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Design and Implementation of an Induction Heating System for Brittle Sheet Metals

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Abstract:

In this paper, the application of metal heating process by means of electromagnetic field is proposed. Electromagnetic sheet metal heating is a process of heating sheet metal without mechanical contact using electromagnetic field. In this process, heating of the work piece takes place by the electric current that is induced in a coil by using a resonance tank circuit. Analysis and modelling of an induction heating system and some experiments and their results are represented.

Keywords: Induction heating, sheet metal heating, resonance circuits

INTRODUCTION

In recent years, there has been high demand and increasing interest for different heating technologies. Electromagnetic heating is one of these significant techniques due to its advantages. It is a high speed process and needs only a few seconds or minutes to heat metal parts. Sheet metal heating is one of the most valuable application areas of electromagnetic heating [1].

Heating electrically conducting materials is one of the important processes in many industries. Electrical heating is preferred over conventional heating methods using fuel. This preferenceis due to certain advantages of electric heating such as high efficiency, low cost, free from pollution, compactness, quick start up and shut down and easy temperature control. Due to these advantages electric heating is more convenient. For an extensive use of these advantages, it is necessary to develop a suitable induction heater [7].

Induction heating process, which is a heat treatment based on electromagnetic principles, is widely used in many places today. The first heating application with this method was made in England in 1897. Induction heating is widely used for processing of metals (hardening and annealing), deformation-free heating (forging, squeezing, bending and punching), soldering, shrinking, coating, melting, crystal growth, cap sealing and Carbon vapor deposition [4].Electric cookers used in homes are an important example of the use areas of the induction heating system. The application area varies according to the frequency used and the frequency of the induction furnaces can be varied from 10Hz to 800 kHz. Induction heating and heat treatment are divided into UHF, HF, RF, and MFworking frequencies according to the frequency of the alternating current.

Induction machines and induction heating technology are currently the technology of metallic materials with high heating efficiency, high speed and environmental protection. In various industries, metal is widely used in heat treatment, hot assembly and welding, melting processes. This process not only heats the work piece as a whole, it can also heat the work piece locally [5].

Design of the induction heating system depends mainly on general calculations and on the experience. This makes the design expensive, tedious, and a timeconsuming task. In this paper, an approach is considered to design an induction heater coil and determines the characteristics of its power supply, that is suitable to ensure the following requirements; "Heating a required part of a certain sheet metal to the required temperature in a required time interval". The suggested approach analysis leads to design the induction heating system including the induction coil and its power source by determining the following [5]:

1- The suitable induction coil shape.
2- The required induction tank circuit.
3- The required frequency of the induction heating system

Resonant load inverters have been designed to allow theoutput power frequency to change during a heating cycle, in order to maintain tuning to the natural frequency of thework coil. The power applied depends only on the limits of the inverter voltages and currents [8].

During induction heating, the Eddy current flows inversely to the first induction current. The metal heats up with the help of Eddy currents. Therefore, every factor that affects Eddy currents must be considered. These usually cover the physical and electrical properties of the metal used. But at high frequencies, the skin effect needs to be taken into account. The skin effect or depth of penetration is the measure of how much the alternating current has penetrated into the metal. As the frequency increases, the current approaches the surface by moving away from the center of the metal; the less it populates the deeper it becomes. The flow of current through the surface of the metal causes the effective resistance of the metal to increase [6].

Analysis of the electromagnetic sheet metal heating is a very complex process and several recent studies propose numerical procedure explain working principles of this process. Through magnetic induction principle induction heaters are used to heat metals. Usually a typical induction heater system is designed with a topology formed by an AC – DC converter (rectifier), a DC – AC converter (inverter) and a resonant circuit. In next sections the working principles of the electromagnetic heating system are studied. Besides the induction heating system analysis and modelling of system in presented.

This paper is organized as follows:Section 2 shows the configuration of induction heating system and its working principle. Section 3 analyzes the basic operation and main parameters and design considerations of the inverter. Section 4 describes inverter switching sequence and the control strategy.Section 5 validates the simulation reports and finally in section 6 experimental results and conclusions are given.

Working principles of system

The induction heating system basically consists of a resonance circuit consisting of a rectifier circuit, an inverter circuit, a coil, a capacitor and a resistor. Resonant circuits are used to transfer the energy to the piece to be heated in the most appropriate and efficient way. One of the standard methods used to generate the high frequency current required in induction heating is a bridge type inverter [2]. Bridge type inverters complicate circuit structure and their cost is high due to the number of devices. However, they have advantages such as wide power control range, high efficiency, and high output power [3].

The system schematic used in this work is shown in Figure 1. The dc bus voltage is typically obtained by rectification of ac line voltages.

Since induction heating systems is an inductive load, the load resonance circuit is obtained by using a heating coil with a capacitor. By adding a series or parallel capacitor to the coil, the system is operated as a load resonance inverter. The inverter may be fed by current or voltage source.

In order to heat a specific work piece, input voltage and current of system must be defined according to materials specific heat, its mass, its density and scales. The inverter switches are turned on and off at high frequency generating a square wave voltage across the load. This frequency and the resonance frequency are chosen to be close. The heating coil forms the inductor part of the resonant circuit.

The resonant current creates an electromagnetic field that, in turn, induces eddy currents on the metal surface and the heat treatment takes place.

In fact, the arrangement of the coil and the work piece can be considered as an electric transformer. The coil forms the primary in the place where the electric energy is fed, and the work piece forms secondary with a short circuit.

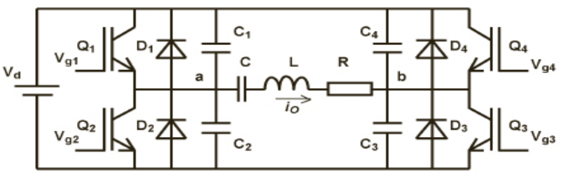

Figure 1. Schematic diagram of circuit

Design considerations

In this work computer design, simulation and implementation of an induction heating system, which can be used in industrial applications has been carried out.

The heating rate of the work piece or furnace depends on the frequency and magnitude of the induced current, the specific heat of the material, the magnetic permeability of the material, and the resistance of the material. The operating frequency affects the energy transfer rate as well as the heating depth in the work piece. The size of the work piece and the heating application determine the operating frequency of the induction heating system.

The minimum value of the impedance is achieved at the resonance condition and this allows the highest power to be transferred to the load. The resonant frequency of RLC circuit consisting of equivalent resistance, equivalent inductance and resonance capacitor is

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

In this work, heating of a 20 cm x 30 cm x 0.5 mm aluminum piece with a maximum output power of 1 kW was aimed. The amount of heat is calculated as

$$Q = mc\,\Delta T \text{(Calories)} \quad (2)$$

where Q is the heat achieved from the electromagnetic process in Joule, m is the mass of the material, c is the … and ΔT is ….

The mass of aforementioned work piece is 90 gr and aluminum material sheet's melting point and specific heat values are 660°C and 0.902 J/g°C respectively. However melting was not aimed in this study therefore heating up to around 300°C was arranged. So the energy required to heat up the work piece is calculated as 21789 Joule.

Operation at high frequency requires one to pay attention to skin effect concept. Skin depth (δ) or depth of the heated layer can be calculated as

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}}\delta = \sqrt{\frac{2\rho}{\mu\omega}} \quad (2)$$

where ρ is the resistivity of the material which is equal to $2.65\,10^{-8}2.65\,10^{-8}$ Ωm for aluminum, μ is relative permeability (1.0002) and ω is the frequency, which is equal to $2\pi 13 = 81.682\pi 13 = 81.68$ krad/s in this application. The depth of the heated layer or skin depth is calculated to be 719.21µm for this application.

Bus voltage for this application was selected to be 100 V. Therefore, the load is subjected to approximately 100 V-amplitude square wave voltage. The rms of the fundamental is approximately 90 V then. As the load operated in resonance, the displacement factor is unity and the rms of the current is calculated as

$$I = \frac{P}{V} = \frac{1000}{90} = 11.1 \text{ A} \quad (3)$$

By using these voltage and current values 600 V, 40 A IGBT devices can be safely selected for the application. Rectifier diodes can be lower rated such as 10 A. However, in case of sudden voltage drops or current increases due to frequency changes, higher capacity devices should be used. Also, in order to have a more powerful system for the future work, devices listed in Table 1 are used. Table 1 also lists the other circuit parameters.

It is so important to produce PWM signals for switching operation of the system. In this work TMS 320F28335 microprocessor developed by TI Company is used as Digital Signal Processor (DSP) in order to produce gate signals.

Simulation

The system was simulated in ANYSYS Simplorer. The 100-V dc bus voltage was obtained from a 50 Hz line by using a three-phase full bridge. Parameters calculated in the design section were used in the simulations. Figure 4 shows the circuit model and Figure 5 and 6 show the operation waveforms at 13 kHz.

Table 1. Devices and their model numbers

Device	Model / Value
Power Supply (including the rectifier)	500 VDC 50ADC output 400 VAC, 50 Hz, 3-phase input
IGBT	SKM150GB12T4 150A 1200V IGBT modules
IGBT Drivers	DA102D2 IGBT LMY
Operating Frequency (kHz)	13 kHz
Resonance capacitor	45μF
Resonance inductance	3μH
DSP	TMS 320F28335

Fig. 2 and Fig. 3 show the hardware developed in the laboratory.

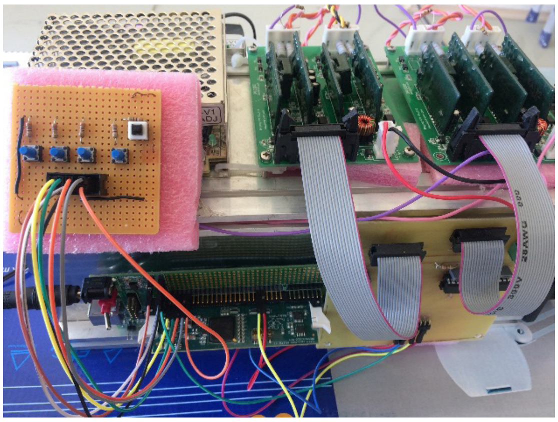

Figure 2. Switches triggered with PWM using IGBT driver circuits controlled by DSP

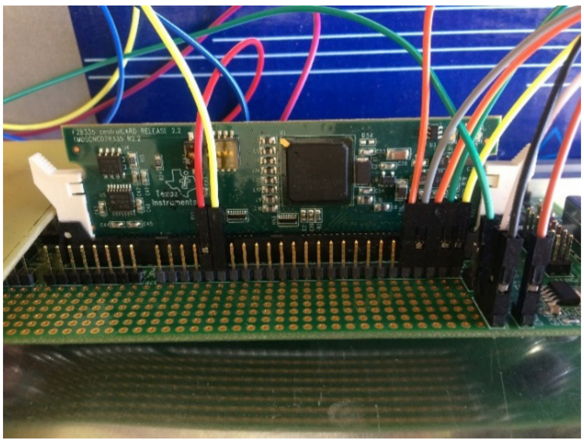

Figure 3. DSP TMS 320F28335 control card

Experimental results

The designed system was built and tested. The coil parameters are given in Table 2. A pancake shaped coil was used to establish the resonance circuit.

The measured results are given in Table 2. The output waveforms of the system are shown in Figure 7.

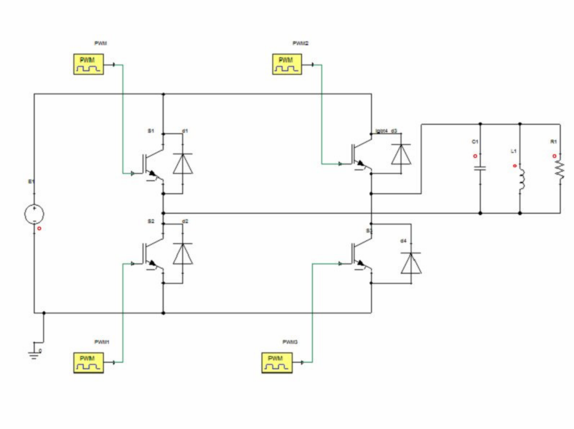

Figure 4. Simulink model of induction heating system

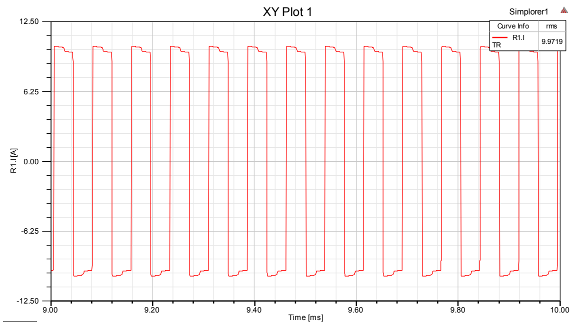

Figure 5. Current waveforms created in resonance inductor (simulation).

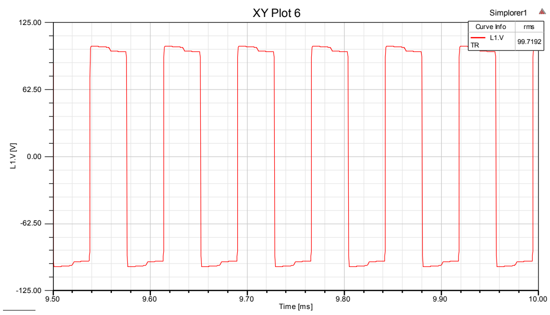

Figure 6. Output voltage wave forms created in resonance inductor (simulation).

Table 2. Induction coil characteristics

Type of material	Copper
Type of dielectric	Hard silicon
Number of turns	8
External coil radius	10 cm
Internal coil radius	1 cm
inductance	3 uH

Table 2. Input voltage and input current of induction heating system

Input Voltage (V)	Input current (A)	Output power (W)	Power factor
50	3	?	?
60	4.2		
70	6		
100	8		
110	9.8		

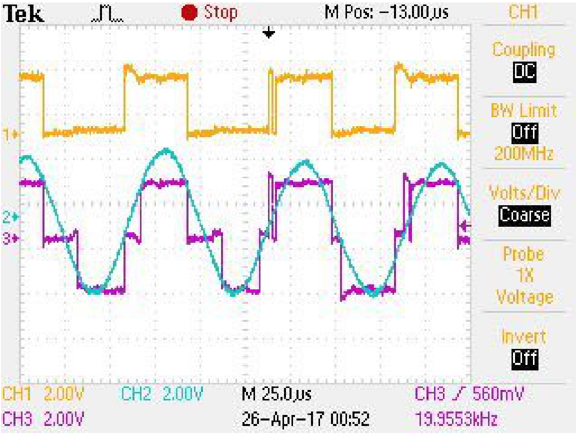

Figure 7. Waveforms of output voltage and current of inverter: (yellow) Voltage across IGBTs, (blue) resonance current and (magenta) voltage across the tank

Figure 8 shows the temperature variation of the heated material over a period of 200 minutes. The measurement was done by using an infrared thermometer as shown in Figure 9.

Figure 9 shows the picture taken by FLIR thermal camera.

CONCLUSION

Heating of an aluminum sheet by electromagnetic field is a process that draws a lot of attention recently. In this work a system was designed and developed for a 1 kW power level. The whole design process, simulation results and experimental results obtained on a laboratory prototype are given.

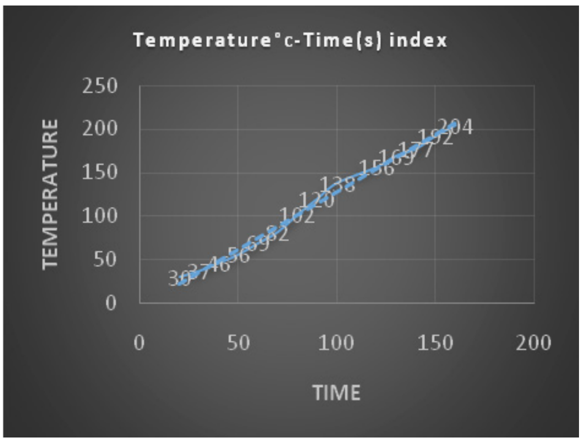

Figure 8. Temperature variation of the heated material

Figure 8. Material to be heated by induction coil

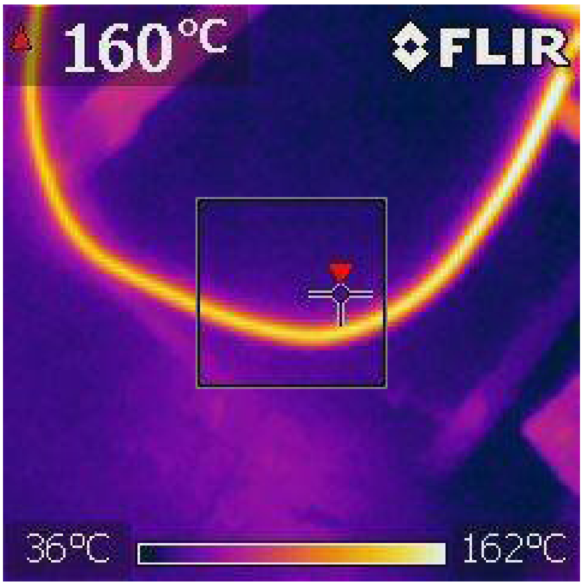

Figure 9. Heated metal measured by thermal camera

Figure 10. Thermal camera to measure heat increment

Table 4. Temperature of aluminum

Time (s)	Temperature (°C)
30	57.9
50	61.6
65	94.7
80	102
95	120
110	138
120	156
140	177.8
150	192
160	204

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