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(Full length research article)

Mathematical Analysis of the Mirror Inverter based High Frequency Domestic Induction Cooker

Dola Sinha[a*], Pradip Kumar Sadhu[b], Nitai Pal[c]

[a]Junior Research Fellow, Department of Electrical Engineering, Indian School of Mines, Dhanbad, Jharkhand, India
[b]Professor, Department of Electrical Engineering Indian School of Mines, Dhanbad, Jharkhand, India
[c]Assistant Professor, Department of Electrical Engineering Indian School of Mines, Dhanbad, Jharkhand, India.

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Abstract

Demand of domestic induction cooker increases day-by-day because of its inherent advantages. Different types of inverters are used in high frequency Induction cooker. This paper deals with the circuit analysis of a half bridge series resonant IGBT-fed mirror inverter based high frequency domestic induction cooker. The principle of inverter operation with waveforms has been presented here. The circuit is also simulated by PSPICE software. One prototype experimental model is fabricated. The analytical result and software simulated result are compared with this real time experimental result. And results are coming almost similar in nature.

Keywords: *Half bridge Series Resonant Inverter, Induction cooker, IGBT, Mirror Inverter, PSPICE Simulation*

1. Introduction

In the domestic induction cooker copper made heating coil is placed beneath the ferromagnetic cooking pan. The heating coil is made up of litz wire and is connected with a high frequency (4kHz to 50kHz) power source. The coupling between heating coil and cooking pan is modeled as the series connection of an inductor and resistor based on transformer analogy. The load power factor is usually considered around 0.5 (Hobson and Tebb, 1985). The induction cooker takes the energy from the mains voltage and this voltage is then rectified by a bridge rectifier. A bus filter is designed to allow a high voltage ripple and the resultant power factor close to one. Then an inverter supplies high frequency alternating current to the heating coil. At high frequency, the alternating magnetic flux is induced at cooking pan and produce eddy current in it. The internal resistance of the cooking pan causes heat to be dissipated following Joules effect. Now-a-days resonant inverter topologies are commonly used for induction cooker to produce high frequency resonance loss at the cooking pan. Mostly used inverter topologies are full bridge (Hobson et al., 1985, Dawson and Jain, 1991,) or half bridge (Koertzen et al., 1995, Kamli et al., 1996, Kwon et al., 1999). Omri et al. (1985) used bipolar Darlington-transistor fed single ended resonant inverter. To reduce the switching loss, inverter is operated in Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS) condition. Two single switch inverter topologies ZVS and ZCS are described by Omori et al. (1985), Leisten and Hobson (1990), and Cohen (1993). Wang et al. (1998) introduced quasi resonant ZVS-PWM inverter. Jung (1999) described dual bridge series resonant inverter for two loads. Forest et al. (2000) built a model based on series resonant ZVS inverter to supply several resonant loads. The overall comparison considering full bridge, half bridge, ZVS and ZCS have been made by Llorente et al. (2002). Sadhu et al. (2005) used hybrid inverter for induction heating using ZVS and ZCS condition. Burdio et al. (2005) developed a series resonant inverter based induction cooker with two heating zone. The circuit of half bridge inverter using the principle of positive negative phase shift control under ZVS and non-ZVS operation for small size and low voltage induction cooker is analysed by Achara et al. (2007). The series resonant based multi-inverter used for multiple induction heaters is described by Lucia et al. (2010). From the literature it can be concluded that due to robustness, cost saving and simple circuit configuration half bridge series resonant inverter is most popular. In this paper an attempt is made to analyze the circuit of half bridge series resonant based mirror inverter analytically and using PSPICE software simulation. The results are validated with the results from real time experimental model.

2. Analytical formulation of a Mirror Inverter based Induction Cooker

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* Email: dola.sinha@gmail.com
Phone No. +918986770026, Fax No. +913262296563

Mirror inverters are basically half bridge series resonant inverter and commonly used for medium power induction heating applications introduced by Sadhu et al. (2010). The series-resonant radio-frequency mirror inverter system has been introduced for induction-heated pipeline or vessel fluid heating in medicinal plant, sterilization plant and drier for surgical instruments by Sadhu et al. (2003).

Figure 1 illustrates the mirror inverter circuit. The AC main (220V, 50Hz) is routed through EMI / EMC filter before being fed to the bridge rectifier. The output of the rectifier is passed through an inductor and a capacitor C. The capacitor C is of small capacity (5uF) so that the DC voltage (V_{dc}) across C does not get leveled. This in turn also helps to improve the overall power factor of the system. The return path of the high frequency current is through this capacitor C as at high frequency C offers negligible capacitive reactance ($X_c = 1/2\pi fC$), where f is in KHz range, hence, the capacitor C acts as a short circuit and allows high frequency current to flow. It also acts as higher order harmonic filter at the same cost. IGBT is used as the power semiconductor switch for its superiority for domestic induction cooker operating below the frequency range of 50 kHz (Pal et al., 2011). Figure 2 shows the equivalent circuit of mirror inverter.

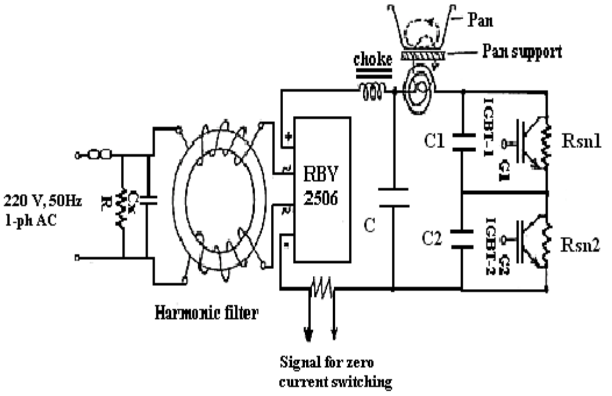

Figure1. Circuit of Mirror inverter.

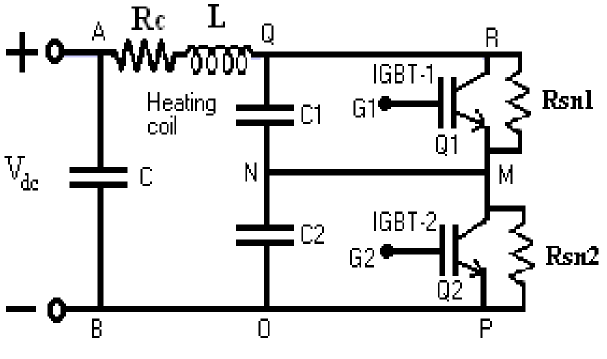

Figure 2.The equivalent circuit of mirror inverter.

The series current flowing through the heating coil is expressed as:

$$i_L(t)= \frac{V_{dc}}{\sqrt{R^2+\left[(\omega C_1)^{-1}-\omega L\right]^2}}\cos\left[\omega t+\tan^{-1}\frac{(\omega C_1)^{-1}-\omega L}{R}\right]$$
$$+Exp(-k_1 t)\left[A_1\cos k_2 + A_2\sin k_2 t\right] \qquad (1)$$

where, $k_1 = \frac{R}{2L}$ and $k_2 = \sqrt{(LC)^{-1}-k_1^2}$

A_1 and A_2 can be calculated from the initial conditions. The first part of the equation shows the steady state condition and the second part is due to transient condition. The voltage stored in capacitors C_1 and C_2 during charging will be expressed as:

$$V_{C1} = V_{C2} = \frac{1}{C_{eq}}\int_0^t i_L(t)dt \qquad (2)$$

Voltage across heating coil will be expressed as

$$V_{coil} = \left(\sqrt{R^2+(\omega L)^2}\right) i_L(t) \qquad (3)$$

Initial mode- When both the IGBTs are OFF and capacitors C_1 and C_2 are not initially charged.

After full bridge rectification the alternating voltage becomes pulsating dc voltage of an operating frequency of 100Hz. The equivalent circuit is as shown in figure 3. The switching device Q_1 and Q_2 are turned off at $t = t_0$. In this mode the circuit current flows through the snubber resistors Rsn1 and Rsn2 and capacitors C_1 and C_2. As the values of snubber resistors are very high (470kohm), so maximum current flows through the capacitors. There has been no conduction through Q_1 and Q_2.

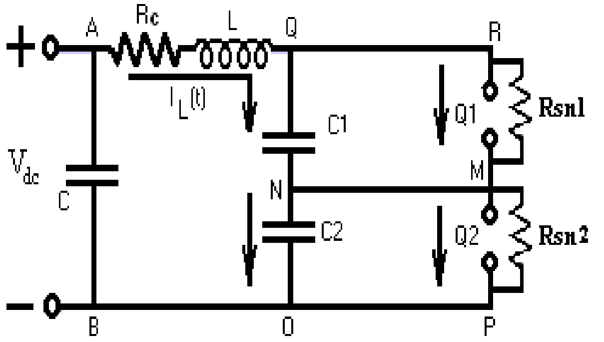

Figure 3.Capacitor charging current path when both switches are OFF.

A small voltage drop appears across the coil impedance and the rest voltage is equally shared by the capacitor C_1 and C_2 and this voltage is stored as initial charge voltages (V_{C1} and V_{C2} respectively) of these capacitors C_1 and C_2. The value of this voltage is almost $V_{dc}/2$.

Now depending on the switching conditions of two IGBTs, there exist four different modes of operations. These have been explained below in step-by step manner.

Mode–1 : When IGBT -1 is ON and IGBT-2 is OFF

The switching device Q_1 is turned on at $t = t_1$. During this mode, the DC-link voltage V_{dc} lets the resonant elements to accumulate energy by supplying power through Q_1. At $t = t_2$, the energy transfer from source to inductor (L) and capacitor (C_2) gets completed i.e. $i_L(t_1) = I_{peak}$ and $V_{C2}(t_2) = V_{dc}$. V_{C2} charged through the path AQRMNOBA shown in figure 4. The high frequency alternating current is flowing through capacitor C because at high frequency the capacitive reactance offered by C is negligible hence the capacitor acts as a as a short circuit and allowing the high frequency current to flow through it. In this mode C1 discharges from $V_{dc}/2$ to zero through the path QRMNQ. It is shown that charging current of C_2 and discharging current of C_1 both follow the same path M to N.

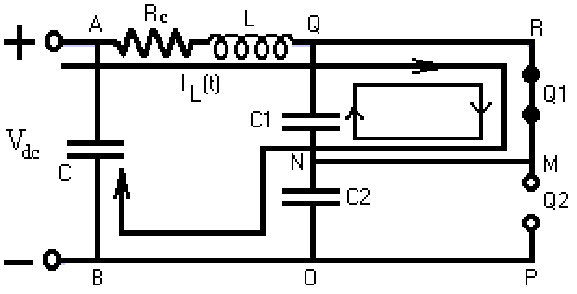

Figure 4.High frequency charging current flowing path of C_2 and discharging current path of C_1 at mode-1.

Mode–2: When both the IGBTs are OFF:

In this mode the charge on capacitor C_2 will act as a source of energy to drive current and charges C_1 from zero to $V_{dc}/2$ and the circuit current will be routed as indicated in figure 5. At the end of this mode i.e., at $t = t_3$ the capacitor voltage V_{C2} (t_3) is $V_{dc}/2$. So, C_1 and C_2 store equal voltage after Mode 3.

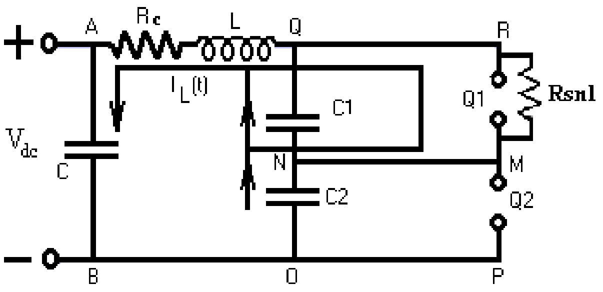

Figure 5.High frequency reverse current flowing path from C_2.

Mode–3: When IGBT -1 is OFF and IGBT-2 is ON

The switching device Q_1 is turned on at $t = t_3$. During this mode the DC-link voltage V_{dc} lets the resonating elements to accumulate energy by supplying power through Q_2. At, $t = t_4$ the energy transfer from source to inductor (L) and capacitor (C_2) gets completed i.e. $V_{C1}(t4) = V_{dc}$. V_{C1} charged through the path AQNMPOBA shown in figure 6. In this mode C_2 discharges from $V_{dc}/2$ to zero through the path NMPON. It is shown that charging current of C_1 and discharging current of C_2 both flow in the same path N to M

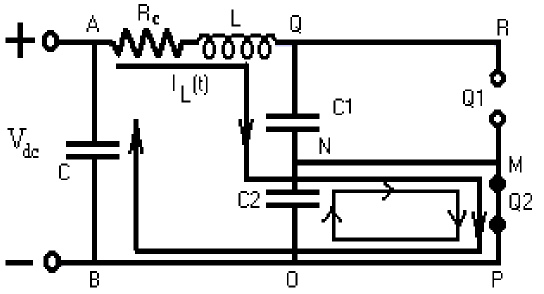

Figure 6.High frequency charging current path of C_1 and discharging current path of C_2 at mode-3.

Mode–4: When both the IGBTs are OFF:

This mode is the second mode (Mode 2) where both the switching devices Q_1 and Q_2 are off. The charge on capacitor C_1 will now act as a source of energy to drive current and thus charge C_2 from zero to $V_{dc}/2$ and the circuit current will be routed as indicated in figure 7. At the end of this mode at $t = t_5$ the capacitor voltage V_{C1} (t_5) is $V_{dc}/2$. After end of this mode both C_1 and C_2 store same voltage i.e., $V_{dc}/2$. Mode 1 to Mode 4 these four modes will repeat for continuous conduction.

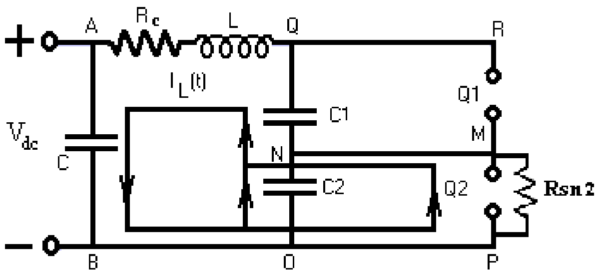

Figure 7.High frequency reverse current flowing path from C_1.

3. PSPICE simulation

The developed PSPICE schematic circuit diagram is shown in figure 8. Four diodes of 1N6392 type are used for bridge rectifier. And for high frequency inverter two IGBTs of HGTP6N 50E1D type are used.

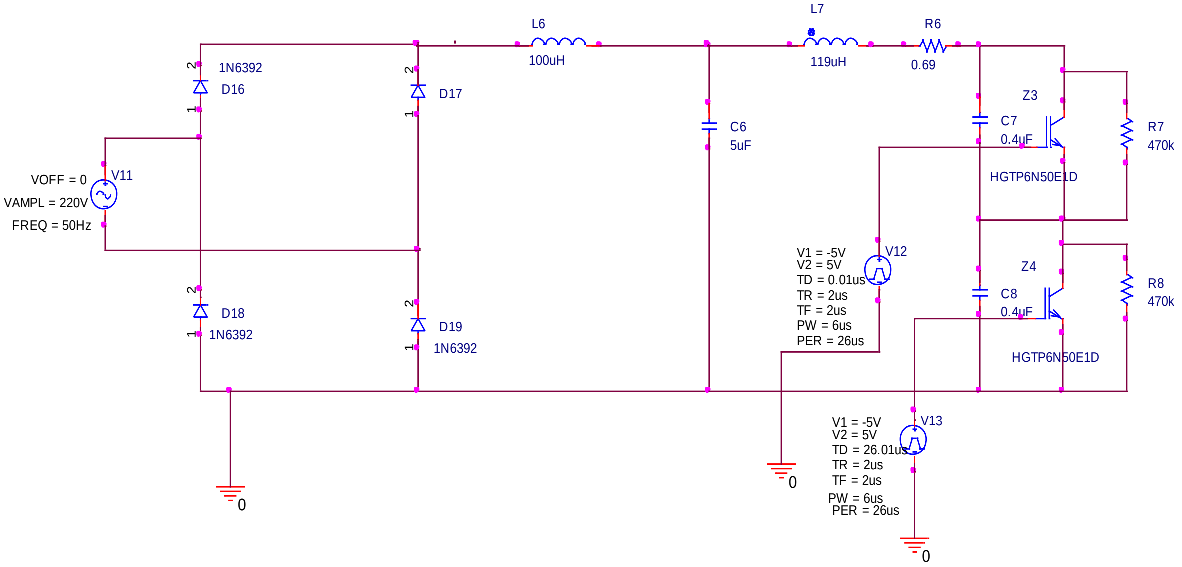

Figure 8.The circuit diagram for PSPICE simulation

Table1. Input parameters of Mirror inverter

Snubber resistors Rsn1 & Rsn2	470kohm	Supply Mains Voltage	220V
Coil inductance (L)	119µH	Operating frequency	38512Hz
Internal resistance (R) of coil	0.69 ohm	Capacitor C	5µF
Capacitors C_1 and C_2	0.4µF	IGBT ON/OFF timing	6 µsec and 20 µsec

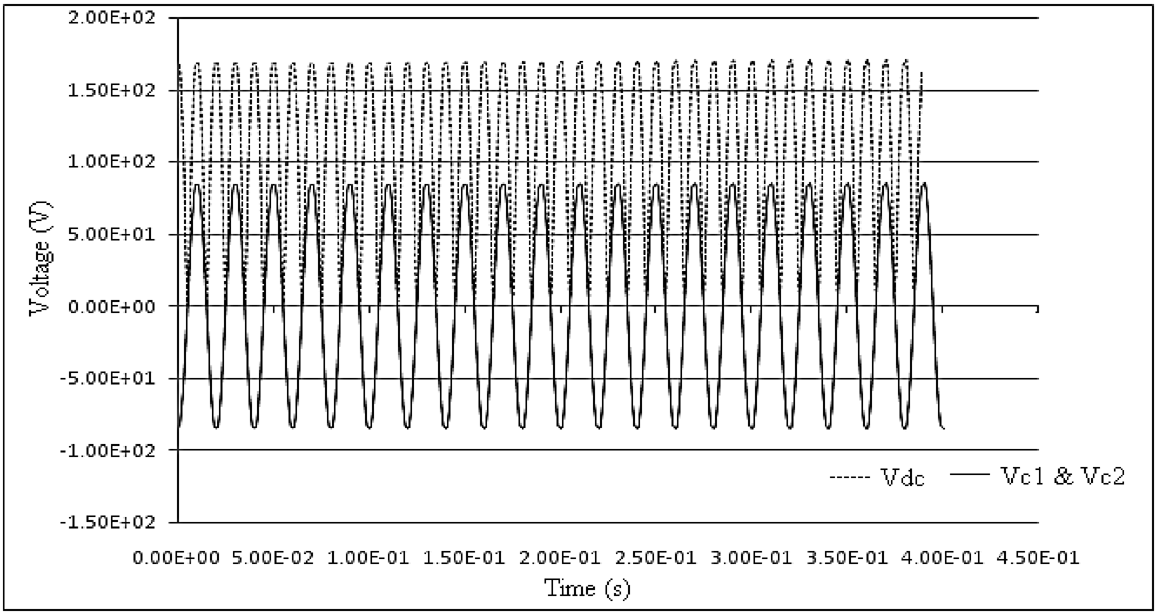

Figure 9.Applied voltage and capacitors voltages at low frequency when both switches are OFF.

4. Results and discussions

The main equivalent circuit of the mirror inverter is shown in figure 2. The parameters considered for the mirror inverter have been shown in table 1. The four modes (mode 1 to mode 4) will repeat according to specified IGBT ON time and OFF time. The depth of heat penetration on cooking pan is inversely proportional to operating frequency and the operating frequency is inversed of operating time period. So, by changing the IGBT ON-OFF time operating frequency can be changed and thus the heat penetration on cooking pan can be controlled. The circuit of mirror inverter is analytically analyzed by MS Excel 2007 and different waveforms are shown in figure 9 and 10.

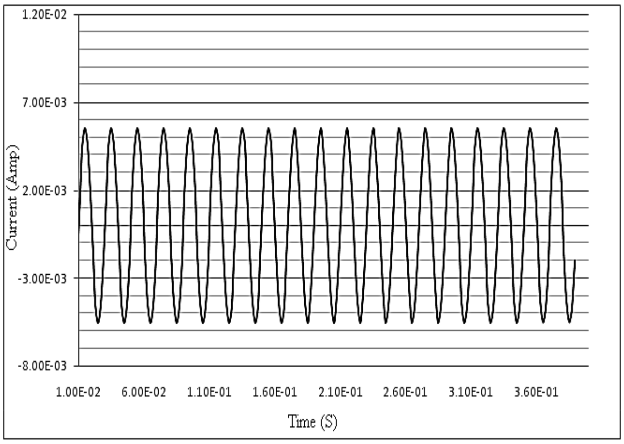

Figure 10.Series current of circuit, at low frequency when both switches are OFF.

The complete waveform including ON and OFF time of each switch at high frequency (38512Hz) is shown in figure 11 and figure 12 and PSpice simulation results are plotted at figure 13 and figure 14.

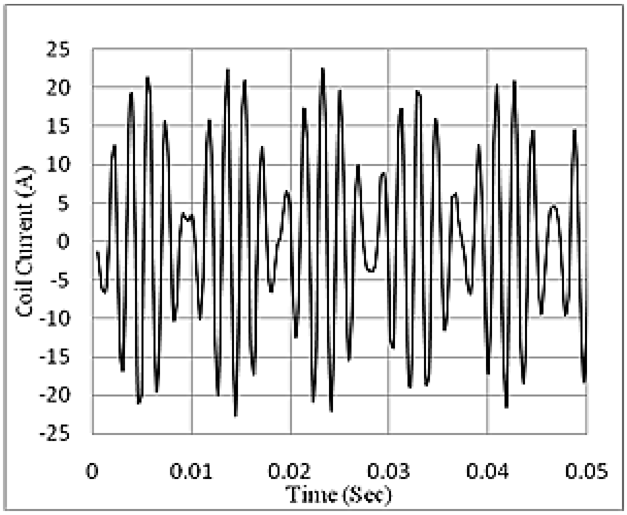

Figure 11.Current through heating coil by analytical analysis.

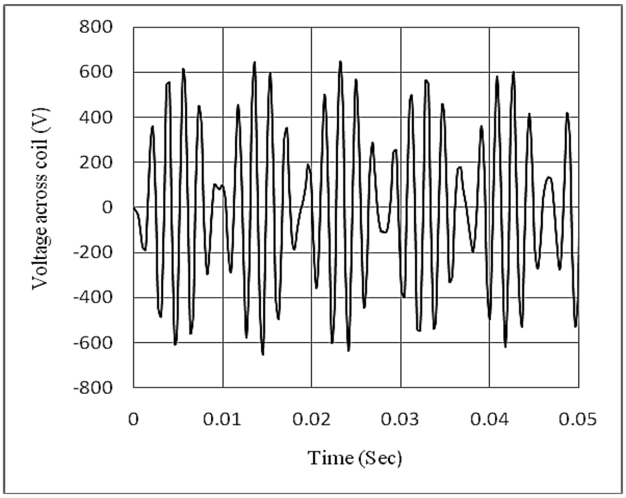

Figure 12.Voltage through heating coil by analytical analysis.

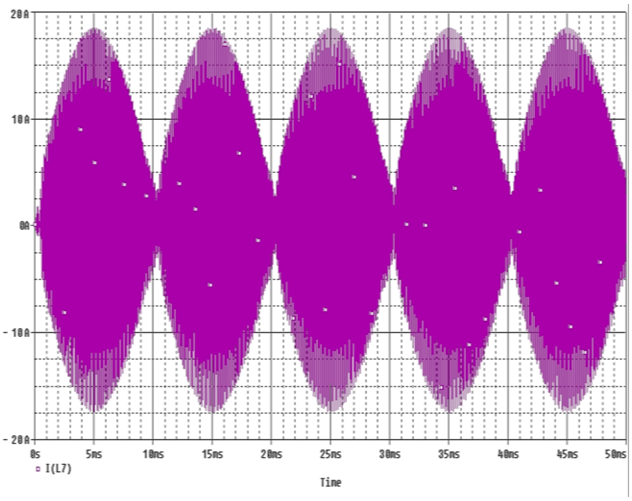

Figure 13.The waveform of current across heating coil by PSPICE simulation.

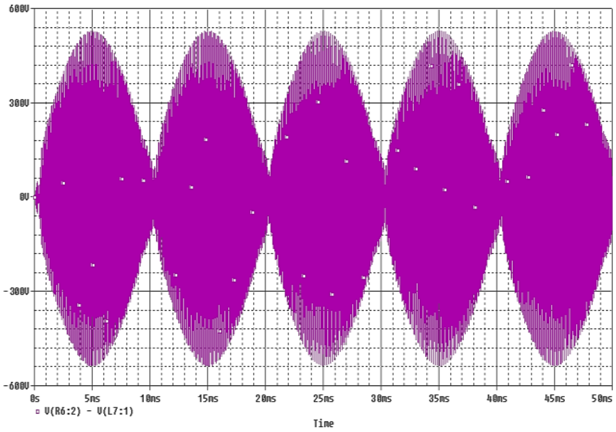

Figure 14.The waveform of voltage across heating coil by PSPICE simulation.

5. Real time Experiment

One prototype model is developed and the real time experimental results from oscilloscope are plotted. The series current flowing through heating coil and the voltage appeared across heating coil at continuous conduction of mirror inverter at high frequency is shown at figure 15 and figure16.

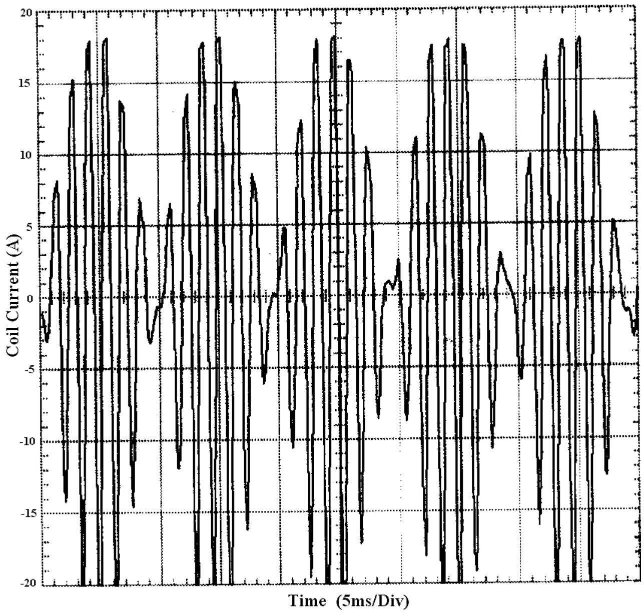

Figure 15.The waveform of series current flowing through heating coil from the real time experiment.

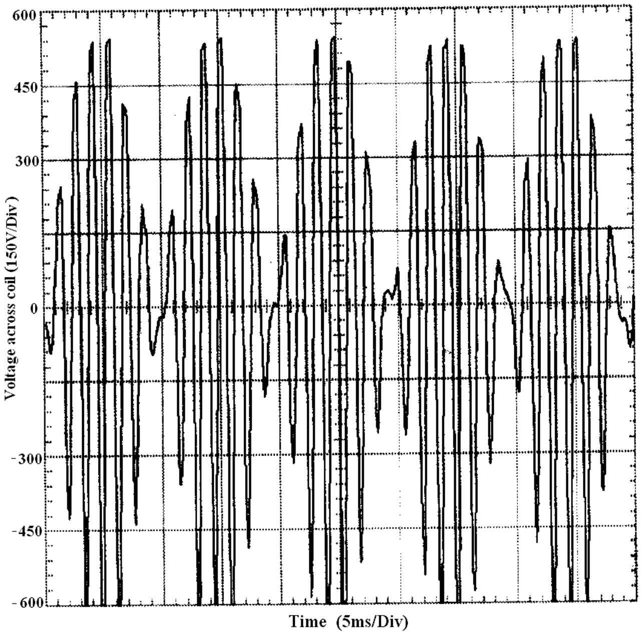

Figure 16.The waveform of voltage across heating coil from the real time experiment.

For the experimental model a heating coil is made up of litz wire with 37 strands of 33 AWG and 50 twist per feet (Sinha et al., 2010). The spiral shaped heating coil has 30 turns with inner radius of 0.02175m and outer radius of 0.16m. Some photographs of real time experimental set-up are shown below.

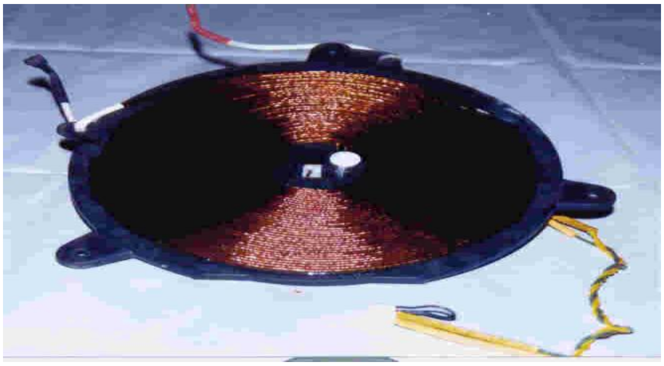

Figure 17.Heating coil.

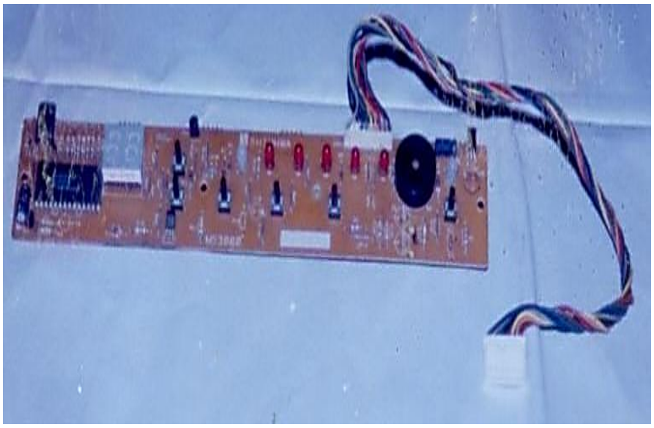

Figure18. Time control PCB.

Figure19. Assembly of induction cooker

5. Conclusions

The circuit of a half bridge series resonant IGBT-fed mirror inverter based high frequency domestic induction cooker was analyzed in this present paper. The principle of inverter operation has been presented and different waveforms are shown. PSPICE software is used to simulate the circuit and the waveforms are plotted. These results are validated with real time experimental model. After having compared the wave-forms of analytically calculated, PSPICE simulation and real time experiment, it is quite obvious that the waveforms are similar in nature. It can be conclude that half bridge series resonant mirror inverter can be used for induction cooker.

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