

## **Prototypic Modelling of Induction Heater Using MOSFET Based Inverter Unit**

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### **Abstract**

This paper presents a study based on how to maximize the heating capacity of an induction heating module working on a single phase, 240 Volt, 50 Hz supply by modifying its inverter design and also correspondingly matching the impedance across the delivery coil and the rest of the circuit and hence effectively increasing the current across the delivery coil and reducing the time required for the coil to heat up and also linearly cool down. Also, the paper will present a study based on how the delivery coil will be designed for the stated conditions.

**Keywords:** Induction heating, MOSFET, warm-up and cool-down cycle, coupling efficiency, Capillary action, Currie Temperature, Joule effect.

### **I. INTRODUCTION**

Induction heating is a byproduct of the heating and the heat generated here as a result of Joule's law is what we use for heating the output coil and the energization of this device is done by using an AC source and in this case (for the sake of improving efficiency) we are using MOSFETs to control the heating parameters. Induction Heating comprises of three basic concepts, electromagnetic induction, skin effect and heat transfer.

Billet heating necessarily as described previously is a combination of three different phenomena namely electromagnetic induction, skin effect and heat transfer. Electromagnetic induction is effectively a result of flux radiated from one end of a transformer to the other or when a supply is passed through a winding or an inductor. Due to the high frequency at which the AC current passes through the winding, it

tends to flow through the outer most layers of the coil and hence energizing the outer most layers. Over time, this develops into heat and we have skin effect due to which we see the net increase in temperature in the coil. This heat is evolved and when drawn into a solenoid, we can concentrate the heating into a particular job as per requirement.

## II. FEATURE PARAMETERS

The success of any system is based on matching the theoretical and practical values calculated and simulated respectively. So, the following parameters shall be tested for and recognized accordingly.

### A. Skin Depth and reference depth

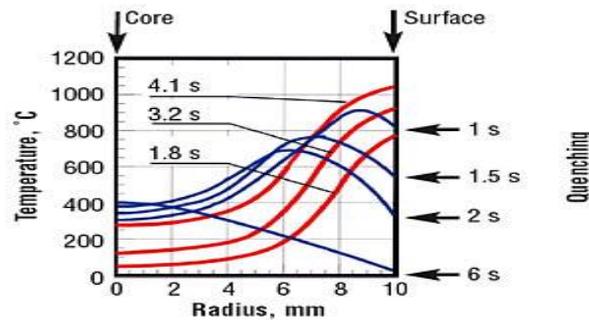
For the heating to be successful and efficient we must make sure that a few parameter such as skin depth and the properties of the work piece must be satisfied. The nature of induction heating is that the eddy currents are produced on the outside of the work piece in what is often referred to as “skin effect” heating. Since almost all of the heat is produced at the surface, the eddy currents flowing in a cylindrical work piece will be most intense at the outer surface, while the currents at the center are negligible. The depth of heating depends on the frequency of the ac field, the electrical resistivity, and the relative magnetic permeability of the work piece. The skin heating effect (reference depth) is defined as the depth at which approximately 86% of the heating due to resistance of the current flow occurs. The reference depths decrease with higher frequency and increase with higher temperature.

$$\delta = \sqrt{\frac{\rho}{\pi \times f \times \mu}}$$

Equation 1: Skin Depth

Where  $\rho$  is the resistivity of the conductor in  $\Omega \cdot m$   $f$  is the frequency in Hertz  
 $\mu$  is the absolute magnetic permeability of the conductor The absolute magnetic permeability ( $\mu$ ) =  $\mu_0 \times \mu_r$   
 $\mu_0 = 4\pi \times 10^{-7}$  H/m

The reference depth, as mentioned, becomes the theoretical minimum depth of heating that a given frequency will produce at a given power and work piece temperature. The cross-sectional size of the work piece being heated must be at four times the reference depth, or what appears to be current cancellation occurs. As the work piece thickness/reference depth of heating ratio decreases below four to one, the net current decreases. For a fixed frequency, the reference depth varies with temperature because the resistivity of conductors varies with temperature. With magnetic steels the magnetic permeability varies with temperature, decreasing to a value of one (the same as free space) at the Curie temperature, at which steel becomes nonmagnetic.



**Figure 1:** Rise in temperature versus thickness (radius) of the work piece for various temperatures.

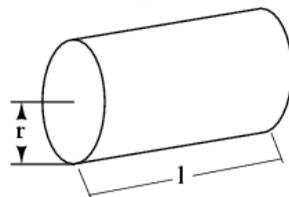
Heating efficiency is the percentage of the energy put through the coil that is transferred to the work piece by induction. If the ratio of work piece diameter to reference depth for a round bar drops below about 4 to 1, the heating efficiency drops. This ratio becomes what is defined for round bars as the critical frequency for heating. Higher frequencies are needed to efficiently heat small bars, once the critical frequency is reached, increasing the frequency has very little effect on relative efficiency. For through heating, a frequency close to the critical frequency should be selected so that the work piece will through heat faster. Once the critical frequency is reached, the case depth requirements will help in frequency selection because lower frequencies have deeper reference depths, thereby producing deeper case depths.

**B. Wheeler’s Formula of Induction**

Wheeler’s formulas for inductance of air core coils which follow are useful for radio frequency inductors. The following formula for the inductance of a single layer air core solenoid coil is accurate to approximately 1% for  $2r/l < 3$ . The thick coil formula is 1% accurate when the denominator terms are approximately equal. Wheeler’s spiral formula is 1% accurate for  $c > 0.2r$ . While this is a “round wire” formula, it may still be applicable to printed circuit spiral inductors at reduced accuracy.

$$L = \frac{N^2 \mu A}{l}$$

$$\mu = \mu_r \mu_0$$

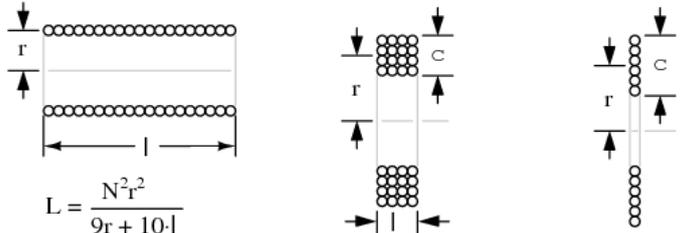


Where,

- L = Inductance of coil in Henrys
- N = Number of turns in wire coil (straight wire = 1)
- $\mu$  = Permeability of core material (absolute, not relative)
- $\mu_r$  = Relative permeability, dimensionless ( $\mu_0=1$  for air)
- $\mu_0 = 1.26 \times 10^{-6}$  T-m/At permeability of free space
- A = Area of coil in square meters =  $\pi r^2$
- l = Average length of coil in meters

Equation 1: Wheeler’s Formula

The above equations tell us about the modeling of the induction coil.



$$L = \frac{N^2 r^2}{9r + 10l}$$

$$L = \frac{0.8 N^2 r^2}{6r + 9l + 10c}$$

$$L = \frac{N^2 r^2}{8r + 11c}$$

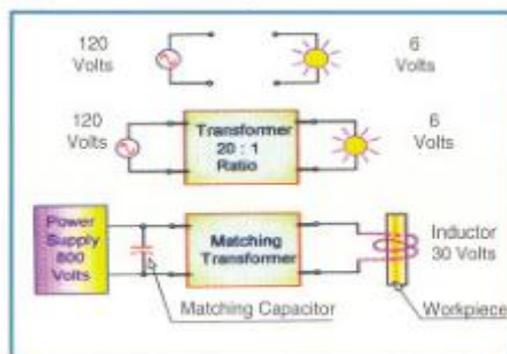
Where,

- L = Inductance of coil in microhenrys
- N = Number of turns of wire
- r = Mean radius of coil in inches
- l = Length of coil in inches
- c = Thickness of coil in inches

Equation 2: Wheeler's formula for various cases.

### C. Impedance Matching

Power supplies have an internal resistance and even something as simple as a battery has an internal resistance which dissipates a part of the power generated. This power is wasted since it does not do anything useful. It must be shown that the maximum power a power source transfers to a load resistor is when there is a higher amount of current passing through the delivery coil at rated voltage so that we have maximum charge density across the heating element. Unfortunately, more often than not this is not the case. We have a higher amount of current passing through the tank circuit and not at the delivery coil because of the internal resistance of the circuit. Hence, we tend to have inadequate heating patterns or delayed response or both in some cases.



**Figure 2: Impedance Matching**

The inverter circuit tends to work better when there is a higher voltage and lower current passing through its circuit but in our case when we try to switch between large

currents on and off in short spans of time, we have design issues and the results aren't favorable and neither does it make the construction simpler. We can use a common switch mode (MOSFETs in this case) by increasing the voltage and decreasing the current across it. The lower amount of current passing through the circuit ensures that there is minimum stray inductance and the circuit does not feel the impact of the ambient conditions. It is the job of the impedance matching circuit in itself to ensure that the working coil/ the heating element carries high current-low voltage and not high voltage-low current parameters.

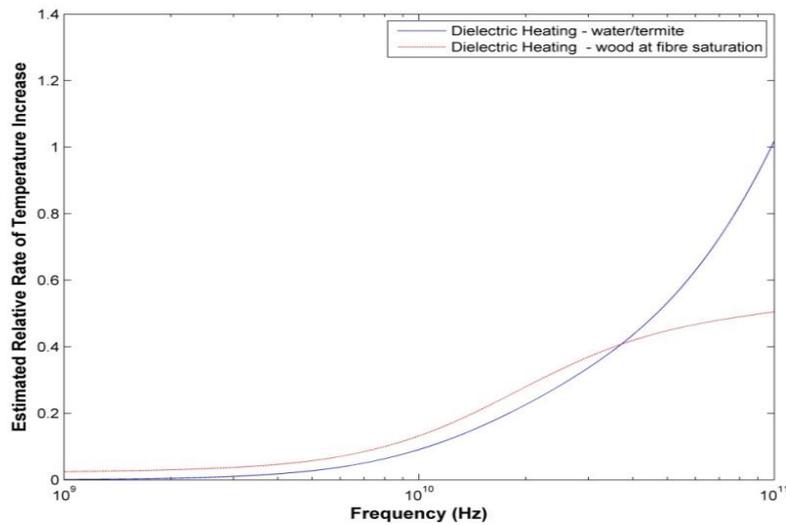
The tank circuit that includes the heating coil and the capacitor as a parallel resonant circuit. This has a resistance due to the lossy job coupled into the work coil because of the magnetic coupling between the two conductors. In reality the resistance of the heating coil, the resistance of the tank capacitor and the absolute resistance of the job put together cause losses in the tank circuit and hence damp the resonance. Cumulatively, we can derive this as a single impedance.

Hence, when operated at resonance condition, we can conclude that the tank capacitor and the heating coil both experience the same parameters and yet have opposing phase orientations and so they cancel out each other. This is from the power source's point of view. From these deductions we can conclude that the only load that matters in our case is the load across the tank circuit. The matching network has to simply transform this relatively large impedance across the tank circuit to a lower value that can be suitable for the inverter driving it.

#### ***D. Power Density***

Selection of power is just as important as the selection of frequency. When case hardening is to be done, the short heat cycles that are necessary require higher power density (energy input per unit of surface) than through-heating applications. The power density at the induction coil is the metered output power divided by the amount of work piece surface within the induction coil and is expressed in kW/cm<sup>2</sup> or kW/in<sup>2</sup>.

Power density requirements, as shown subsequently, can be used to rate the power requirements for an application. Power requirements are related to the amount of energy required to heat a work piece and to the induction heating system power losses. The energy or heat content required to heat the work piece can be calculated when the material, its specific heat, and the effective weight of material to be heated per hour are known. The value kWh is, where the pounds per hour relate to (3,600 seconds\*/ part weight)/actual heat cycle. Heat input required to heat a specific work piece represents only the energy or power that needs to be induced from the coil into the work piece.



**Figure 3:** Temperature rise to frequency graph.

Other system losses such as coil losses, transmission losses, conversion losses, and the ability to load match for required output power determine the power supply rating. Through calculation of the heat content requirements of the work piece at the coil, and with the system losses known, the power requirements for heating can be determined. If a heat content of 25 kWh is needed by the work piece and system losses are 50%, then a minimum output power rating of 50 kW is needed from the power supply. The ability of a power supply to produce rated output power depends on the ability to load match the power supply to the induction coil. When in doubt it is advisable, to use power supplies with higher output power ratings than needed. From calculation of the surface of the area to be heated in relationship to power, power density curves define power supply ratings. In general, obtaining higher production rates for specific case depths for surface hardening requires higher power densities. Through heating systems can be defined from knowing the cross sectional size and the weight of steel to be heated per hour. Lower power densities and frequencies are used for through heating because the work pieces need to have the heat soak and penetrate to the core. Higher productivity is obtained from using more power heating and from heating more work piece area at the same time, thereby not increasing the power density. Higher power densities provide the ability to heat surfaces more rapidly. However, there may be limitations to the amount of power that an individual induction coil can handle

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the coil into the work piece. Other system losses such as coil losses, transmission losses, conversion losses, and the ability to load match for required output power determine the power supply rating.

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In general, obtaining higher production rates for specific case depths for surface hardening requires higher power densities. Through heating systems can be defined from knowing the cross sectional size and the weight of steel to be heated per hour. Lower power densities and frequencies are used for through heating because the work pieces need to have the heat soak and penetrate to the core. Higher productivity is thus achieved by implying more power heating simultaneously, thereby not increasing the power density more surface area . Higher power densities provide the ability to heat surfaces more rapidly. However, there may be limitations to the amount of power that an individual induction coil can handle.

The fact that the power supply has a more than adequate power rating does not necessarily mean that the power can be induced into the work piece. Only 125 kW of a 250 kW power supply may load into a given coil and part.

### **III. EXISTING SCHEMES AND ALTERNATIVE SOLUTION**

The existing schemes include IGBTs for small capacity induction heaters for the switching purposes but we must also note that the IGBT has a large current tail and the lack of a body-drain diode. They are also known to have a negative temperature coefficient and this could lead to thermal runaway. All these when put up against the likes of a MOSFET gives us a better output compared to the former .MOSFETs are voltage driven devices and have lower rise and fall times that attribute to the higher switching frequency which is highly favorable.

#### **A. Design alterations**

To obtain higher ratings of current across the coil we place the coil between the inverter bridge and accordingly match our impedance to obtain higher ratings of current across the coil.

#### **B. Dimensions and calculations**

Skin depth:

$$\delta = 1 \div (\sqrt{\pi f \sigma}) \quad (m)$$

Case (i):  $I = 398\text{A}$

$$r = 0.007\Omega$$

$$\sigma = 142.9$$

$$\delta = 1 \div \left( \sqrt{\pi \times 50 \times 4\pi \times 10^{-7}} \times 142.9 \right) \text{ (m)}$$

$$\delta = 5.949 \text{ m}$$

Case (ii):  $I = 17.8\text{kA}$

$$r = 0.332\Omega$$

$$\sigma = 3.01$$

$$\delta = 1 \div \left( \sqrt{\pi \times 50 \times 4\pi \times 10^{-7}} \times 3.01 \right) \text{ (m)}$$

$$\delta = 82.05 \text{ m}$$

Equivalent circuit (for coil):

$$L_C = r_{OUT} \cdot N^2 \div (0.0254 \times (9 r_{OUT} + 10 l_{WC}))$$

Case (i):  $I = 398\text{A}$

$$L_C = 2.4779 \times 10^2 \div ((9 \times 1.5748) + (10 \times 3.9370))$$

$$L_C = 4.6315 \mu\text{H}$$

Case (ii):  $I = 17.8\text{kA}$

$$L_C = 0.6199 \times 10^2 \div ((9 \times 1.5748) + (10 \times 3.9370))$$

$$L_C = 1.334 \mu\text{H}$$

Number of Turns

$$N = l_W \div (d_C + C_P)$$

where  $l_W = 40\text{cm} = 15.748\text{inches}$

$$d_C = 40\text{mm} = 1.5748\text{inches}$$

$$N = 15.748 \div (1.5748 + 376 \times 10^{-9})$$

$$N = 10$$



The dimensions of the tube to be used for the heating tube is assumed to be a 40mm cylindrical diameter tube wound for about 10 turns and the tube is hollow and made of copper

#### IV. CIRCUITRY

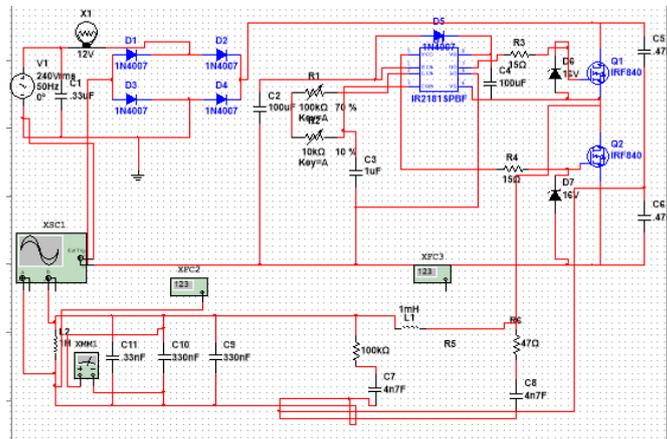


Figure 4: Proposed Circuit

The above given circuitry describes the setup of the induction heater to be tested and we can notice the simulation is done on NI's multisim14 and the simulated results shall be shown in the following images.

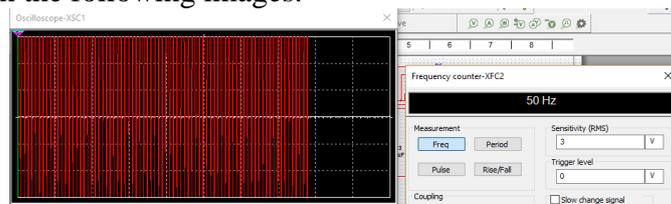


Figure 5: Output obtained

#### V. MODIFIED INVERTER ARRANGEMENT

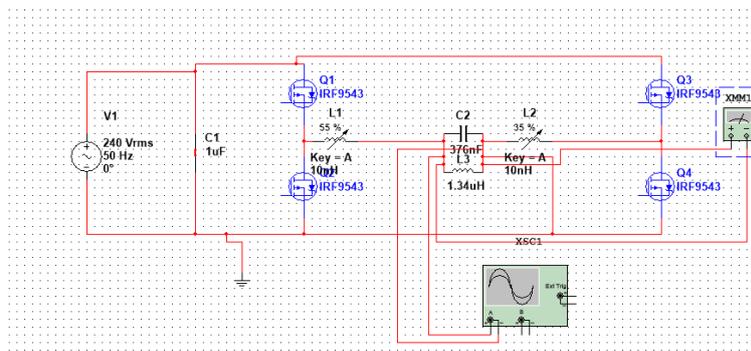
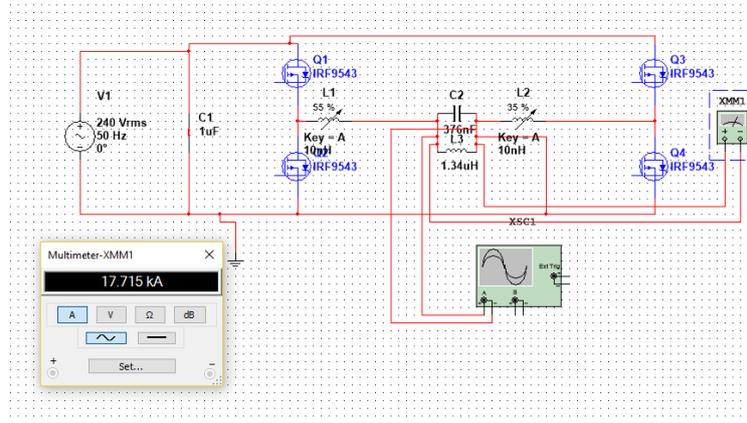


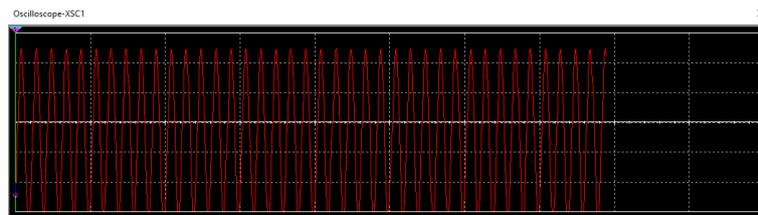
Figure 6: Modified Inverter Unit

As shown in the circuit of the inverter unit, we can see that the modified double bridge arrangement has effectively changed the dynamics of the parameter modulation of the whole unit.



**Figure 7:** Current obtained across the heating coil

The modified inverter arrangement has helped us attain higher amount of current across the delivery coil with effective penetration across the coil and hence offering larger amount of skin depth and hence a shorter duration to heat up.



**Figure 8:** Voltage drop vs. Time Graph

The graph represents the current build up against time and the continuous penetration of current across the delivery coil.

## VI. CONCLUSION

From the above represented circuits and their outputs we can verify that a system which can produce high amounts of heat for billets can be localized and made available from a domestic power source. This proposition hence ensures that billet heating can be economized and not be bound to just large scale plants but also be applied to domestic requirements and suffice the need in an inexpensive manner too. Hence, the above stated results are proof that technology for localizing billet heating is possible. The novel design of the delivery coil placement has proven to be the key factor in this case and has made possible the results achieved. Thus, a revised look at the inverter design has led to an extremely inexpensive and yet effective billet heating system.

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