The 6th International Conference on Engineering, Energy, and Environment
27-29 November 2019, Thammasat University, Rangsit Campus, Thailand

Output Power Control Method of High Frequency Resonant Inverter for IH cooking heater with Hill Climbing Method

Sho Igarashi [a*], Hitoshi Haga [b]
[a]*Nagaoka University of Technology, 1603-1, Kamitomioka Nagaoka, Niigata, 940-2188, JAPAN*
[b]*Nagaoka University of Technology , 1603-1, Kamitomioka Nagaoka, Niigata, 940-2188, JAPAN*

Abstract

This paper proposes a control method of high frequency inverter for high efficiency and high power of induction heating (IH). Because of corresponding with unknown load resonant frequency which determined by kind of metal, shape or tempurature of pans. The proposed control method has the feature that it can search the resonant frequency of high frequency inverter with high accuracy based on hill climbing method. The proposed method confirmed the conversion efficiency 96.4% by the high frequency inverter of 80 kHz by experiment. In addition, the phase shift angle increases 11.4~47.4% compared with conventional method.The increase of phase shift angle is directly connected to the increase of output power range.The proposed method contributes high efficiency and high power operation of IH system.

Keywords: High frequency inverter; Induction heating applications; Resonant frequency tracking

---

1. Introduction

In recent years, an induction heating (IH) systems are spreading to the industrial and domestic applications from the viewpoint of high efficiency, high controllable and safeness. The IH systems generally required the output power control, all metal heating, high efficiency, low cost. The inverter used by IH systems required to operate corresponding with load resonant frequency in order to increase load power factor for high efficiency and stability operation. However, the problem was reported that the load impedance changes with the changing temperature of pots or pans. According to change load impedance, the load resonant frequency changes too. Therefore, inverter operating frequency needs to tracking to the unknown load resonant frequency. Moreover, it required high frequency operation to heat non ferromagnetic metals by skin effect. Non ferromagnetic metals are not easy to heat because the magnetic fluxes generated by heating (working) coil are not easy to enter to metal's inside and they have not high resistance for Joule heating. Therefore, inverter required wide range operating frequency more than when heat only ferromagnetic metals.

This paper proposes a control method of high frequency inverter for high efficiency and high power of the IH.

* Sho Igarashi. Tel.: +81-258-47-9553
E-mail address: igarashi@stn.nagaokaut.ac.jp

2. Control method for high frequency inverter

2.1. Conventional control method

Against the problem of need to tracking to the resonant frequency, conventional method succeeds this problem by making detected phase difference between output voltage and current equal zero. Integrate the output current while inverter outputs zero voltage generated by phase shift PWM. The leading phase or lagging phase determined by the integral results positive or negative signal. If leading phase detected, increase inverter operating frequency. If lagging phase detected, decrease inverter operating frequency. However, zero voltage interval has to be installed, and limits output high power area. In addition, this limited area spread with increase inverter operating frequency. Equation (1) shows the limited area of output power of conventional control method. Fig. 1 shows area of eq. (1).

$$\theta > 180 \cdot 2 \cdot \frac{f_{inv}}{f_{samp}} \quad (1)$$

Here, f_{inv} : inverter frequency, f_{samp} : sampling frequency(350kHz), θ : phase shift angle. The sampling frequency 350kHz is that of our lab. controller.

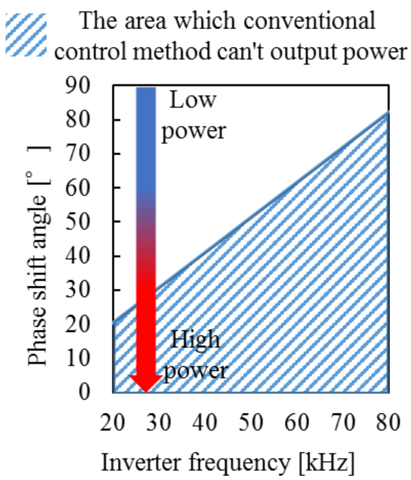


Fig. 1 The area which conventional control method can't output power

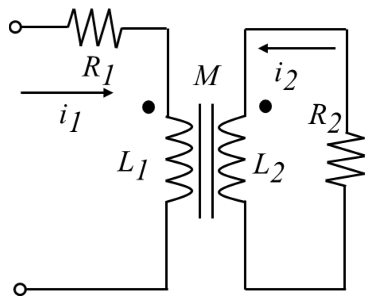


Fig. 2 Equivalent circuit model

2.2. Proposed control method

In this paper, hill climbing method adapts to high frequency inverter for the load resonant frequency tracking. It was confirmed about inverter operates high power even in high frequency area and tracking to the load resonant frequency by hill climbing method, so reported.

In order to validate tracking to the load resonant frequency, make model from IH system to RLC series resonant circuit.

A) Modeling

Fig. 2 shows an equivalent circuit model of induction heating load.

where, L_1 : heating coil self-inductance, R_1: heating coil equivalent resistance, L_2: heating object self-inductance, R_2: heating object equivalent resistance, M: mutual inductance, i_1 : primary side current, i_2 : secondary side current. Equation (2) and (3) show primary and secondary closed loop equation.

$$V_{in} = R_1 i_1 + j\omega L_1 i_1 + j\omega M i_2 \quad (2)$$
$$0 = R_2 i_2 + j\omega L_2 i_2 + j\omega M i_1 \quad (3)$$

here, delete i_2

$$V_{in}=\left\{R_1+\frac{\omega^2 M^2 R_2}{R_2^2+\omega^2 L_2^2}+j\omega\left(L_1-\frac{\omega^2 M^2 L_2 i_2}{R_2^2+\omega^2 L_2^2}\right)\right\} i_2 \quad (4)$$

$$R=R_1+\frac{\omega^2 M^2 R_2}{R_2^2+\omega^2 L_2^2} \quad (5)$$

$$L=L_1-\frac{\omega^2 M^2 L_2}{R_2^2+\omega^2 L_2^2} \quad (6)$$

equations (5) and (6) are equivalent RL load. Further, added for resonant capacitor Fig. 3 shows induction heating model.

B) Control method

Hill climbing method adapted as proposed method is extreme value exploration method. The current through the RLC series resonant circuit gets the maximum value when inverter operating frequency equals LC resonant frequency. Therefore, inverter operating frequency changes to exploring for the maximum current point (frequency) succeeds resonant frequency tracking. Fig. 4 shows control block diagram. Hill climbing method compares previous value and this time value. Therefore, controller keeps the output current value as the inverter operating frequency at that times. Then, controller gets the new output current value after shift the inverter operating frequency by Δf and compares previous current value with this time current value. Hence, controller increases/decreases the inverter operating frequency in the direction of bigger current. Calculate the current RMS of output current at first dashed line block diagram in Fig.3. The second dashed line block diagram is hill climbing method and determine inverter operating frequency (carrier frequency). The final dashed line block diagram is gate signal generator. Insert the arbitrary phase shift angle which using for output power control at this block diagram.

3. Simulation results

Simulated by PSIM (simulation software of power electronics) to confirm the availability of this proposed method. The response waveform of inverter operating frequency shown in Fig.5. In order to validate tracking to the load resonant frequency, changed inductance at 50ms. Fig.5 shows inverter tracking to the load resonant frequency after changed load resonant frequency. Output voltage and current waveform shown in Fig.6. It was verified that inverter operates at load resonant frequency because the phase difference is zero between output voltage and current. The waveform of inserted 90° phase shift angle shown in Fig. 7. See Fig. 7, it decreases output current by phase shift angle.

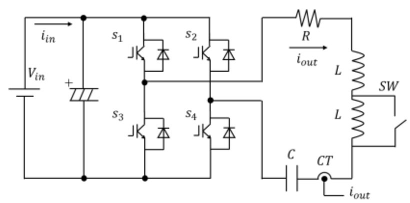


Fig. 3 RLC series resonant circuit

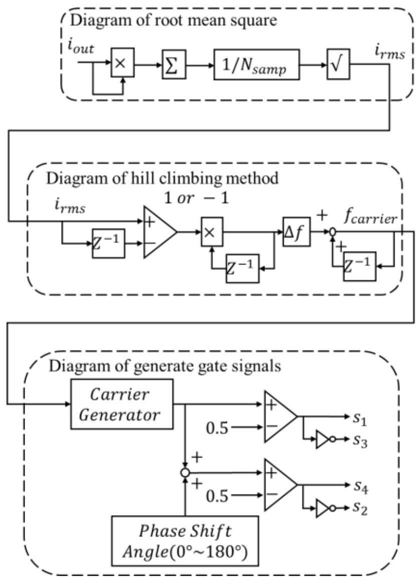


Fig. 4 Control block diagram

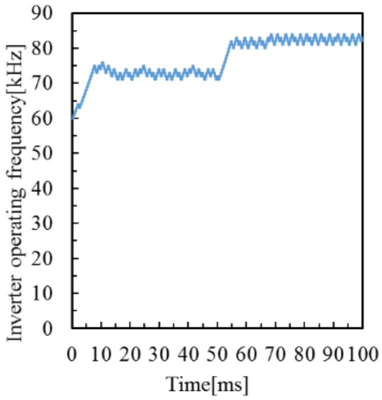
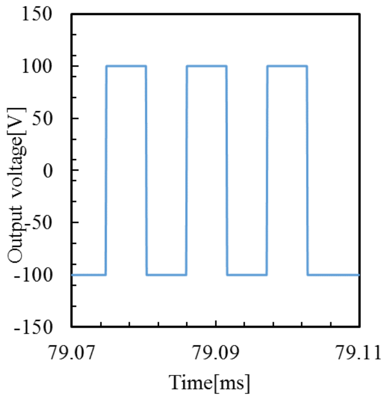
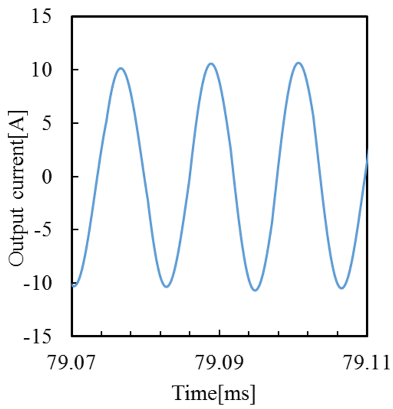


Fig. 5 Response waveform of inverter operating frequency

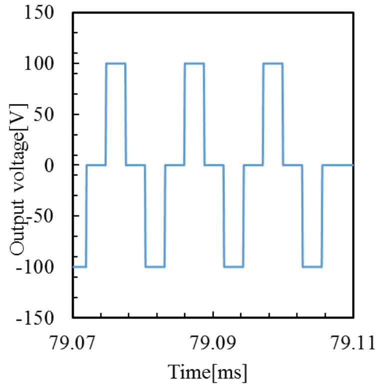


(a)

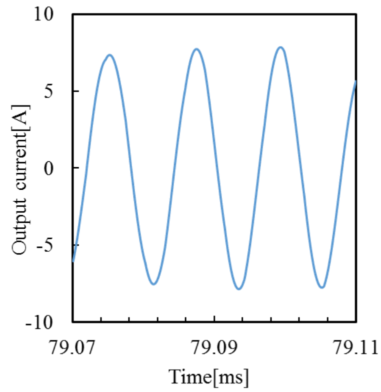


(b)

Fig. 6 Output voltage and current waveform (phase shift angle=0°)



(a)



(b)

Fig. 7 Output voltage and current waveform (phase shift angle=90°)

4. Experimental results

The experimental prototype for testing proposed method shown in Fig. 8. It used 2 phase of general purpose 3 phase inverter. CT is a high frequency compatible product (LTS 25NP). Capacitor made series and parallel for withstand voltage and capacitance. Inductor made series for inductance. It was validated that the characteristic of simulation result with experiment. The response waveform of inverter operating frequency shown in Fig.9. It's shows that inverter operating frequency tracking to the load resonant frequency which changing according to change load as like Fig. 5. Furthermore, output current decrease when load changing however it increase according to inverter operating frequency tracking to the load resonant frequency. Fig. 10 shows the output voltage and current waveform. It seems that phase difference is zero and inverter operate at load resonant frequency as like Fig.6. The waveform inserted phase shift angle shown in Fig. 11 to Fig.14. It was validated that decrease output current by inserting phase shift angle as like Fig.7. The parameters shown in Table 1. These

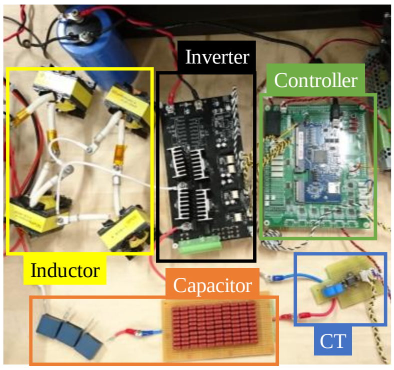


Fig. 8 Experimental prototype

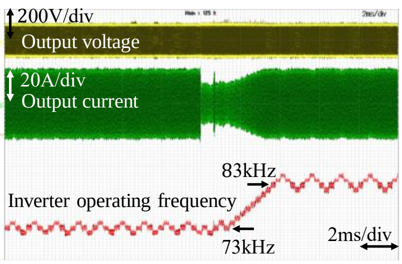


Fig. 9 Waveform of inverter operating frequency

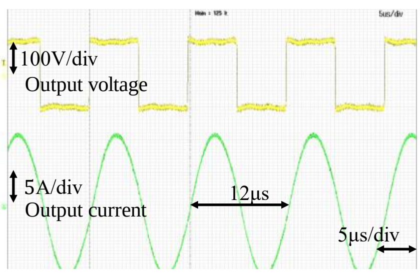


Fig. 10 Output voltage and current waveform (phase shift angle=0°)

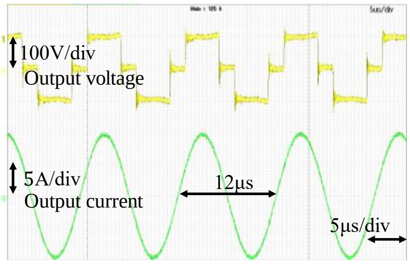


Fig. 11 Output voltage and current waveform (phase shift angle=45°)

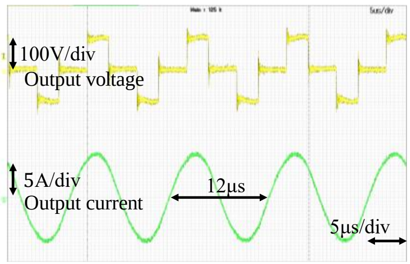


Fig. 12 Output voltage and current waveform (phase shift angle=90°)

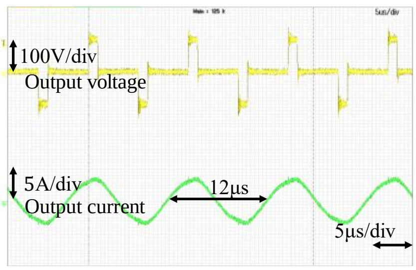


Fig. 13 Output voltage and current waveform (phase shift angle=135°)

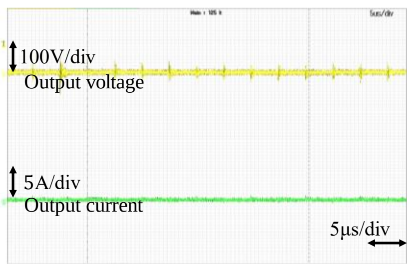


Fig. 14 Output voltage and current waveform (phase shift angle=180°)

Table 1 Experiment parameter

Item	Value
Resistance	11Ω
Inductance	146μH → 187μH
Capacitance	25.4nF
Input voltage	100V
Load resonant frequency	73kHz→83kHz
Power MOSFET	FDA38N30
Power meter	WT330

parameters were designed to be load resonant frequency is 73kHz to 83kHz. Because around these high frequency band used to heat non ferromagnetic pans. High precision components value was required for load resonant frequency because high frequency area is especially sensitive. Therefore, each component was measured by LCR meter. In addition, measured 96.4% high efficiency when input power is 674.5W and output power is 650W. The phase shift angle increased 11.4(around 20kHz)~47.4%(around 80kHz) compared with the high power area of conventional method can't output.

5. Conclusion

This paper proposed a control method of high frequency inverter for high efficiency and high power of the IH. The proposed hill climbing method for unknown load resonant frequency tracking changing by pots temperature. Compared with the conventional method, the phase shift angle increases 11.4~47.4%. The output power (current) is controllable by phase shift control. Moreover, total power efficiency was measured 96.4% high efficiency in this experiment. In addition, expect low cost because use just one current CT as sensor.

References

[1] Hiroyasu Kifune, Yoshihiro Hatanaka "Resonant frequency tracking control by using one CT for high frequency inverter" 13th ECPEA、2009

[2] Hideki Sadakata, Atsushi Fujita, Shinichiro Sumiyoshi, Hideki Omori, Bishwajit Saha, Tarek Ahmed, Mutsuo Nakaoka "Latest Practical Developments of Triplex Series Load Resonant Frequency-Operated High Frequency Inverter for Induction-Heated Low Resistivity Metallic Appliances in Consumer Built-In Cooktops" 2010 Twenty-Fifth Annual IEEE APEC

[3] Hironobu Yonemori and Miki Kobayashi "Development of Double-Coil Drive Type IH Cooking Heater Corresponding to All-Metals"IEEJ Trans. IA, Vol.127, No.3, 2007

[4] Wei Han, K.T.Chau, Chaoqiang Jiang and Wei Liu"All-Metal Domestic Induction Heating Using Single-TRANSACTIONS ON MAGNETICS, VOL.54, NO.11, NOVEMBER 2018

[5] Shin Zenitani, Masayuki Okamoto, Eiji Hiraki and Toshihiko Tanaka "A Charge Boost Type Multi Oputput Full Bridge High Frequency Soft Switching Inverter for IH Cooking Appliance" 14th International Power Electronics and Motion Control Conference, EPE-EPMC2010

[6] Takuya Shijo, Shinya Kurachi, Yuki Uchino, Yujiro Noda, Hiroaki Yamada and Toshihiko Tanaka "High-Frequency Induction Heating for Small-Foreign-Metal Particle Detection Using 400kHz SiC-MOSFETs Inverter" 2017 IEEE ECCE

[7] Hiroyasu Kifune and Yoshihiro Hatakana "Optimal Frequency Tracking Method for Phase-Shift PWM Inverter" IEEJ Trans. 7(S1), S167-S172(2012)

[8] Sachio Kubota "Soft Switching Inverter with Resonance Tracking Control Using Quasi Variable Capacitor" 2016 IEEE 2nd Annual Southern Power Electronics Conference

[9] Takayuki Hirokawa, Makoto Imai and Atsushi Fujita "Multi-resonant Inverter Realizing Downsizing and Loss Reduction for All-metallic IH Cooktop" The 2018 International Power Electronics Conference

[10] J. Serrano, J. Acero, I. Lope, C. Carretero, J.M. Burdion and R. Alonso "Modeling of Domestic Induction Heating Systems with Non-Linear Saturable Loads" 2017 IEEE Applied Power Electronics Conference and Expossition