Study of Induction Heating using Half Bridge Series Resonant Inverter

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Abstract— This paper presents study, design and implementation of an open loop induction heating system using a half bridge series resonant inverter. The resonant inverter is controlled using pulse density modulation (PDM) technique. The functionality of PDM and induction heating are presented with simulation and experimental results.

Keywords—Induction Heating, Modulation, Pulse Density Modulation, Series Resonant, Inverter, VSI

1. INTRODUCTION

Induction heating is an accurate, repeatable, efficient, clean and non-contact technique for heating any electrically conductive material. The heating is done by principle of induction which produces an electromagnetic field in a coil to transfer energy to a work piece to be heated. Both eddy current and hysteretic losses have been involved in the overall heating of the material. Heating due to eddy current is occurred from the I^2R losses caused from the resistivity of the work piece's material whereas by hysteresis the energy is produced within a part by the alternating magnetic field generated by the coil modifying the work piece's magnetic polarity. Induction heating relies on the unique characteristics of radio frequency energy, that portion of the electromagnetic spectrum below infrared and microwave energy. Since heat is transferred to the product via electromagnetic waves, the work piece never comes into direct contact with any flame, the inductor itself does not get hot, and there is no product contamination. The process becomes very repeatable and controllable for a correctly built set up.

Although the basic principles of induction heating are well known, modern advances in solid state technology have made induction heating a remarkably simple and cost-effective heating method. It finds applications in both domestic and industrial areas as it can generate heating effect with temperatures as low as 100^0C and as high as 3000^0C. The applications which involve joining, materials testing, domestic cooking, heat treating, soldering, pre-heating for welding, scaling, brazing and curing. A general circuit configuration for induction heating using a half bridge series resonant inverter is shown Fig.1. The resonant inverter is used for high frequency supply generation for the resonant tank circuit. The power density and the circuit performance of an inverter get improved with increasing switching frequency. It makes harmonic filtering easier, because of reduced audible noise. However, higher switching frequencies are limited by the switching stresses on the power semiconductor devices, switching losses and electromagnetic interference (EMI).
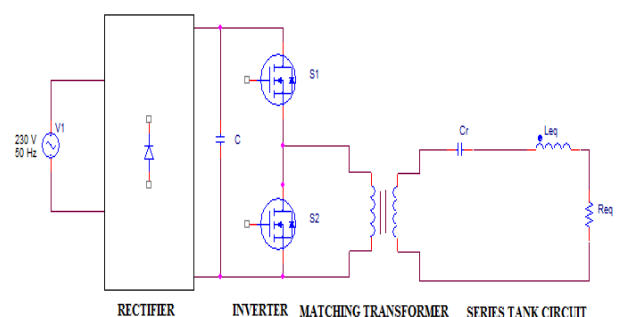

Fig.1. General circuit configuration of induction heatiing using half bridge series resonant inverter

In order to achieve high frequency operation with reduced switching losses and EMI, various soft-switched resonant

dc-ac converters have been proposed [1- 2] which use either zero-voltage switching (ZVS) or zero-current switching (ZCS). The work coil and the work piece are represented as a transformer with single turn secondary short circuited.

The output voltage and power of the resonant inverters have been traditionally controlled by Pulse frequency modulation (PFM) technique [1, 5], which involves variable switching frequencies. But it has several drawbacks like wide noise spectrum which makes it difficult to control EMI. The design of filter becomes difficult and the utilization of magnetic component becomes poor. To overcome these problems associated with PFM, fixed frequency or narrow frequency range control techniques are required. The two fixed frequency control techniques for the resonant inverters are the Phase shift (PS) [4-10] and Asymmetrical duty cycle (ADC) control [5]. In Phase shift (PS) control technique, the output power is controlled by phase shifting the sequences of conduction for the switches and it can be used only for the full bridge topology. Asymmetrical duty cycle (ADC) control technique is used in half bridge as well as full bridge topologies and it is based on unequal duty-cycle operation of the switches in the inverter. Both of these fixed frequency control techniques do not guarantee soft switching of the switches for a wide range of output power [6]. A High-frequency soft-switching ac conversion circuit with dual-mode PWM/PDM control strategy for high-power IH applications is presented in literature. This paper presents study, design and implementation of an induction heating system using a half bridge series resonant inverter with PDM technique. Section II of the paper describes the basic principle of induction heating. The operation of half bridge resonant inverter and PDM technique are discussed in section III. Section IV presents the design implementation and results of PSpice simulation and hardware prototype. The conclusion is presented in section V.

2. PRINCIPLE OF INDUCTION HEATING

The basic principle of induction heating is to heat an electric conductor such as iron or steel placed in the inductor by induced eddy current caused by electromagnetic induction and hysteresis heat loss which is generated by vibration and friction of the molecules in the magnetic material under high frequency AC magnetic flux. In many of the induction heating applications, the work pieces are of cylindrical in shape and are heated by being placed inside of coils with one or more turns. When the coil is fed with an alternating current, it induces eddy currents in the work piece and this gives rise to heating effect. But most of these heat generated in the work piece have been concentrated on the peripheral layer of thickness δ, called skin depth and is given by the equation

$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$ where, μ, ρ and f are the magnetic permeability, electrical resistivity of the work piece and the frequency of the alternating magnetic field respectively. If the frequency of the alternating magnetic field is higher, then the depth to which it gets heated up is less. So, high frequency is used for heating the work pieces of comparatively less thickness whereas low or medium frequency supplies are used for heating thick work pieces by several cycles of magnetization and demagnetization.

3. OPEARTION OF HALF BRIDGE RESONANT INVERTER AND PULSE DENSITY MODULATION TECHNIQUE

The series resonant half bridge inverter achieves the best balance between cost and performance considering domestic and industrial induction heating applications. The operation of the half bridge series inverter is presented based on the envelope of the resonant current. A half bridge series resonant inverter is shown in Fig. 2.
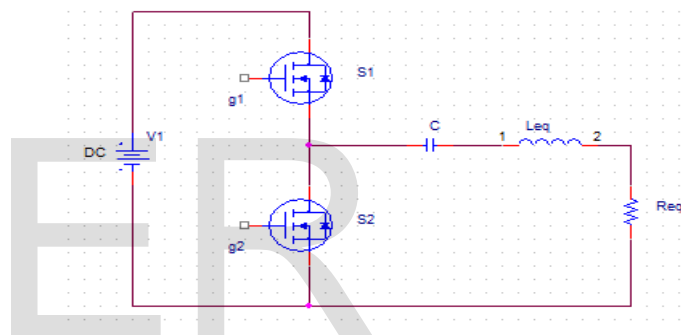

Fig.2. A half bridge series resonant inverter

A square wave voltage with an angular frequency of ω and amplitude of V_1 applied to the series RLC circuit. The KVL expression is given by (1).

$$L_{eq} \frac{di_1}{dt} + \frac{1}{C} \int i_1 \, dt + R_{eq} i_1 = \frac{4V_1}{\pi} sin\omega t$$
(1)

where i_1 is the current which flows in the loop.

The resonant frequency ω_r of the circuit is given by (2)
$$\omega_r = \frac{1}{\sqrt{L_{eq}*C_r}}$$

(2)

The current i_1 at resonant frequency is given by

$$i_1 = \frac{4V_1}{\pi R_{eq}} \left(1 - e^{-\frac{R_{eq}*t}{2L_{eq}}} \right) sin\omega_r t$$
(3)

The resonant current exhibits the first order response although

the series resonant circuit is a second order system. An envelope of the resonant current i_E is developed and given by

$$i_E(t) = I_{max}\left(1 - e^{-\frac{t}{\tau}}\right) + I_{E_0} e^{-\frac{t}{\tau}} \qquad 0 \le t < T_{on}$$
(4)

$$i_E(t) = i_E(T_{on})\, e^{-\frac{t}{\tau}} \qquad\qquad T_{on} \le t < \tau$$
(5)

where,

$$\tau = \frac{2L_{eq}}{R_{eq}} = \frac{2Q}{\omega_r} \qquad\qquad (6)$$

and called the time constant of the envelope and Q is the quality factor of the series resonant circuit.

There are four modes of operation of the half bridge series inverter which are presented based on the envelope of the resonant current.

Mode I: The resonant current flows in opposite direction through D1. S_1 is turned on and current flows through S_1. The resonant circuit accumulates energy during this time.

Mode II: S_1 is turned off. Current freewheels through the diode D_2. S_2 is turned on. As S_2 remains at zero voltage no switching loss takes place at turn on. After turning off S_1, the resonant current passes for a short period through the snubber capacitor C_1 before freewheeling to D_2.

Mode III: Current freely resonates. Current flows in reverse direction through S_2. Here, C_r serves as the source of voltage.

Mode IV: S_2 is turned off. Current starts freewheeling through D_1. The energy of the resonant circuit is converted to V_1 by passing through D_1. Before freewheeling through D_1, the resonant current passes through C_r.

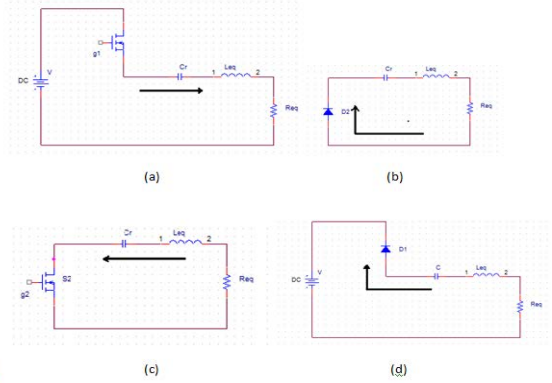The equivalent circuits for different modes of operation are shown in Fig 3(a), (b), (c) and (d) respectively.

Fig.3.Modes of operation (a) Mode I. (b) Mode II. (c)Mode III (d) Mode IV

The switches start conducting when the load current crosses zero during the modes I and III. The average output power of the circuit can be obtained from (7).

$$P = \frac{1}{T}\int_0^{T_{on}} \frac{4}{\pi} V_1 \sin \omega_r t * i_E(t)\sin(\omega_r t - \varphi)\,dt \quad (7)$$

From (7) the output power can be expressed as

$$P = P_{max} * \left(\frac{T_{on}}{T} + \frac{\tau}{T}\left(\frac{1 - e^{-\frac{T_{on}}{\tau}}}{1 - e^{-\frac{T}{\tau}}} \right) * \left(e^{-\frac{T_{on}}{\tau}} - e^{-\frac{T}{\tau}} \right) \right) 8)$$

Case 1: $\ll \tau$, then the amplitude of the resonant current is in proportion to the pulse density. The output power becomes

$$\lim_{\tau \to \infty} P = P_{max} * \left(\frac{T_{on}}{T}\right)^2$$
(9)

Case 2: $\gg \tau$, then the resonant current becomes discontinuous and the output power is in proportion to the pulse density.

$$\lim_{\tau \to 0} P = P_{max} * \frac{T_{on}}{T}$$
(10)

The expression (9) and (10) conclude that the output power can be controlled by controlling the duty ratio.

The control of power semiconductor devices of the half bridge series inverter is carried out using PDM technique. The control method is discussed below. Next section presents the design implementation of the half bridge series inverter with PDM technique and results.

A. Control Method

In PDM technique [18], the switching frequency of the inverter is kept constant and it is chosen slightly greater than the load resonant frequency in order to reduce the switching losses. Pulses for the switches S1 and S2 are generated at the zero crossing of current. Using the pulse

density modulation technique, the number of pulses to the switches is being controlled and thus the power delivered to the resonant tank circuit. A high frequency (25 kHz) and a low frequency (2 kHz) carrier signals are logically compared with a constant control signal to generate the PDM pulses for the switches.

4. DESIGN IMPLEMENTATION

The design and implementation of the circuit are carried out in

Pspice and Hardware setup.

A. Pspice Simulation and Results

The Pspice model of the circuit is shown in Fig.4. The circuit consists of a full bridge rectifier, half bridge series resonant circuit with a matching transformer and control logic. For doing the simulation in PSPICE the coil and work piece system has been modeled by taking the equivalent transformer modeling and the corresponding values for resistance and inductance obtained are R_{eq} and L_{eq} respectively. The design specifications of the circuit are listed in Table I.

Table I Design Specifications

Rating/Components		Values
Power	P	500W
Supply voltage	V_S	230V
Resonant capacitor	C_r	8uF
Equivalent inductance	L_{eq}	5.48uH
Equivalent resistance	R_{eq}	0.568ohm
Snubber capacitor	C_1, C_2	2 x 22nF
Switching devices(MOSFETs)	S_1 & S_2	IRFP460
Switching frequency	f_{sw}	25kHz

Fig.5 presents the input supply and capacitor filter output of full bridge rectifier. The output voltage across the secondary terminals of the transformer is shown in Fig.6. Fig.7 demonstrates the envelope of the current in the resonant circuit. Fig.8 (a) and (b) present the current waveform corresponding to 75% and 25% of duty ratio in PDM respectively. It is observed that density of current is more with 75% duty ratio compared to 25% duty ratio.
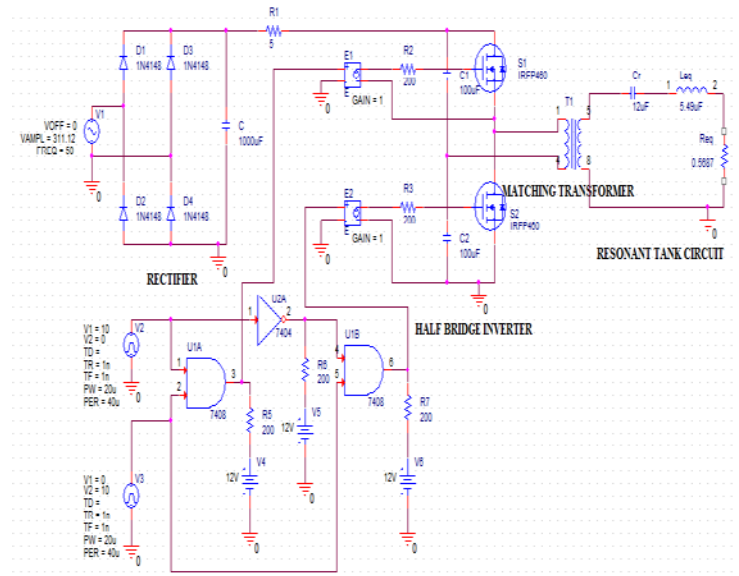

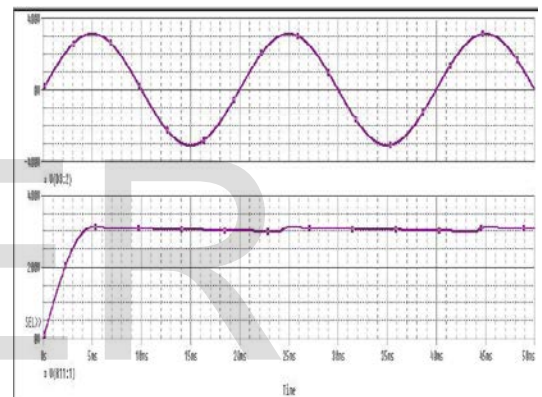Fig.4. Pspice simulation model of Half bridge series resonant inverter
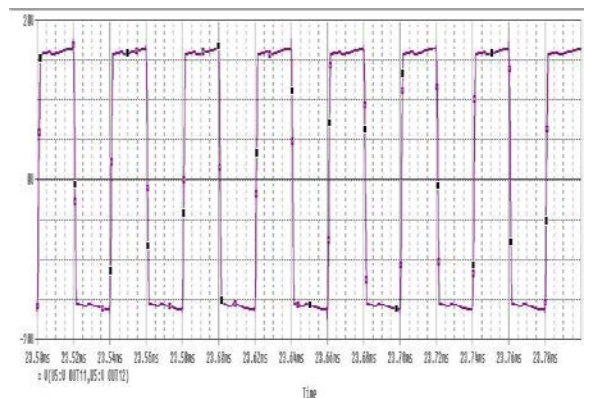

Fig.5.Input supply voltage and capacitor filter output

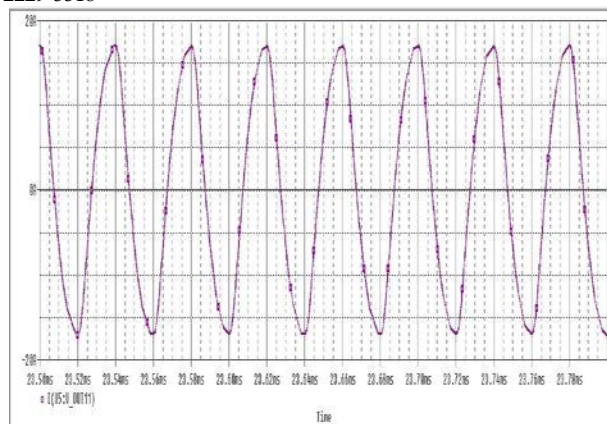Fig.6. Output voltage across the secondary terminals of the transformer

Fig.7. Current in the tank circuit

(a)

(b)

Fig.8. current corresponding to (a)75% duty ratio and
(b)25% duty ratio of the control pulse

B. Hardware Setup and Results

A 500W half bridge series resonant inverter has been designed and developed. The ac supply voltage of 230V, 50Hz has been rectified by using full bridge rectifier module D10SBA60 and then filtered by a capacitor filter of 1000µF. The dc voltage thus generated is then applied to the half bridge inverter composed of two IRFP460 power MOSFETs. In order to reduce the voltage spikes in the switches snubber capacitors of value 22nF are being used. Gate pulses of frequency 25 kHz for the two MOSFETs are produced by the PIC microcontroller (PIC18f452) and are given through the driver IC of TLP250.

The high frequency ac supply thus generated is applied to the series resonant tank circuit via the matching transformer of turns ratio 6:1. The matching transformer is made up of two sets of E65/32/27 ferrite core and wounded with 18SWG and 14SWG copper wires on primary and secondary side respectively. The under damped resonant circuit is composed of coil, work piece and the resonant capacitor which are connected in series. Polypropylene capacitors are connected accordingly to have a capacitance value of 8µF. The coil is made up of 12 SWG copper wire having number of turns 22.

The series tank circuit is connected to the half bridge inverter through a matching transformer in order to reduce the current through the switches. The complete experimental setup with heated up material is shown in Fig. 15. The control pulses obtained from TLP250 for S1 and S2 switches are shown in Fig. 10. Fig. 11 presents the output voltage measured from transformer secondary with 6:1 step down ratio. The output voltage obtained from half bridge series inverter and current in the resonant circuit are illustrated in Fig.12.   Fig. 13 and Fig. 14 show the resonant tank circuit currents corresponding to 75% and 25% duty ratio of PDM respectively. It is observed that density of high frequency resonant current is more with 75% duty compared to 25% duty. This high frequency and high density current flows through the coil, work piece and the resonant capacitor which are connected in series. The temperature of the material was measured from the experimental setup by using Flir thermal imager and the variation in temperature with voltage and frequency. The values for 100% PDM, 75% PDM and 25% PDM are plotted by using the software ORIGIN and are shown in Fig. 15 (a) and (b) respectively. It is observed that the temperature varies with voltage in an approximate linear with different PDM duty ratio. Whereas the temperature variation with frequency it is nonlinear and at resonant frequency it reaches at different peak for different PDM duty ratio. The experimental prototype is shown in Fig. 16.
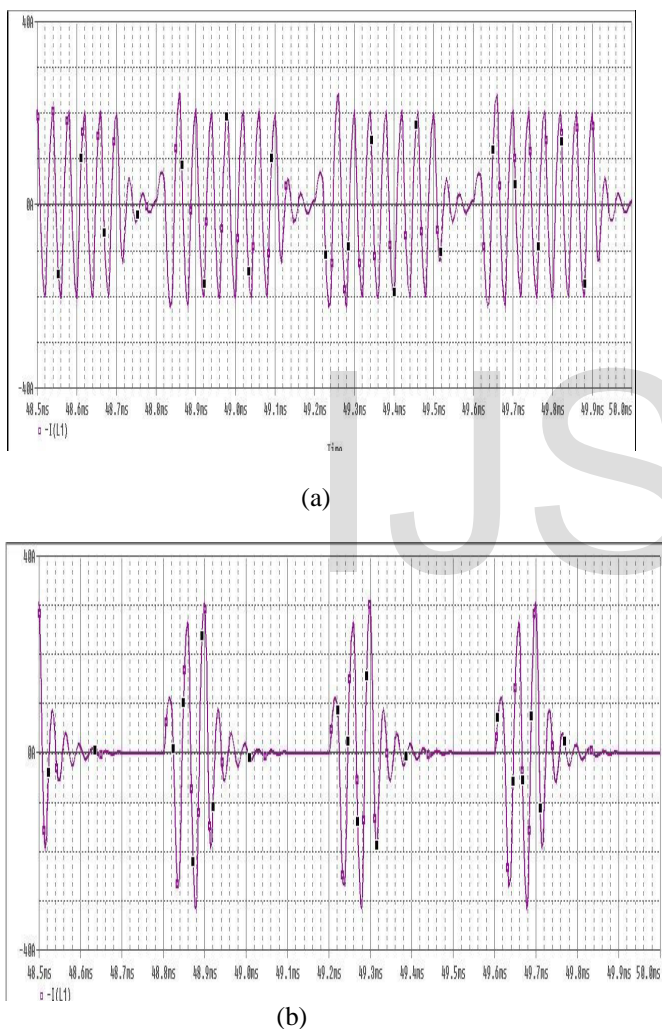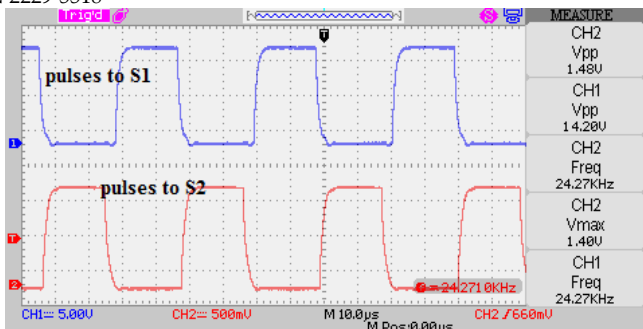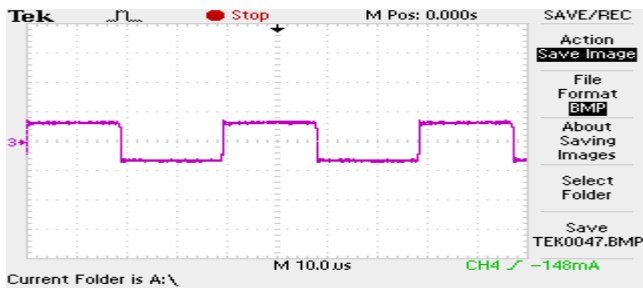
Fig.10. Pulses to the switches S1 and S2

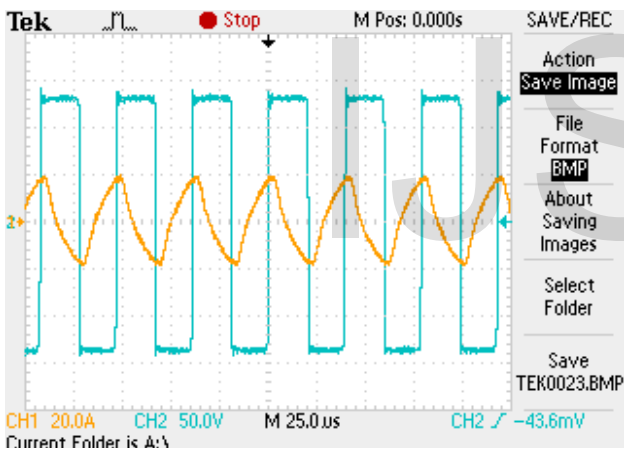Fig.11.Secondary output voltage of the transformer
(50V/div)

Fig.12.Half bridge resonant inverter output voltage
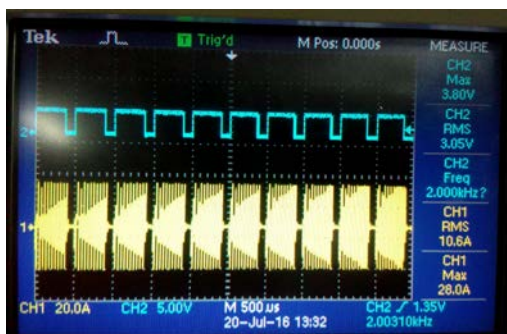and current

Fig.13. Control pulse of 75% duty ratio and the
corresponding tank circuit current

Fig.14. Control pulse of 25% duty ratio and the
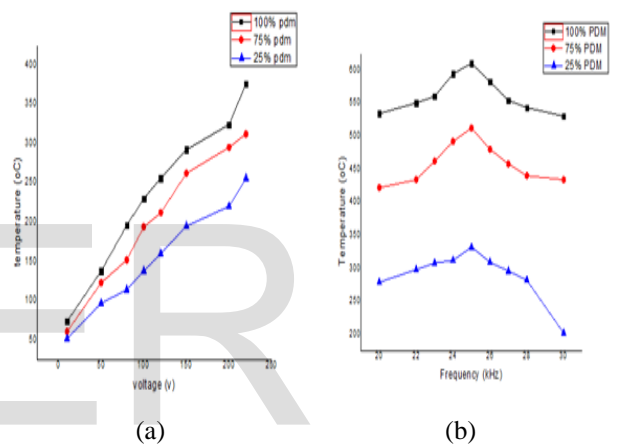corresponding tank circuit current

(a)   (b)

Fig.16. Graphs showing the variation of temperature for
100% PDM,75% PDM and 25% PDM with (a) supply
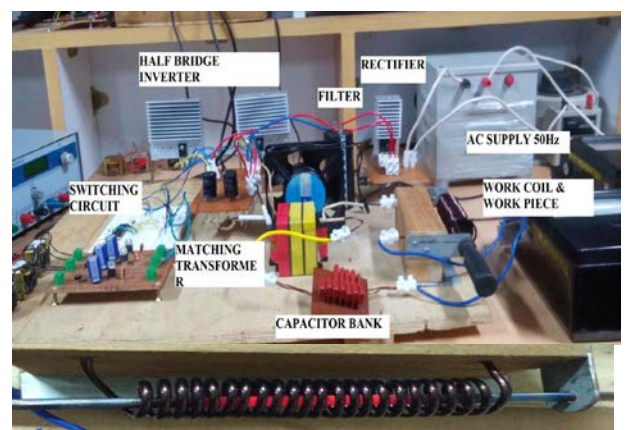voltage and (b) frequency

Fig.15. Hardware setup with the heated up material

5. CONCLUSION

This paper presents design and implementation of an induction heating system with PDM technique using half bridge series resonant inverter. The principle of operation of the resonant inverter circuit, PDM technique and induction heating are analyzed. The design is presented with PSPICE and hardware model. Simulation and experimental results demonstrate the operation of half bridge series inverter and power control in induction heating system by PDM duty cycle variation without the change in frequency.

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