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Adjustable High Frequency Quasi-Resonant Inverter for Induction Heating

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Kazuki Saso†, Takahiro Ito*, Yusuke Ishimaru*, Kouki Matsuse* and Masayoshi Tsukahara**

Abstract - This paper presents the considerations of driving the Adjustable Frequency Quasi-Resonant Inverter Circuit in the high frequency. This inverter is requested to output frequency from 160kHz to 400kHz. Resonant inverter used for metalworking by the induction heating. In induction heating, high frequency can heat the shallow point, and low frequency can heat the deep point. So when heated depth is replaced, the frequency that inverter must output is different. It is necessary for the inverter to output two or more frequencies. In addition, in the heat-treatment called the hardening, only the metal surface must be heated. So, to heat-treat metal that a radius is small, it is necessary for the inverter to output high frequency. This inverter can output the frequency more than 100kHz by using Power Metal Oxide Semiconductor Field Effect Transistor (MOSFET) as power device. The circuit includes the first resonant capacitor and second one with a one-way short-circuit switch. Because synthetic series capacitance is varied by manipulating the switch, this inverter can change a period during a half period. We confirmed this inverter can output an arbitrary frequency by the experiment.

Keywords: Adjustable high frequency, Quasi-resonant inverter, Induction heating

1. Introduction

Induction heating is often used for the heat-treatment of a metal work-piece. The heated depth depends on the inverter output frequency. Induction heating has characteristics that lower and higher frequency heats the deeper and slighter part of the load respectively. So the inverter for induction heating must change the output frequency into the best value.

For example, the metal can become harder by heat-treat "Harden" being done. Induction heating machine must not heat the deeper part of the load so much, and heat slighter one intensively. But, because the needed heating depth of each metallic part is different, the required output frequency is also different.

The purpose of this inverter is induction heating by high frequency from 160 kHz to 400 kHz.

The heated object of the inverter is a columnar metal with a small radius. Inverter must output higher frequency to heat only the surface of load.

This paper presents the basic principle of this inverter and the effect of using series connected power MOSFETs for high frequency inverter, and shows the experiment result.

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2. Circuit Configuration

Fig. 1 shows a main circuit configuration. In the Fig. 1, E is DC power supply voltage. R and L are resistance and inductance in an equivalent circuit of the heating coil and heated metallic part respectively. C_1 and C_2 ($C_1 >> C_2$ are resonance capacitor. C_2 can be short-circuited by switching. Q_1 Q_4 are Power Metal Oxide Semiconductor Field Effect Transistors (power MOSFETs). D_1 D_4 are diodes.

3. Operation Principle

Because the circuit in Fig.1 is a series resonance circuit, the equation is as follows.

$$E = Ri(t) + L\frac{di(t)}{dt} + \frac{1}{C}\int i(t)dt$$

mode1

Q_1,Q_2 : ON Q_3,Q_4: OFF

This is a series resonance state by R, L, C_1. C_2 is short-circuited by Q_2. "Resonance A" with comparatively long period happens.

mode2

Q_1 : ON　Q_2,Q_3,Q_4 : OFF

This is a series resonance state by R, L, C_1, C_2. Because Q_2 is OFF, combined capacitance decreases. When C_1>>C_2, the combined capacitance is

$$C = \frac{C_1 C_2}{C_1 + C_2} \qquad C_2 \quad (<< C_1) \quad .$$

As a result, "Resonance B" with comparatively short period happens. So Q_2 reaches 0 [A] earlier than the state with the open on (Fig. 2).

mode3

Q_1,Q_2,Q_3,Q_4 : OFF

This is dead time for prevention of arm short circuit.

mode4

Q_1,Q_2: OFF　Q_3,Q_4 : ON

This is a state that a power supply was open (E=0). And, current flows backward till the voltage is charged by C_2 becoming Vc_2 = 0. This is a series resonance state by R, L, C_1, C_2.

mode5

Q_1,Q_2 : OFF　Q_3,Q_4 : ON

Vc_2=0, and the forward bias voltage is impressed on D_2. This mode is a series resonance state by R, L, C_1, before becoming i = 0 [A].

mode6

Q_1,Q_2,Q_3,Q_4: OFF

This is dead time for prevention of arm short circuit.

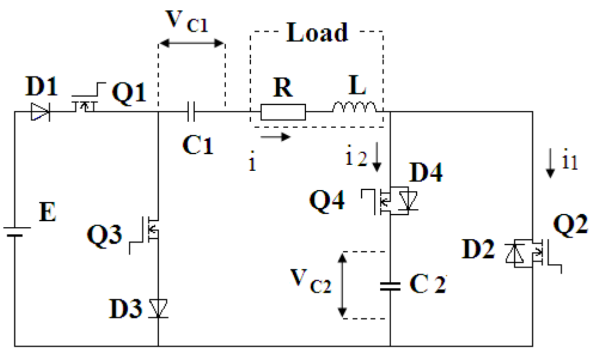


Fig. 1. Configuration of main circuit.

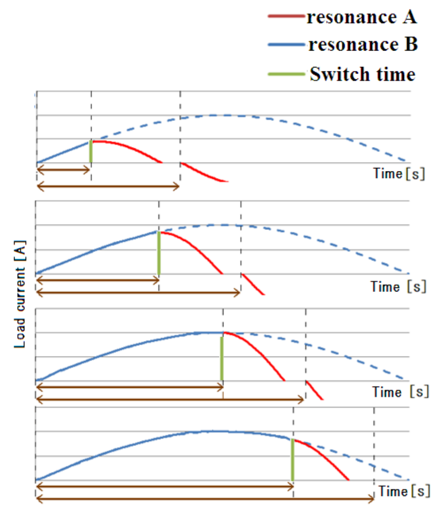


Fig. 2. A change of the resonance.

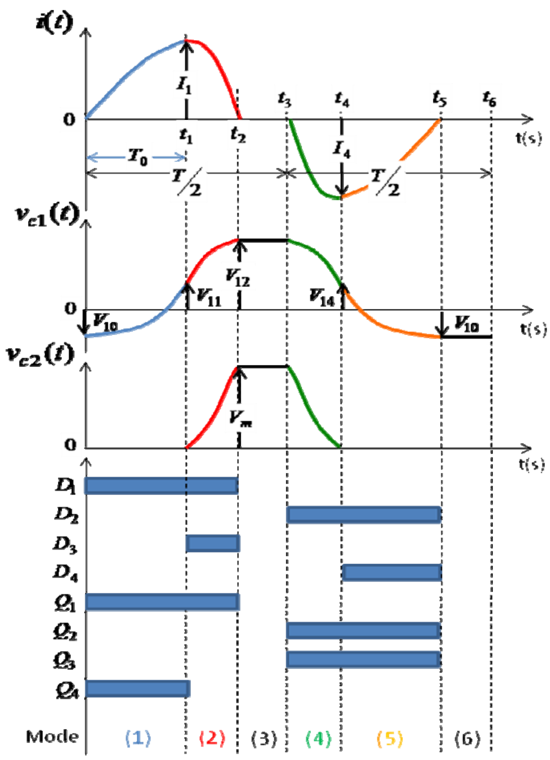


Fig. 3. The timing of the ON signal.

Fig. 3 expresses the output current waveform and ON timing of the power MOSFETs and diodes. This inverter can change the resonance period by opening Q_2 during a half period.

The dead time must be made in current waveform so that this inverter is driven, because it takes turn on/off time so that a power device changes on/off. If there was not dead time, the power supply is short-circuited for an instant and broken.

4. Characteristics

4.1 Relation Between Turn On/Off Time and Output Frequency

This inverter does not flow output current during the dead time. When the power device with long turn on/off time is used, long dead time is needed. At that time, the output power decreases because the ratio at the period when the current flows to the load decreases. It happens remarkably when a high frequency is outputted. Fig.4 shows the influence that dead time gives to output power. When it is defined as follows,

$$P = i \times v_R$$

$$i = I_m \sin(\frac{2}{Ts}t)$$

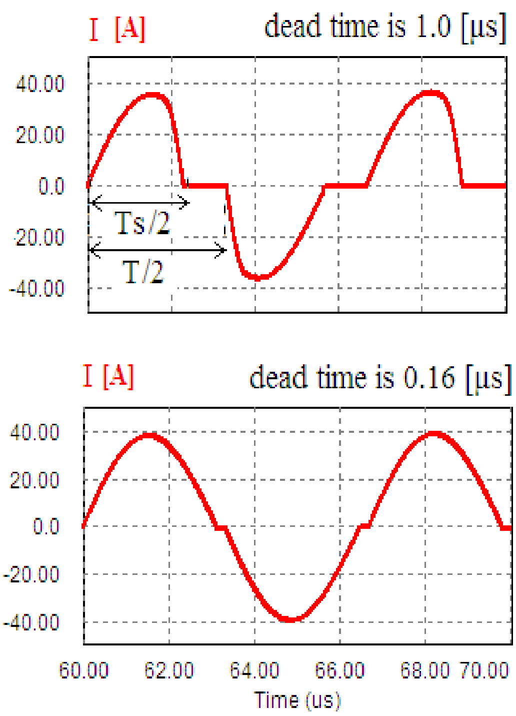
The dead time is $T_{d,}$
Average power, P_R is

$$P_R = \frac{1}{(T/2)}\int_0^{Ts} R \times (\mathrm{I_m}\sin(\frac{2}{\mathrm{Ts}}\mathrm{t}))^2 dt$$

$$= \frac{RI_m^2}{2}(1 - 2\frac{T_d}{T})$$

It is shown that P_R decreases when T_d increases. As a result, this inverter needs high speed power device.

4.2 Influence of Wiring Inductance



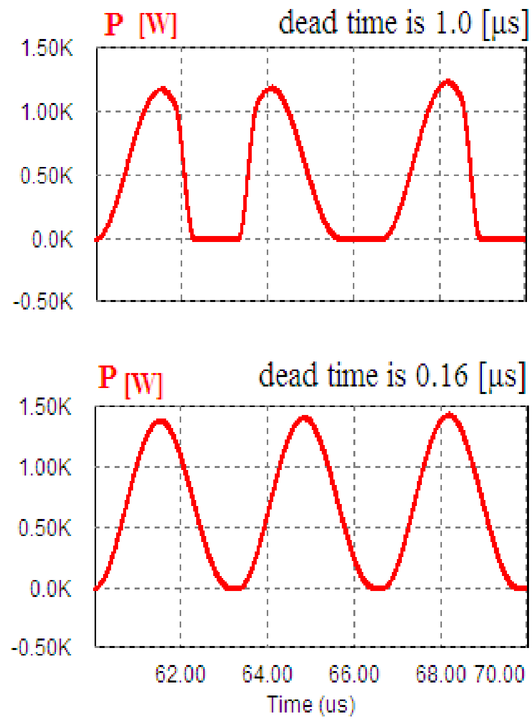


Fig. 4. Simulation result of 150 kHz when the dead time is different.

Because this inverter uses resonance, the product of inductance L of the coil and capacitance C of the capacitor is set small. When the coil with small inductance is used, the influence of the wiring inductance relatively grows.

Fig. 5 shows the distribution of wiring inductance (l_1~l_{10}). These are causes of going mad of the timing of the signal spent to the power device and the resonance period.

Especially, l_5~l_9 causes the resonance with C_2 in the short-circuit circuit, and there is a possibility of putting the power device out of order. It is necessary to design these wiring inductances smaller.

Fig.6 shows Influence of wiring inductance.

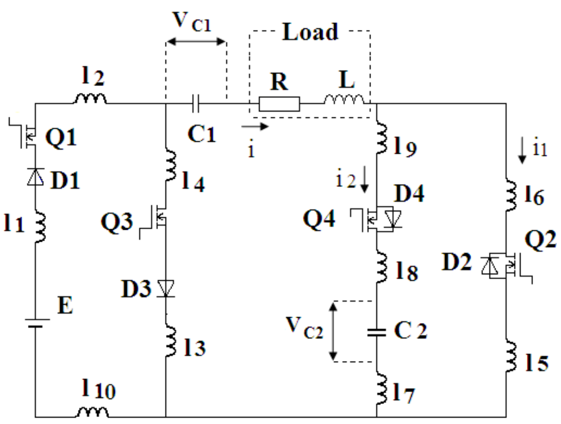
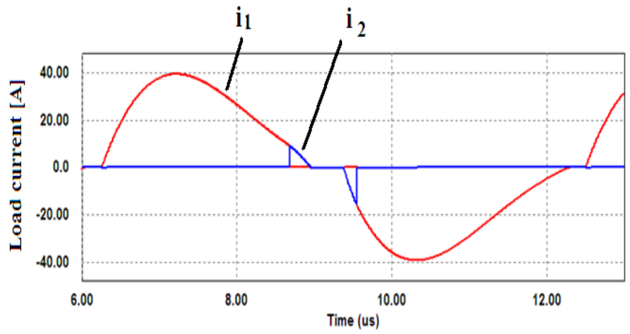
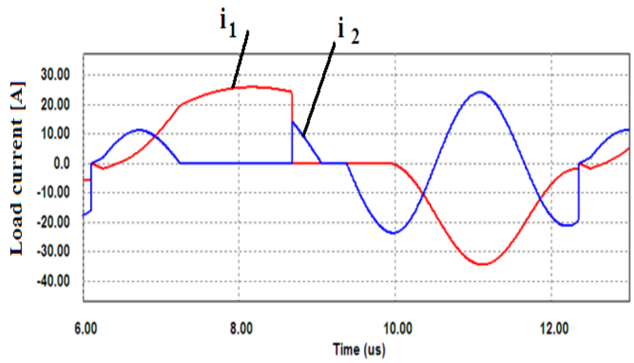


Fig. 5. Distribution of wiring inductance.



(a) Ideal circuit



(b) Wiring inductance having

Fig. 6. Influence of wiring inductance (160 kHz).

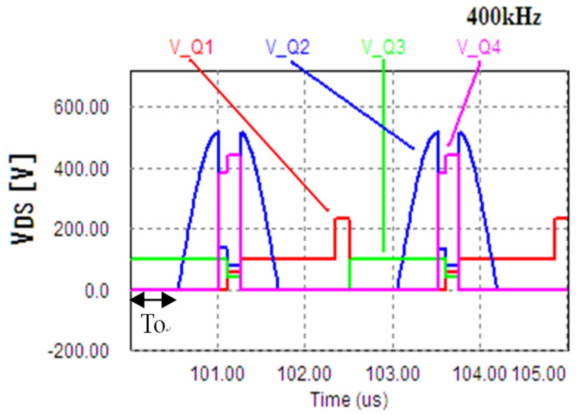


Fig. 7. The voltage between D and S V_{DS} of power devices when outputting 400 kHz (E=100 [V]).

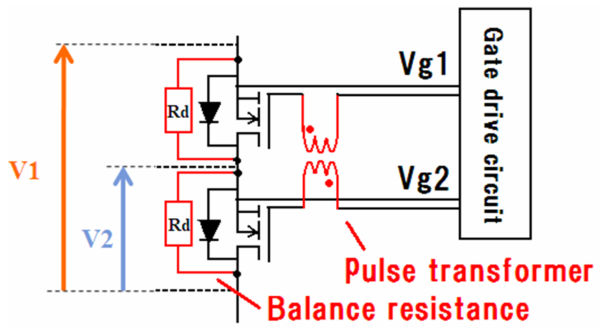


Fig. 8. The series connected devices.

4.3 The Series Connection Method of the Power Device

Turn off time t_{off} of the power device must be below 200 [ns] to output 400 kHz. This inverter has power MOSFETs that t_{off} is 138 [ns] as power device (Table 1). Generally Withstand voltage is low in the power device with short t_{off}.

This inverter has the second resonance capacitor C_2. When time of mode1 (T_0) is 0.55 [us] to output 400kHz, Q_2 and Q_4 requires higher withstand voltage than that of Q_1 and Q_2 to charge C_2. (Fig. 7).

We can get twice withstand voltage with connecting two power MOSFETs in series [2].

The gate signal must completely synchronize by a pulse transformer. Then, the terminal voltage when device OFF period must be balance by balance resistance (Fig. 8).

Table 1. the parameter of the power device

	Power MOSFET	IGBT
Withstand voltage [V]	300	600
Current capacity [A]	50	50
Turn-OFF time t_{off} [ns]	92 to 138	600 to 800

5. Experimental result

Table 2 is the parameter of the inverter.

Fig. 9 is voltages obtained by experiment. V1 and V2 are the voltages between D and S V_{DS} of series connected power MOSFETs at Q_2. V1 is reverse voltage added to the two devices. V2 is voltage added to the one of them. Then, Power-supply voltage E = 10 [V].

Fig. 9 shows that the reverse voltage of series connected power MOSFETs evenly divided.

Fig. 10 is simulation and experiment results of the load current of 240 kHz. Fig.11 is simulation and experiment results of the load current of 400 kHz. These experiment results are outputted by the same parameter of inverter excluding switching timing.

These figures show that two or more frequencies including 400 kHz can be output by changing the switching timing.

Fig. 12 is FFT result of load current of 240 kHz and 400 kHz. This figure shows this inverter can output the load current whose error margin with the command frequency is 3% or less.

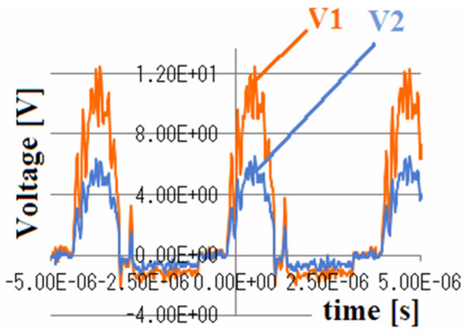
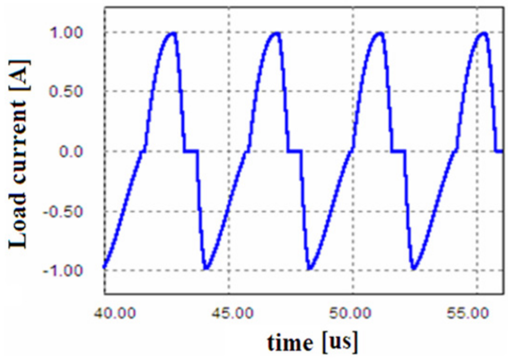


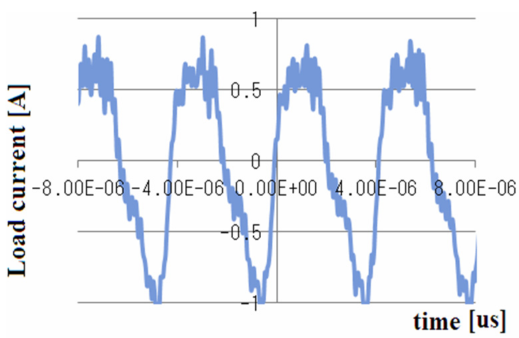
Fig. 9. Voltage of series connected power MOSFET (Q_2) (E=10 [V]).

Table 2. The parameter of the inverter

Capacitance C1	0.50 [uF]
Capacitance C2	0.05 [uF]
Inductance of coil L	1.46 [uH]
l1	50 [nH]
l2	850 [nH]
l3	1634 [nH]
l4, l5, l6, l9	10~15 [nH]
l7	250 [nH]
l8	250 [nH]
l10	1203 [nH]
Power-supply voltage E	10 [V]

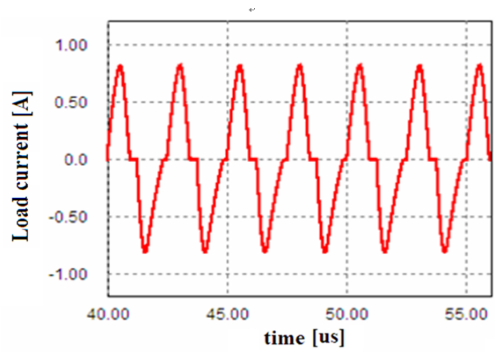


(a) Simulation result

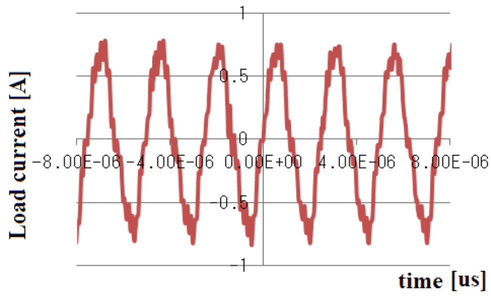


(b) Experiment result

Fig. 10. Simulation and experiment results of the load current of 240 kHz.



(a) Simulation result

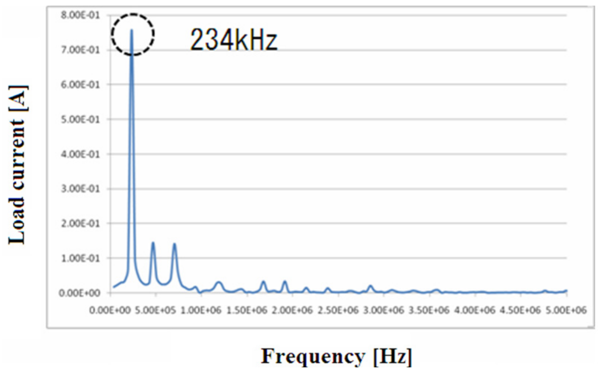


(b) Experiment result

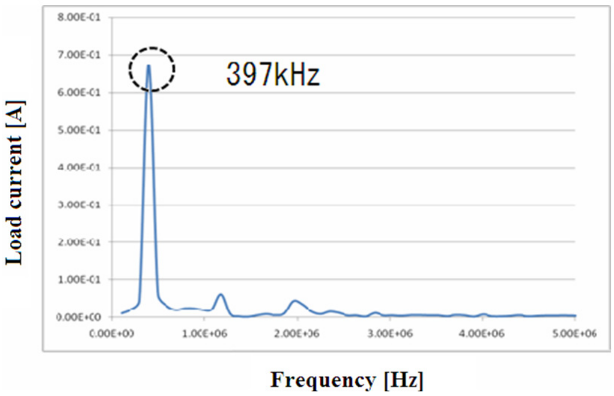
Fig. 11. Simulation and experiment results of the load current of 400 kHz.

6. Conclusion

We research the adjustable high frequency inverter circuit with series connected power MOSFET for induction heating. And we make the inverter which can output higher frequency than 100 kHz. This paper shows this inverter can output two or more frequencies including 400 kHz by changing the switching timing, and the power MOSFETs can withstand twice voltage by series connected two devices.



(a) Experiment result of 240kHz



(b) Experiment result of 400kHz

Fig. 12. FFT result of load current.

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