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HALF BRIDGE INDUCTIVE HEATER

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Abstract

Induction heating performs contactless, efficient and fast heating of conductive materials, therefore became one of the preferred heating procedure in industrial, domestic and medical applications. During induction heating the high-frequency alternating currents that heat the material are induced by means of electromagnetic induction. The material to be heated is placed inside the time-varying magnetic field generated by applying a high-frequency alternating current to an induction coil. The alternating electromagnetic field induces eddy currents in the workpiece, resulting resistive losses, which then heat the material. This paper describes the design of a power electronic converter circuit for induction heating equipment and presents the obtained results. The realized circuit is a low power half bridge resonant inverter which uses power MOS transistors and adequate driver circuits.

Keywords: induction heating, power inverter, power electronics, time-varying magnetic field

1. Introduction

Induction heating is a fast, efficient, precise and repeatable non-contact method for heating electrically-conductive materials. This technology started being introduced for industrial applications in the 1960s. Since then, it has constantly been developed and generated in innovative solutions [12].

The demand for better quality, safe and less energy consuming products is rising [1]. The heated material may be a metal such as copper, aluminum, brass, steel, or it can be a semiconductor material such as carbon, graphite or silicon carbide. It's possible to heat non-conductive materials such as plastics or glass, in this case a so called electrically-conductive susceptor is used (usually graphite), which then transfers the heat to the non-conducting material.

Induction heating is used in domestic and industrial applications where temperatures are between 100 ºC and 3000 °C, the heating process can be short (seconds) or long (weeks, months) [2,3,4]. An induction heating system includes an induction power supply which converts AC line power (or a DC voltage obtained from this) to a higher frequency alternating current and work coil creating an electromagnetic field within the coil [6].

The work piece is placed in that field which induces an alternating current in the work piece. Heat is generated in the work piece due to the I^2R losses of the work piece's material resistivity [11].

Generally, the power supplies are with semiconductor switching devices which operate in Hard Switch Mode in various types of PWM DC-DC converters and DC-AC inverter topologies. The main topologies are half-bridge or full-bridge configured resonant or quasi-resonant inverters. In all of these methods a specific current is turned on or off at a specific level of voltage whenever switching occurs.

2. Induction heating principle

The basic electromagnetic phenomena of induction heating are based on two fundamental laws of physics: the Lenz law and the Joule law [1].

Induction heating is comprised of three basic factors: electromagnetic induction, the skin effect and heat transfer. An alternating voltage applied to an induction coil (solenoid coil) will result in an alternating current in the coil circuit. An alternating coil current will produce in its surroundings a time-variable magnetic field that has the same frequency as the coil current. This magnetic fields induces eddy currents in the workpiece located inside the coil [12].

These currents have the same frequency as the coil current; however their direction is opposite to the coil current [4]. These currents produce heat by Joule effect. In addition to this, magnetic hysteresis creates additional heating in ferromagnetic materials, usually far smaller than the energy generated by induction current.

A conventional induction heating system that consists of a cylindrical load surrounded by a multiturn induction coil is shown in fig. 1.

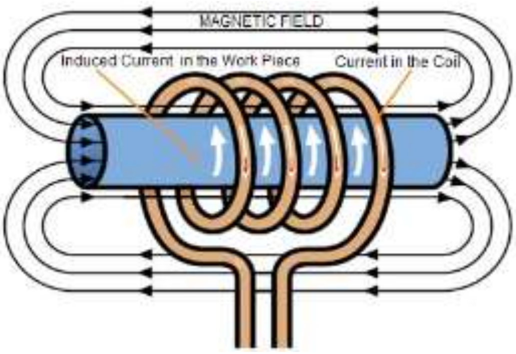

Fig. 1: The principle of conventional inductive heating

The typical operating frequencies of these systems ranges from line frequency, e.g. industrial and high power applications, up to a few MHz's, typical of medical systems [12].

When an alternating current flows through a conductor, the current distribution is not uniform, The maximum value of current density will always be located on the surface of the conductor; the current density will decrease from the surface of the conductor toward its center. This phenomenon of non-uniform current distribution within the conductor cross-section is called the skin effect .Because of this effect, more than 80% of the power will be concentrated in the surface layer of the conductor. This layer is the reference or penetration depth [7].

From this effect, the heat energy converted from electric energy is concentrated on the skin depth. The degree of skin effect is determined by frequency, material properties, the resistivity and the relative magnetic permeability of the object. From another perspective, penetration depth is a function of temperature. At the beginning of heating cycle, the current penetration the will increase slightly because of the increase in electrical resistivity of the workpiece with temperature [15].

Higher energy conversion efficiency at high frequency switching can be obtained by controlling the voltage or current at the moment of switching to become zero, named soft switching. The voltage or current administered to the switching circuit can be made zero by using the resonance created by an L-C resonant circuit, therefore resonant converters provide most of the energy conversion efficiency in a power system by minimizing switching loss The quality of energy transmission to the part being treated depends on the placement of the inductors and the parts (connection, respective lengths), the power frequency and the skin effect, which characterizes the distribution of currents induced in the part on the surface or at the core.

All these electric and magnetic properties require a good choice of the power supply circuit.

3. The half bridge inverter configuration

When DC power supplies to AC load, it must convert DC to AC. This is carried out by a circuit named inverter. The proposed and realized circuit is a resonant inverter in half-bridge configuration.

The half-bridge configuration is one of the most common inverter circuit topologies used in power electronics and offers such benefits as four-quadrant switching, zero-voltage switching, zero-current switching, high-frequency operation, low EMI and high efficiency [10].

The two switches realized by power MOS transistors, are turned on and off complementary to each other with a non-overlapping dead-time. This can be realized by applying the correct control voltage waveforms at each of the gate drive inputs. The result is a square-wave voltage at the mid-point connected AC load that switches between the DC supply voltage and ground as presented on fig. 2. A portion of this AC current flows in each of the half-bridge switches, depending on which switch is on or off.

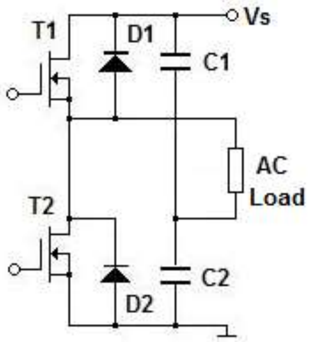

Fig. 2: The half-bridge inverter configuration

The AC load includes the main L-C resonant circuit and the matching L-C circuit too. The voltage and current waveforms can be divided up into the following four functional time zones, presented on fig. 3.

Zone 1: The T1 switch turns on and the mid-point is connected to the DC bus voltage. Current flows from the +Vs, through the T1 switch, through the C-L load, and back to the ground return path. The current ramps up to a positive peak level during the on-time of the T1 switch.

Zone 2: The T1 switch turns off and both switches remain off during this short dead-time. The load current continues to flow out of the mid-point node. The mid-point voltage reaches ground and continues to go negative until it gets limited by the antiparallel diode D2 of the T2.

Zone 3: The dead-time ends and the T2 switch turns on. Because the mid-point voltage is at ground, zero-voltage switching occurs when the T2 switch turns on. Current continues to flow through the channel of T2 (instead of the diode due to the T2 resistance of the channel) and through the C-L circuit.

The current crosses zero and continues to ramp down to a negative peak level during the on-time of the T2 switch.

Zone 4: The T2 switch turns off and both switches remain off again during this dead time. The load current continues to flow into the mid-point node. The mid-point voltage gets limited by the DC bus voltage plus the diode drop of the internal anti-parallel diode (D1) of the T1 MOSFET (S1). The current continues to flow through this diode until the T1 switch is turned on again at the start of Zone I. Because the mid-point voltage is at the DC bus voltage at the end of Zone IV, zero-voltage switching (ZVS) is achieved when the T1 switch is turned on again at the beginning of Zone I.

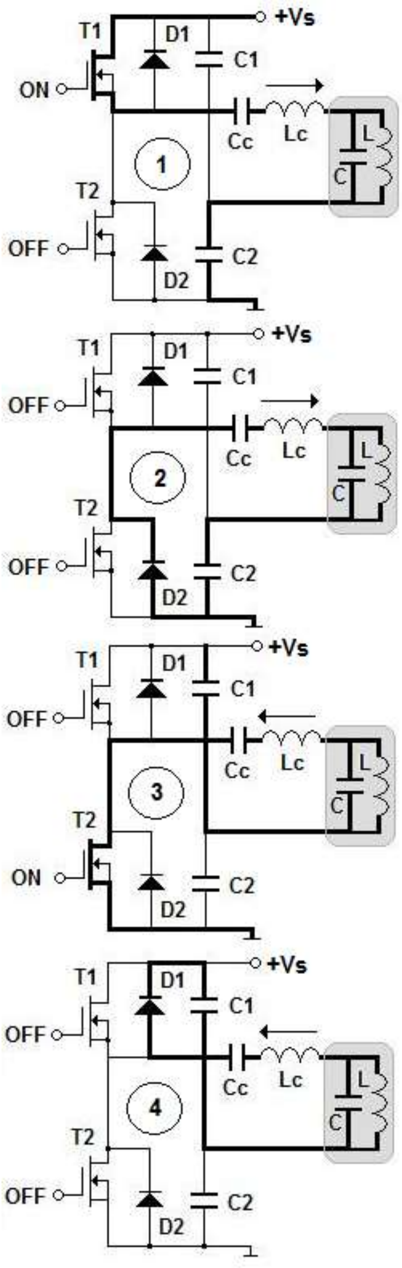

Fig. 3: The command of half bridge sinusoidal inverter

4. The realized induction heater

The realized induction heater is a resonant DC-AC converter in half bridge configuration, the switches are performed using n-channel power MOS transistors [5]. The half-bridge circuit offers many benefits which are realizable only when the circuit, the gate drive circuit, and layout, are all properly designed. The half-bridge mid-point voltage and current waveforms should be checked carefully to confirm that zero-voltage switch (ZVS) is maintained during all operating conditions. The gate drive circuit uses specific dedicated components (IRS 21844) in order to assure ZVS, supplied by a tunable PWM signal generator circuit (TL494). The resonant circuit of a resonant converter consists of a capacitor, and an inductor. When power is connected, electric energy is stored in the inductor and transferred to the capacitor. Resonance occurs while the inductor and the capacitor exchange the energy. The total amount of energy stored in the circuit during resonance remains unchanged [8]. This total amount is the same as the amount of energy stored at peak in the conductor or capacitor. As some energy is lost due to resistance in the resonance process, the total amount of energy stored in the inductor decrements in each resonant exchange. The resonance frequency, which is the speed of energy transfer, is determined by capacitance (C) and inductance (L).

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The half-bridge requires a ground referenced low-side gate drive circuit for turning the T2 MOSFET on and off, and requires a “floating” high-side driver (referenced to the mid-point) for turning the T1 MOSFET on and off as shown on fig. 4. These are assured by the used gate drive circuit which depends on the input and Miller capacitances of the MOSFETs, the switching frequency and the half-bridge current amplitude [10]. The block schematics of realized induction heating inverter is presented on fig. 4. The AC load (meaning the work coil and capacitor in parallel configuration) are connected through a matching L,C circuit, the most important reason for matching is to maximize the power transfer from the source to the load. The only load seen by the power source at the resonant frequency is the loss resistance across the tank circuit, therefore the role of the matching network is to transform this relatively large loss resistance down to a lower value [13].

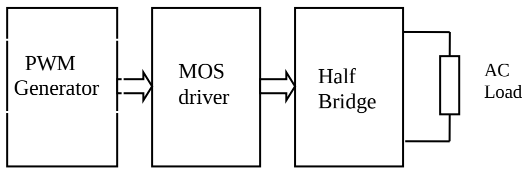

Fig. 4: The block schematics of the realized inverter

5. Experimental results

Resonance circuit (coil-capacitor) must be driven at its resonant frequency. The current in the circuit reaches its peak when the source frequency becomes identical to the resonance frequency. It decrements when the source frequency gets higher or lower than the resonance frequency. The working coil and the resonant load circuit were tested in order to estimate the resonant frequency. Measurements of transfer characteristics versus frequency were made both with and without coupled matching LcCc circuit, the obtained results are presented on fig. 5.

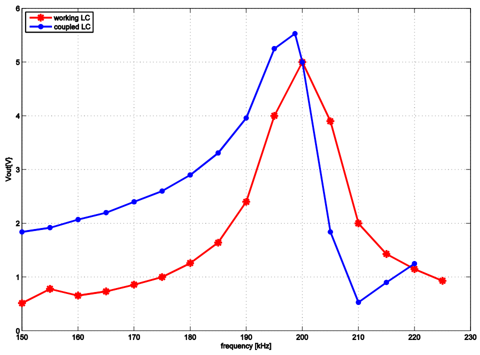

Fig. 5: The frequency characteristics of LC load

It is important to remark that the coupling circuit has small influence over the resonance frequency, more than the resonant circuit's frequency decreases with temperature. Operating frequency is tuned to resonance by a potentiometer. The measured resonance frequency of the inverter is around 200 kHz, as can be seen on the oscilloscope capture presented on fig. 6.

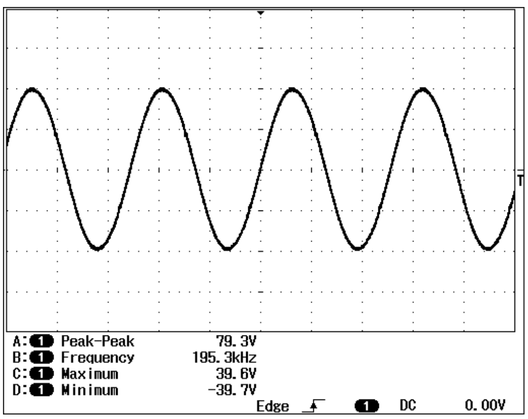

Fig. 6: The obtained inverters output signal

The work coil is made to resonate at the intended operating frequency by means of a capacitor placed in parallel with it. This causes the current through the work coil to be sinusoidal. The inverter sees a sinusoidal load current. In order to evaluate the realized resonant inverter, the output peak-to-peak voltage (U_{pp} on the LC load), the output current (I_o through LC load) and the temperature (T) were measured at different input (supply) voltages. These measurements were repeated for different workpieces different materials. One of the most representative measured results were obtained for an iron alloy piece, the results are shown in table 1.

Table 1: Measured values for an iron alloy workpiece

U_{in} [V]	U_{pp} [V]	T [C°]	I_{out} [A]
5	0.3	32.4	0.03
10	13.1	34.4	0.06
15	16.8	42.4	0.11
20	22.5	52.4	0.16
25	28.1	67.6	0.24
30	34.3	94.2	0.33
40	40.6	141.6	0.41
50	53.7	228.4	0.63
60	59.3	255.2	0.73
65	61.2	284.6	0.78
70	62.5	309.6	0.82
75	64.3	360.6	0.86
80	66.2	368.8	0.91
90	72.5	392.6	1.03
95	126	485.8	1.04
100	131	511.8	1.05
105	135	516	1.08

Figures 7 presents the measured parameters as function of input (supply) voltage, fig. 8 emphasizes the obtained temperature values.

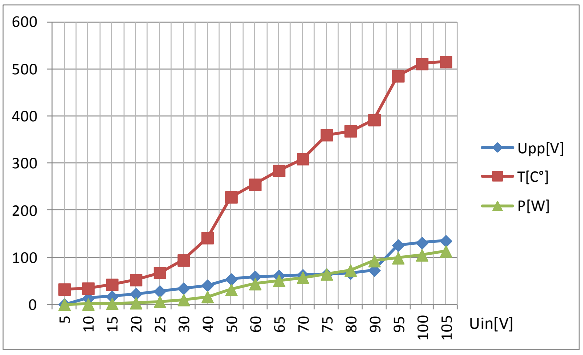

Fig. 7: The measured parameters versus input voltage

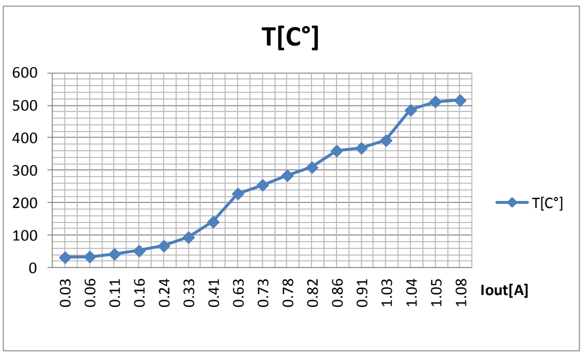

Fig. 8: The relationship between input current (from power supply) and obtained temperature

6. Conclusions

The power required to heat depends on the mass, on the material properties of used workpiece, the required temperature rise, heating time required to meet the process needs, the effectiveness of the field owing to the coil design and the inevitable heat losses during the heating process. If eddy currents heat the transformer's magnetic core, power is wasted and further problems could occur, such as structural damage. In this half-bridge configuration the voltage across the semiconductors is clamped and even though two switches are needed, at least half the voltage blocking capability is required. The switching is done at a duty ratio of 50%, feedback is not needed.

In practice the resistance of the work coil, the resistance of the tank capacitor, and the reflected resistance of the workpiece all introduce a loss into the tank circuit and damp the resonance. The power processed by the inverter can be increased by expanding the supply voltage to higher values. This can be done by running the inverter from a variable voltage DC supply such as a controlled rectifier.

As further work a full bridge configuration can be performed in order to have increased power.

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