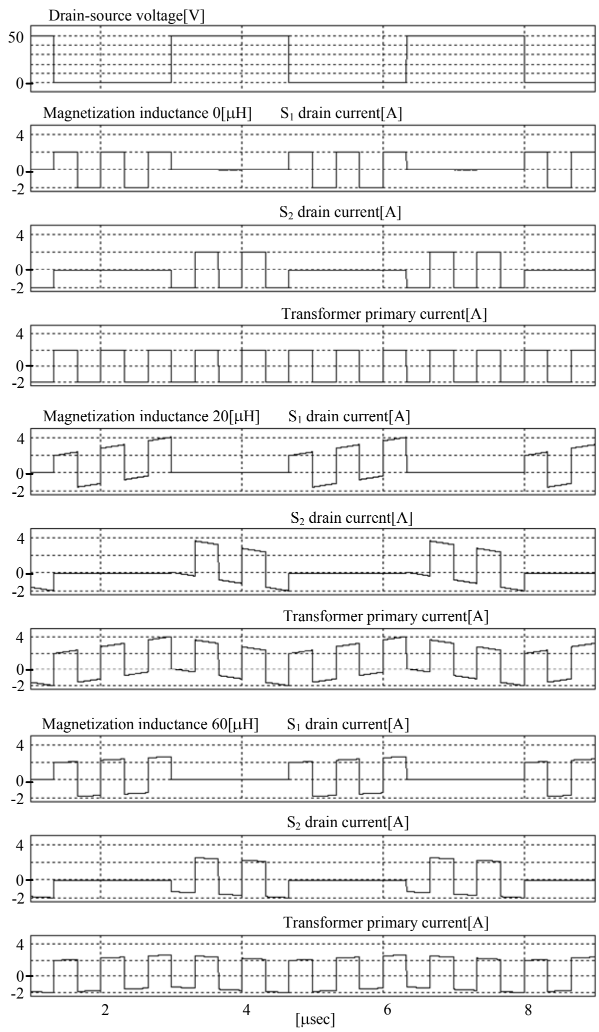


Figure 7. Simulation result of varying parameter of magnetization inductance.

In addition, the secondary side of transformer U-phase output voltage is confirmed that twice the voltage of the primary side of the transformer, which is determined by the turns ratio. However, the transformer secondary winding is a penetrating wound. As therefore, measuring the phase voltage of the secondary side of the transformer becomes impossible. Therefore, the secondary side voltage of the transformer is measured by using auxiliary winding that has the same number of turns to the secondary side.

B. Characteristics of the load test

Figure 12 shows the experimental result with 10Ω load. Comparing this result with Figure 6 (no-load test), oscillation occurs on the output waveform. The output voltage has been reduced from 50V to 25V. In addition, the output current is a triangular wave. Therefore, the load power factor is approximately 0.1, which is a very low value. This inductance value is large to use in 1.5MHz.

VI. CONCLUSION

A frequency multiplying circuit which consists of a multi-phase voltage-source inverter and multiple toroidal core is proposed in this paper. It is possible to make a high frequency power source without using exclusive element that corresponds to the high frequency from the proposed method.

The experimental result confirms the operation at 1.5MHz square wave output voltage. However, high efficiency power conversion is failed on the load experiment. This is because the load power factor is affected by leakage inductance coincide within the transformer and load inductance.

In the future work, a low leakage inductance for transformer will be designed to achieve high efficiency.

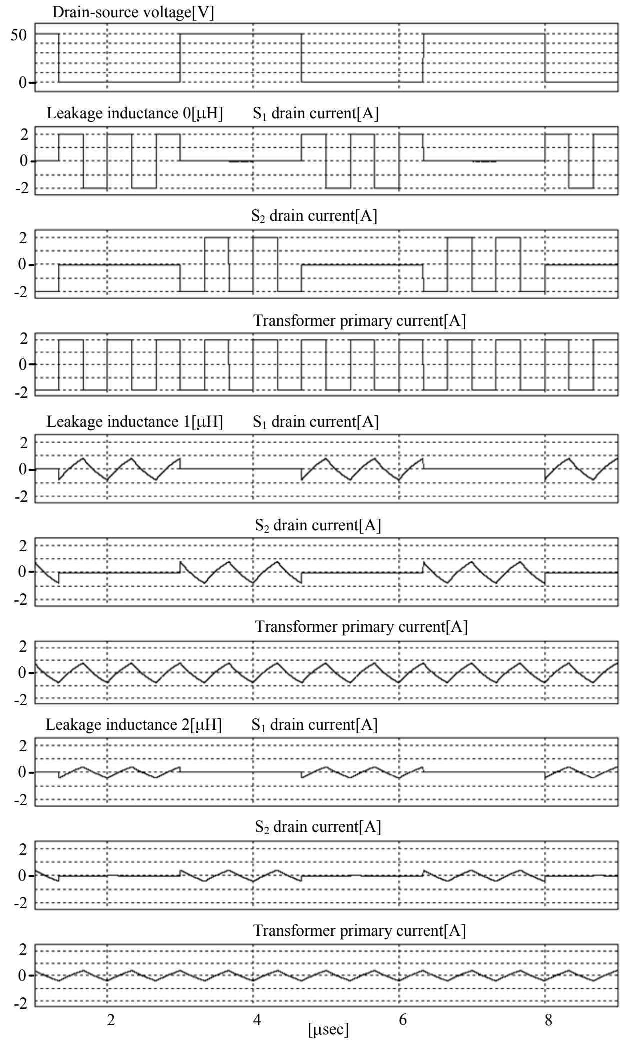


Figure 8. Simulation result of varying parameter of leakage inductance

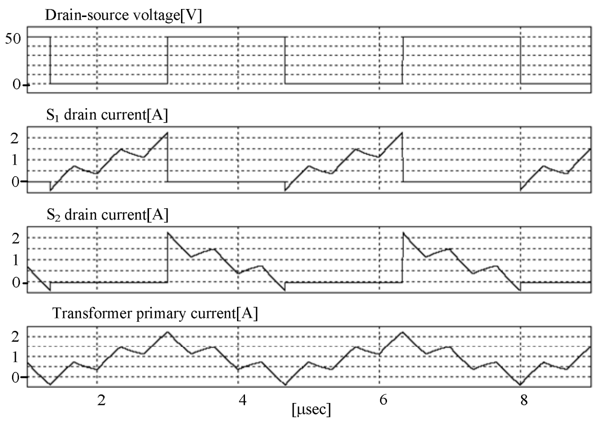


Figure 9. Simulation result of given magnetization inductance and leakage inductance.

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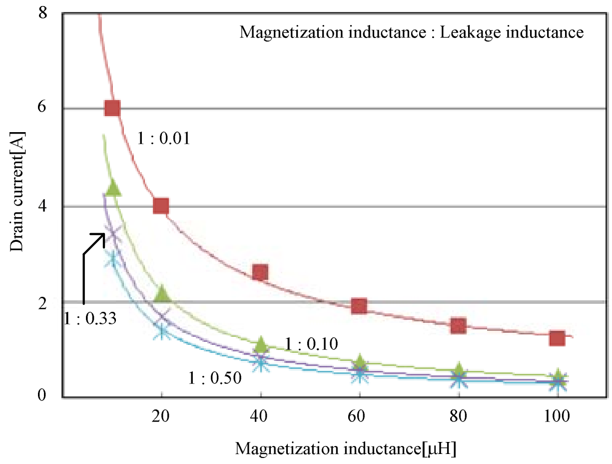

Figure 10. Current characteristics for the magnetizing inductance element

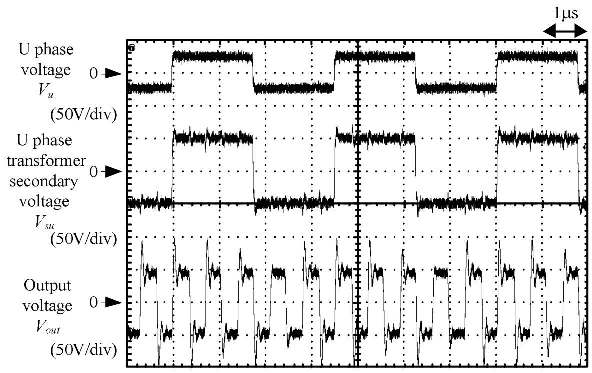

Figure 11. Oparation waveforms of the proposed cicruit at no-load;each leg operates 300 kHz, then output frequency of 1.5MHz is obtained.).

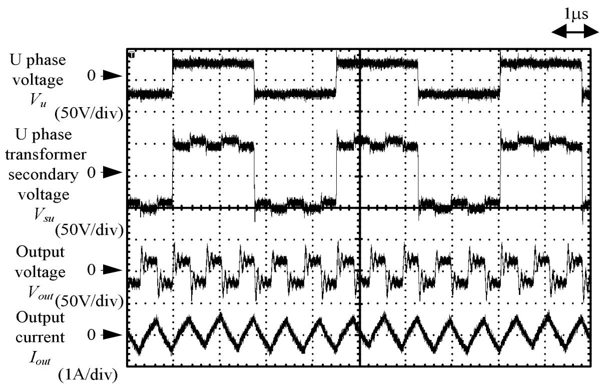

Figure 12. Operation waveforms at with 10 ohm resitive load