Modeling and Simulation of Class E Resonant Inverter for Induction Cooking Application

Vilas Bugade[1], Hemlata Joshi[2],Ekta Mishra[3]
Department of Electrical Engineering, Dr. D. Y. Patil Institute of Technology, Pimpri, Pune,India

Abstract

Induction cooking system for residential and commercial use is appreciated by increasing number of users. The characteristics of induction cooking amongst other heating method are fast heating, pollution free, efficient and safe for operating by a user. In induction cooking, the heat is produced inside the cooking pot only. There are some disadvantages like the loss, harmonic currents, poor efficiency and low power factor. The key parameters of induction cookware must be corrected, which can be very attractive in terms of commercial production also. In order to increase the efficiency, certainparameters need to be designed properly. Theclass E series resonant inverter is fabricatedwherean inductor coil is designed as per requirement. The paper deals with the software simulation in MATLAB and the hardware implementation of proposed high efficiency induction cooking plate designed for an operating frequency of 25 kHz frequency, 24 V supply to inverter circuit, 50 Hz line frequency and approximately 45 W output. Switching and resonant frequencies are assumed equal. The temperature and duty cycleare observed for high frequency induction cooker based on class E DC AC resonant inverter.

Keywords

Inductor coil, Class E resonant inverter, Pulse width modulation, Capacitor, Inductor

I. INTRODUCTION

Induction cooking is a very fast heating method producing extensively high temperature in fraction of second (>2000º F. in < 1 second). The conventional cooking methods are contact heating methods with the disadvantages like poor efficiency, high heat loss. In induction heating AC current is flowing through the inductor coil generates flux producing eddy currents to flow in the load causing electric energy gets converted to heat. The main factors for induction cooking are appropriate frequency and skin depth. In general, induction cooking system consists of an inverter for generating AC, inductor coil, insulator between coil and pan and cooking vessel. High frequency resonant inverters are used which consists of half bridge or full bridge configuration depending on the requirement of the performance and control capabilities. Half bridge topology is used due to its simplicity and compactness where as full bridge is used due to its control capabilities[3] [8].

In Induction cooking AC supply is passed through rectifier for getting required DC voltage as inverter’s input [11]. When current reaches tothe inductor coil, it has been increased to the frequency 1000 times higher than that of a wall socket. The resonant tankconsists of an inductor coil, a capacitor and MOSFET/IGBT. MOSFET/ IGBT operate at a very high frequency (20 kHz to 100 kHz) that’s why pulse width modulation technology is used in system to provide pulses to the MOSFET/IGBT.

The objective of this paper is to introduce modeling and simulation of class E resonant inverter for induction cooking application. Simulation of the system is done using MATLAB Simulink.Hardware implementation is done. The results of MATLAB Simulink and hardware setup are compared. The output power can be controlled by varying switching frequency. The pulse width modulation method regulates the output power by varying the period in which the inverter supplies high frequency current to the induction coil. The prototype is designed for an resonant frequency of 25 kHz, 50 Hz line frequency and a 45 W output power and the prototype hardware is constructed which gives approximate same output power as software[1] [3].

The paper is organized as follows, Section I gives brief introduction of the project. Section II explains system model with mathematical modeling. Section III has overview of simulation model with results. Hardware construction and results are explained in section IV. Section V has hardware results from the actual hardware setup and Conclusion in the sectionVI.

II. SYSTEM MODELLING

The heat required for cooking within the cookware needs a very high rate of change in the magnetic field and a high frequency of alternating current flowing through the induction coil. Induction cooktops contains electronic devices like inverters that increase the frequency and protects the circuit. Induction cooking appliances made up of ferrous metals because these materials are poor conductor of electricity with high resistance and large amount of the current is converted to heat. The heat used for cooking the food on an induction cooktop comes from electrical resistance and changes in the magnetic field of the cookware [6]. Series resonant inverter impedance is small at resonant frequency so maximum gain can be obtained at resonant frequency. The class E resonant inverter has characteristics of low conduction loss, high efficiency and low total harmonic distortion. Implemented hardware prototype can be developed for industrial, commercial and residentialconsumers.

Fig.1 illustrates the circuit of the proposed zero voltage switching class E resonant inverter for induction cooking [4]. The circuit contains a bridge rectifier, an electromagnetic filter and a class E resonant inverter. The pulse width modulation of the gate signal is used to observe the temperature [1][2].As shown in figure 1, the diodes D_1, D_4 operate in the positive half cycle. Mode 1 is active when switch Q is ON, the current flow the through L_r. The collector current through Q increases and Q gets off. The diodes D_2, D_3 operate during the negative half cycle.Mode 2 is active when Q is turned OFF [4][6].

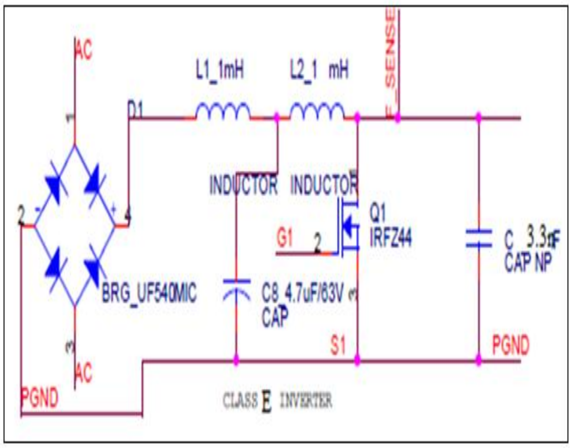

Figure 1: Implemented induction cooker with Class E Resonant Inverter

Let, Line voltage V_{in} = 24 V,
Line frequencyf_L= 50 Hz,
Switching frequencyf_s= Resonant frequency f_r=25 KHz,
Equivalent resistance = R_e, Resonant inductor = L_r,
Resonant capacitor = C_r, Duty cycle = D,
Output power Po = 48 W.

$$\Delta I_L = \frac{P_o}{V_{in}} * ripple\ factor = \frac{24*2}{24}(0.45)$$
$$= 0.90\ Amp$$

$$L_r = \frac{Vin * D}{\Delta I_L * f_r} = \frac{24*0.99}{0.9*25*10^3}$$
$$= 1.056 * 10^{-3} H$$

Depending on the resonant inductor value, resonant capacitor value is decided as follows,calculating the value of capacitor is(C),

$$C_r = \frac{1}{4\pi^2 L_r F_r^{\ 2}} = 3.3\ nF$$

After finalizing values of resonant inverter parameters using filter parameters are calculated as

$$C = \frac{I}{V}$$

$$V_C = \frac{d_i}{d_t} = \frac{1}{1/50} = 50\ V(\text{Nearly About 63v})$$

$$C = \frac{I_{max}\, T_{discharge}}{V_{max} - V_{min}} = \frac{2*10*10^{-3}}{24-2.8}$$
$$= 952 * 10^{-6}$$
$$= appox. 1000\ mF$$

III. SOFTWARESIMULATION

The circuit of class E resonant inverter with other components for induction cooking is designed in Simulink using parameters from the Table I and shown in figure 2.

Table I: Circuit parameters for the implemented system

Paramet er	Parameter Expanded	Value of the
Vin	Input Voltage	24 V
Lf	Filter Inductor	1mH
Cf	Filter Capacitance	1000mF
Lr	Resonant Inductor	1 mH
Cr	Resonant Capacitance	3.3 nF

After calculating all the circuit parameters, MATLAB Simulink model and its hardware design is carried out in figure 2**.**

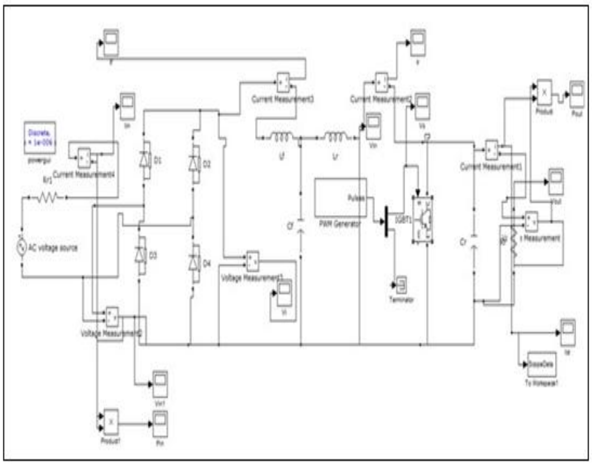

Figure 2:Modeling of implemented system in MATLAB

Following are the waveforms taken for 1 second time span.

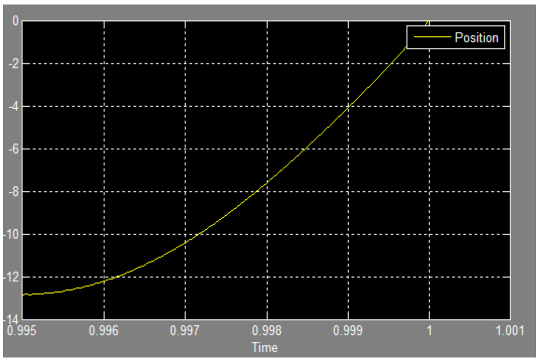

Figure 3: Input voltage (V_{in})

In figure 4 the input voltage achieved through DC source and it acts as input supply to resonant tank circuit.

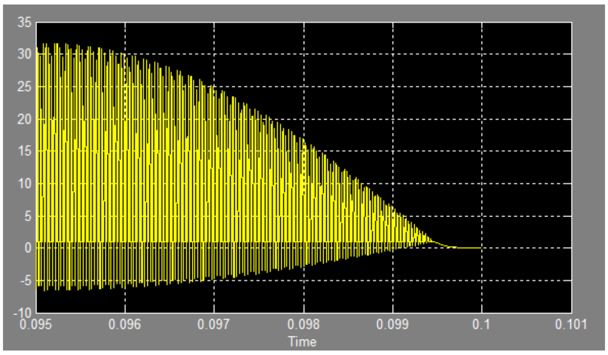

Figure 4: Output voltage (Vout)

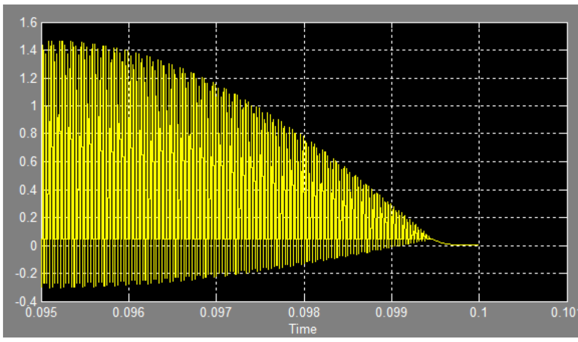

Figure 5: Resonant inductor current (ILr)

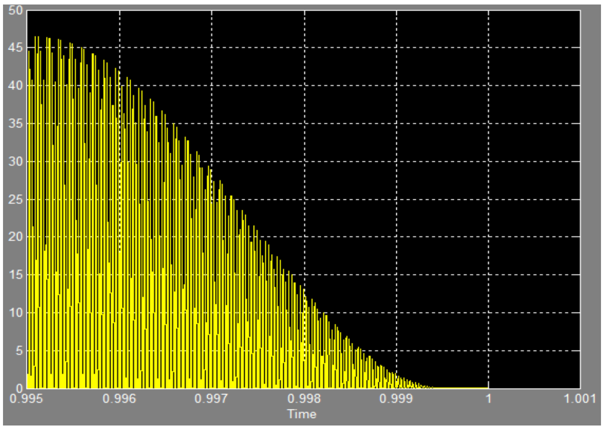

Figure 6: Output Power waveform (Pout)

The observed results from MATLAB Simulink are shown in figure 3 -6 and they are summarized in Table II.

Table II: Software results obtained with MATLAB Simulink

Parameter	Parameter expanded	Measured Value
V_{in}	Input voltage	24 V
V_{out}	Output voltage	30 V
I_r	Resonant Inductor current	1.4 A
P_{out}	Output power	48 W

By observing and comparing all the calculated values in Table I and software results in Table II, the proposed circuit design and component values for gives approximately same output power as considered. Hardware implementation is explained in third section.

IV. HARDWAREIMPLEMENTATION

The induction cooking depends on principle of electromagnetic induction to cook the food inside the pan. Figure 7 shows the functional block diagram of proposed hardware for induction cooking purpose with temperature indicator feature. Induction appliances get input from the supply voltage and get converted to DC by a rectifier. Filter removes pulsating DC from rectifier output and voltage regulator converts it to regulated voltage for further use. The inverter is supplied with the DC voltage and pulses from PIC microcontroller for triggering of MOSFET. By the time supply reaches to MOSFET, the frequency is increased to a very high level (between 20 kHz to 100 kHz).It is then supplied to the induction coil. Temperature sensor, comparator circuit and LCD are mounted for observing the changes in temperature, dutycycle [6].

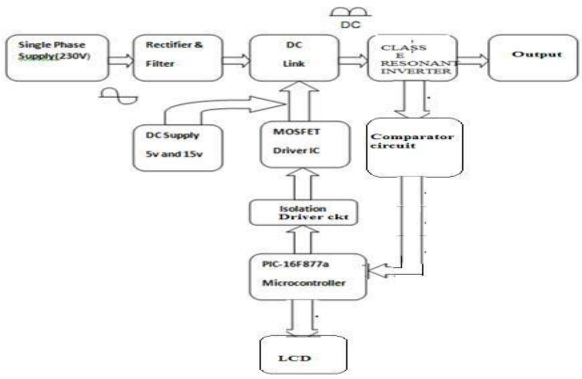

Fig.7. Functional block diagram of implemented hardware

The hardware has following parts,

A. Power Supply:

24 V DC is used for input to the single phase Class E inverter. 5v supply is requiredfor the PIC microcontroller, +5v and +12v supply is used for the gate drive circuit operation.

B. Control Circuit:

The peripheral interface controller (PIC) is the control circuit. It runs on a voltage 5V DC only which is obtained through 7805 voltageregulator.

C. Driver Circuit:

Driver circuit isolated PIC from rest of the circuit as PIC requires only 5 V. It amplifies the voltage from PIC microcontroller for triggering the gate terminal. It's about 12-20 V. In the implemented hardware TLP250 is used as gate driver.

D. InverterCircuit:

Inverter consists of perfectly constructed inductor, capacitor and MOSFET/IGBT. It produces heat in the induction cooker. The MOSFET IRF460 is chosen in the hardware.

E. Temperature Sensor:

Temperature sensor is used for displaying the temperature at different instants of time. The output voltage of the sensor is proportional to Celsius temperature. Temperature sensor LM35 is used for the sensing the temperature in the circuit.

F. ComparatorCircuit:

A comparator is included for the comparison of operating and resonant frequency. In this project, 74LS14 Schmitt trigger is used for comparing resonant and switching (operating) frequency each time when the circuit isON.

G. InductorDesign:

Inductor stores the energy in a magnetic field Inductor calculations of coil depend on the value of inductance. Inductor design is very crucial part of this project. After finding out value of inductor, the available inductors in the market are considered but not allinductors are compatible with heating procedure so inductor is constructed with the help of following material which is easily available in the market [7].

T23 ferrite core is used on with wounded copper wire has following dimensions,

- Outerdiameter=23mm=0.9inch.
- Depth(thicknessofcoil)=10mm=0.4inch.
- 30AWG=0.2546mm=Wirediameter

Theformulaforfindingoutnumberofturnsdepending oninductorvalue,outerdiameteranddepthofferritecoreis,

$$L = N^2 \mu_0 \mu_r (D/2) \ln[(8D/d) - 2]$$

Where, L = 1 mH, $\mu_0 = \mu_r = 1$,
D = loop diameter = 23mm,
d = wire diameter = 0.2543 mm,
N=Number of turns = 125

After finalizing values of resonant tank inductor and capacitor values, hardware is implemented to carry out induction heating [10].

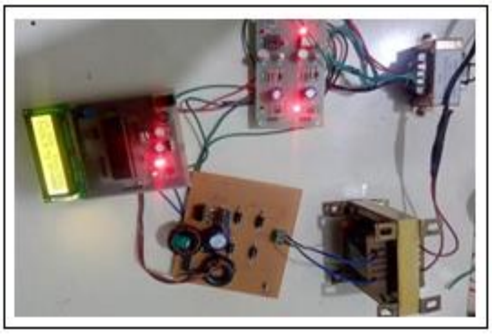

Figure 8: Pictorial view of implemented hardware

The single phase class E resonant inverter circuit needs three type of power supply+ 5v, +12v and single phase power supply. PIC microcontroller produces PWM pulse at port C. The output to TLP250 is connected to the gate and source terminal of MOSFET which is an important component in Class E series resonant inverter. For the resonant circuit, step down voltage of value 24 V AC voltage is supplied to the rectifier and the output DC voltage is considered to the capacitor bank of value 1000 mF is considered for filtering action [8]. If the input exceeds 24 V then the fuse will get damaged and circuit acts as open circuit, which protect the circuit components from high voltage. The positive DC voltage is applied to the Drain terminal of MOSFET IRF460 and negative DC voltage is applied at the source terminal of MOSFET IRF460. Control circuit and main circuit should not turn ON simultaneously, otherwise it will short circuit the source and may damage the MOSFET. There must be some short time delay to turn ON and turn OFF MOSFET device, for this purpose initially the control circuit is switched ON and later the inverter circuit is switched ON after sometime.

Due to inverter topology, the line frequency 50 Hz is increased upto 25 kHz which acts as resonant frequency andheating application takes place only when switching frequency (provided by PWM from microcontroller) and resonant frequency both are equal. Resultant AC current flows through the inductor coil. This process depends on the generated eddy current in the material to produce heat. The Inductor coil is placed around the carbon rod so that MOSFET should not get heated and heating should be maximum for the inductor. Then it is observed that as temperature goes on increasing and duty cycle decreases [1] [5].

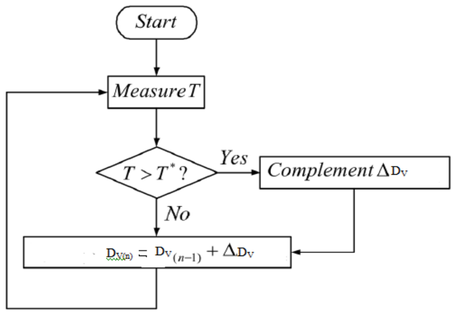

Fig.10 Flow Chart of Process

Let vessel temperature – T in ^{O}C,
Instantaneous value of vessel temperature at any instant - T* in ^{O}C, D – Duty cycle

If the vessel temperature is less than the any instantaneous temperature value then duty cycle will increase otherwise it will decrease. Initially temp is 24 ^{0}C and duty cycle is 90 %. As temperature increases, duty cycle decreases. For maximum temperature duty cycle is 0 % i.e. minimum.

V. HARDWARERESULTS

The different duty cycles are measured on digital storage oscilloscope (DSO) and LCD are listed as below,

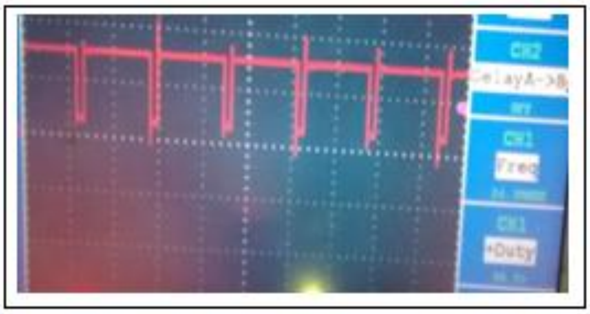

Figure 9: Waveform of 90% duty cycle

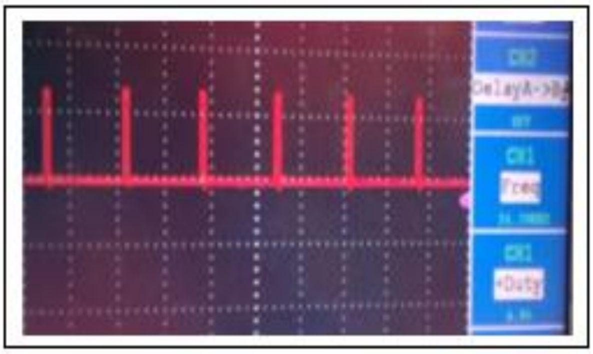

Figure 10: Waveform of 29% duty cycle

Different duty cycles, temperature readings, inductor and capacitor voltages are taken on LCD are as shown in Table III.

Table III. Temperature observation table

Duty cycle	Temperature	Ind. Vol	Cap.Vol
36%	22.9^{0} C	0	0 V
2%	34.7^{0} C	16	9 V

Hardware implementation result can be tabulated as follows,

Table IV. Hardware results

Parameter	Parameter expanded	Value
V_{in}	Input voltage	24 V
V_L	Inductor voltage	16 V
V_C	Capacitor voltage	9 V
I_r	Resonant Inductor current	2A

Mathematical calculations depending on the formulae are verified in MATLAB Simulink model and implemented hardware which shows same result. From figure 9 – 10, it proves that temperature is inversely proportional to duty cycle.

VI. CONCLUSION

Induction cooking technique isconsidered as an advanced techniqueand it is being appreciated by anincreasing number of customers. Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction phenomenon in which eddycurrents are generated within inside metal that is to be heated and it leads to the heating of the metal. Efficiency of the power electronics devices can also be upgraded by use of developed resonant inverters.

The software simulation in MATLAB simulink aswell as hardware implementation is done and their outputs arecompared.The results suggests that class E resonant inverter has advantages like low switching losses, increased efficiency, increased bandwidth, better power transfer. It can also work efficiently with non-linear and dynamic systems. It eliminates drawbacks of series and parallel resonant topology. Class E resonant inverter should be implemented in residential and commercial usage. In proposed hardware the use multiple power electronics switches is eliminated by single resonant inverter with customized inductor design as per output power requirement for Induction Cooking. It is not only limited to cooking applicationbut can be easily extended to other induction heating applications in industries, manufacturing plants. This new system may provide a valuable reference to decide environmental control strategies because induction heating is pollution free, clean, safe heating technique.

VII. ACKNOWLEDGEMENT

Thanks to Department of Electrical Engineering atDr. D. Y. Patil Institute of Technology, Pimpri, Pune, India for their kind cooperation for giving permission to use Power Electronics Laboratory and equipment's like DSO, thermostat etc. for performing testing of said analysis.

REFERENCES

[1] ChainarinEkkaravarodome, PatipongCharoenwiangnuea, KamonJirasereeamornkul, "The Simple Temperature Control for Induction Cooker based on Class-E Resonant Inverter", 10th InternationalConference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, 13th-15th July, 2013.

[2] J.Acero, J.M. Burdio, L.A. Barrangan, D.Navarro, R.lonso "The domestic induction heating appliance: an overview of research" Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition, 2008, Pp651-657.

[3] A. Beato, C. Bocchiola, and S. Frattesi, "Modeling and design of the half- bridge resonant inverter for induction," 14thMediterranean Conference on Control and Automation, Jun. 2006, pp. 1 - 6.

[4] ElzbietaSzychta, "Analysis of class E ZVS Resonant inverter", Electrical power quality and utilization journal, Vol XI, No.1, 2005.

[5] C. Charoenwiangnuea, I. Boonyaroonate, and S. Po-ngam, "The simple temperature control for the low cost, high efficiency and high power factor induction cooking," 9thECTI Conference, May 2012, pp. 1 - 4.

[6] M. K. Kazimierczuk, "Exact analysis of Class E tuned power amplifier with only one inductor and one capacitor in load network", IEEE Journal of Solid-State Circuits, Vol. SC-18, No. 2, Apr. 1983, pp. 214 - 221.

[7] William G. Hurley, John G. Kassakian, "Induction heating of circular ferromagnetic plates", IEEE Transactions on Magnetics, Vol. 15, No. 3, Jul. 1979, pp. 1174 – 1181.

[8] Sreenivasperam, VaddiRamesh, J.SriRanganayakulu," Full bridge resonant inverter for induction heating applications", International journal of Engineering Research and applications(IJERA), Vol3, issue1, January-february2013, pp.66-73

[9] Pablo Hernandez, Fernando Monterde, J. M. Burdio, "Power loss optimization of foil coils for induction cooking", IEEE Transactions on Power Electronics, Vol. 20, No. 2, Mar. 2005, pp. 261 - 267.

[10] "Transformer & Inductor design handbook, 3rdedition", by Colonel W.M. Mclyman.

[11] Vilas Bugade, Pradeepkatti "Optimal Power Flow Approach for Cognitive and Reliable Operation of Distributed Generation as Smart Grid" SGRE, Scientific Research Publications, 2017, Vol.8, 87-98.