DESIGN AND DEVELOPMENT OF A EFFICIENT COIL FOR A RESONANT HIGH FREQUENCY INVERTER FOR INDUCTION HEATING.

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ABSTRACT.
Induction heating systems employ non-contact heating. Inducing heat electromagnetically rather than using a heating element in contact with a part to conduct heat, as does resistance heating. This paper presents a technique to calculate the parameters of the coil to be used to heat an iron piece of given parameters, to 850°C. A design of the full bridge power resonant inverter is presented followed by the results.

I. BACKGROUND.

When a ferromagnetic material is placed in a time varying magnetic field , an E.M.F is induced in the ferromagnetic material. This induced E.M.F causes eddy currents to flow along the surface of the material. The major factors that control the magnitude of these eddy currents are (i) the magnitude of the time varying magnetic field , (ii) frequency of the time varying magnetic field, and (iii) the resistivity of the material.

These eddy currents are beneficial in the case of induction heating because they flow inside the material and produce I^2R losses which causes the material to heat up. So by controlling the amount of eddy current we can control the temperature of the material.

This requires a coil suitably dimensioned to heat up a workpiece to a given temperature.

II. PROBLEM DEFINITION

To design and develop a coil to heat steel metal AISI 1045 cylinder from 25 °C to 800 °C ~ 850°C in 30 seconds.

<u>Parameters of the workpiece:</u>

Diameter (D)	*= 1 cm.*
Length (l)	*= 2 cm.*
Relative Permeability(μ_r)	*= 50.*
Specific Heat (c)	*= 486J/Kg.°C.*
Density (γ)	*= 7870 Kg/m^3.*
Resistivity (ρ)	*= 1.62 x 10 $^{-7}\Omega$.m.*

III. CALCULATIONS FOR FINDING THE COIL NUMBER OF TURNS AND AMPERES REQUIRED FOR INDUCTION HEATING OF A GIVEN CYLINDER.

For the material to be heated let us visualize it as shown in figure 1. The coil assembly consists of a multi turn coil and an ironwork piece as the core. [1],[2],[3],[4],[5],[6].

The ampere-turn must be equal on the both primary i.e., the coil it self and the secondary i.e., the work piece (core).

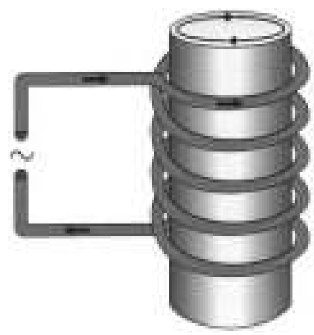

Figure 1: A workpiece in coil, the coil is energized from an AC source.

Figure 2 shows the electrical circuit analogy between induction heating and transformer principle.

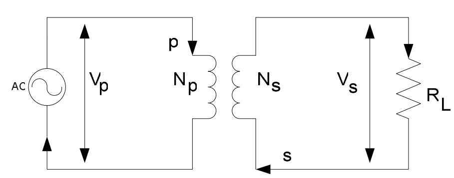

Figure 2:Equivalent model of the workpiece placed in the coil. Where : Vp = primary voltage (V); Ip = primary current (A); Np = number of primary turns; Is = secondary current (A); Ns = number of secondary turns; Vs = secondary voltage (V); R_L = load resistance(Ω)

From the equivalent model shown in figure 2, we can apply the transformer equation as follows.

$$I_p N_p = I_s N_s$$

But in our case .

$$N_s = 1$$

so

$$I_p N_p = I_s$$

The heat generated in the workpiece is given as :

$$P = I_s^{\,2} R \;\; watts$$

Where R is the resistance path of the eddy currents.
Again

$$P = \frac{\left(I_p N_p\right)^2 \pi\rho D}{\delta l} \; watts$$

Where

D is the diameter of workpiece.
l is the length of workpiece.
δ is the skin depth .

The power density or surface power gives the amount of power entering unit area of the cylinder.
As

Area of cylinder = π D l

So Surface Power will be

$$P_{sur} = \frac{P}{\pi Dl} \;\; watts / m^2$$

or

$$P_{sur} = \frac{\left(I_p N_p\right)^2 \pi\rho D}{\delta l.\pi Dl} \;\; watts / m^2$$

which finally becomes :

$$P_{sur} = \frac{\left(I_p N_p\right)^2 \rho}{\delta l^2} \;\; watts / m^2$$

Now the skin depth is given as :

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}} \;\; meters$$

where;
δ is the skin depth.
ρ is the resistivety of the workpiece.
μ is the magnetic permeability of workpiece.
ω is the angular frequency of the varying magnetic field.

So,

$$P_{sur} = \left(\frac{I_p N_p}{l}\right)^2 2\pi\rho\sqrt{\frac{\mu_r f}{\rho.10^7}} \;\; watts / m^2$$

The magnetizing force is:

$$H = \frac{I_p N_p}{l} \;\; ampere.turn / m$$

considering l to be equal to one meter then;

$$P_{sur} = 2\pi\left(H\right)^2 \sqrt{\mu_r f \rho \, 10^{-7}} \;\; watts / m^2 \quad \text{\_\_(1)}$$

Equation 1 plays a vital role in calculating the magnetizing force required for the correct power density. From the magnetizing force we can calculate the number of turns required and amperes for the design of the coil.

IV. RELATIONSHIP BETWEEN POWER, MEAN TEMPERATURE AND TIME.

[5],[6],[7],[8],[9],[10],[11],[12].

If a cylinder is heated uniformly at a constant surface power density and there is no losses , then all the heat is stored in the cylinder, i.e.,

Energy in = Energy stored

$$Energy \; in = P_{sur}.t.\left(Surface \; area\right)$$

$$Energy \; stored = \theta_m c\gamma\pi r^2 l$$

where :

t	*= time.*
θ_m	*= temperature rise.*
c	*= specific heat.*
γ	*= density.*
r	*= radius.*

Now,

$$P_{sur}.t.\left(\pi Dl\right) = \theta_m c\gamma\pi r^2 l$$

$$P_{sur} = \frac{\theta_m c\gamma R}{2t} \;\; watts / m^2 \quad \text{\_\_(2)}$$

V. SOLUTION TO OUR PROBLEM

By using figure 2.6 of chapter 2 of reference [2], we select frequency to be 10kHz.

Heat up time = 30 Seconds.
Rise in Temperture = 25 ^oC To 800 ^oC ~ 850^oC
Now first we find the skin depth.

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}} \;\; meters$$

$$= 0.000286 \; meters$$

$$= 0.286 mm.$$

From equation (2) the surface Power entering the cylinder is :

$$P_{sur} = 254988 \ watts/m^2 \ \_\_(3)$$

To find number of turns and amperes of the primary coil, we make use of equation 1.

$$P_{sur} = 2\pi (H)^2 \sqrt{\mu_r f \rho \, 10^{-7}} \ \ watts/m^2$$

$$P_{sur} = 0.000565 H^2 \ \ watts/m^2 \ \_\_(4)$$

Equating Eq.3 and Eq.4

$$254988 = 0.000565 H^2$$

$$H = 21234 \text{ ampere.turn./meter}$$

And for a length of 0.02m the H required will be :

$$H_{required} = 21234 \text{ x } 0.02$$

$$H_{required} = 425 \ ampere.turn$$

So One Possibility is :

$$H = NI = 425$$

$$I = 14 \ amperes.$$

$$N = 30 \ turns$$

Now we are concerned to design the inverter that can supply the required amount of current that is needed as concluded above. Our power circuit will be a VOLTAGE FED INVERTER as in figure 3.
For this we have to design the following :

- *Proper SCR selection.*
- *Proper Fast Recovery Diodes*
- *Snubber Circuit.*
- *Resonant Inverter.*
- *Resonant Inductor .*
- *Resonant Capacitor.*

VI. SELECTION OF SCR .

Required frequency that the SCR must maintain is 10 KHz.
Required current that will pass through the SCR is 14 Amp.
The SCR selected for this purpose is **ACR25U12.**
It's datasheet is as follows :

Maximum controllable current=25 Amp.
Maximum breakdown voltage=1200 Volts
Maximum operable frequency=12 KHz.
di/dt rating =10 A/μsec
dv/dt rating =50 V/μsec
Turn On Time =12 μsec
Turn On Gate Current =50 mA.
Working Temperature = -40 to 120^o C
Recommended Snubber Resistance= 20Ω..

VII. SELECTION OF FAST DIODE .

The fast diode must support a frequency of 10 KHz .The diode selected is **YG912S6.**
The characteristics of this diode are as follows :

- *High Speed Switching.*
- *Maximum Breakdown Voltage=1000V*
- *Maximum Current = 10 A.*

VIII. $\frac{di}{dt}$ PROTECTION OF THE SCR :

[13],[14],[15],[16].

For the di/dt protection we have to design an inductor .The equation that will help us in designing is as follows:

$$\frac{V}{L} = \frac{di}{dt}$$

in our case

$$V = 150 \ volts.$$

$$\frac{di}{dt} = 10 \ A/\mu\text{sec}$$

Hence

$$L_{\frac{di}{dt}} > 15 \ \mu H$$

We choose L=33μH as it is easy to build so

$$L_{\frac{di}{dt}} = 33 \ \mu H$$

IX. THE SNUBBER DESIGN. [14],[15],[16],[17],[18].

The snubber circuit is connected in parallel to the power SCR . It consists of a series RC circuit. The snubber circuit design comprises of the design of the resistance R_{snub} and the capacitance C_{snub} .

X. DESIGN OF RESISTANCE R_{snub}

The value of the snubber resistance is recommended by the manufacture. The manufacture of the SCR used in this project i.e, ACR25U12 recommends the snubber resistance to be 20 ohms A snubber resistance of 22 ohms has been used as it is easily available.
So

$$R_{snub} = 22 \ \Omega$$

XI. DESIGN OF CAPACITANCE C_{snub}

[14],[16],[22],[24],[23].

By calculations from the reference text , we get ,

$$C_{snub} > 0.086\ \mu F$$

we choose,

$$C_{snub} = 0.1\ \mu F$$

XII. DESIGN OF RESONANT INVERTER

[14],[16],[19],[20],[21],[22],[23],[24].

The Resonant circuit consists of $L_{resonant}$, $C_{resonant}$ & $R_{reflected}$. The $R_{reflected}$ is the reflected resistance of the workpiece when placed in the coil .

XIII. DESIGN OF RESONANT INDUCTOR $L_{resonant}$

Instead of designing a separate resonant inductor we will make use of the inductance of the workpiece in the coil and inductance of the *di/dt* protection coil .We will consider the resultant of the two inductances as our total resonant inductance of the resonant circuit.

We measure the inductance of the workpiece in the coil. Its value is :

$$L_{coil} = 35\ \mu H$$

The inductance of the $\frac{di}{dt}$ protection coil is :

$$L_{\frac{di}{dt}} = 33\ \mu H$$

The total inductance becomes :

$$L_{total} = L_{coil} + 2.L_{\frac{di}{dt}}$$

$$L_{total} = 101\ \mu H$$

XIV. DESIGN OF THE RESONANT CAPACITANCE $C_{resonant}$

The resonant inductance is ;

$$L_{total} = 101\ \mu H$$

The resonant frequency is given as ;

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}}\ Hz$$

Now

$$f_{resonant} = 10\ kHz$$

$$L_{resonant} = L_{total} = 101\ \mu H$$

so

$$C_{resonant} = 2.5\ \mu F$$

XV. TEST RESULTS

Given below the results of various tests conducted at different frequencies on the test piece. Efforts have been made to have as correct measurements as possible. The test circuit has been removed away from any large piece of metals to avoid any induction effects. The measurements taken are as shown in tabular form in table 1 , 2 ,3 and in graphical form in figure 4.

XVI. CONCLUSIONS.

The design of a Resonant High Frequency inverter has been presented and a device based on this design has been developed using normal commercial components. The test piece of ferrous metals had been heated to the point that it was red hot , using the inverter as of figure 3 and the measurements made to determine various input and output parameters.

From the measurements it can be seen that for steel cylinders (workpiece) with small diameters the frequency of the pulsating electromagnetic field in which the cylinder is placed ,must be high.

As the diameter of the cylinder of the workpiece increases the frequency of the pulsating electromagnetic field should be decreased . This is obvious because at low frequency more eddy currents penetrate the cylinder i.e., skin depth increases with the decrease in frequency and hence more I^2R loses are produced inside the workpiece.

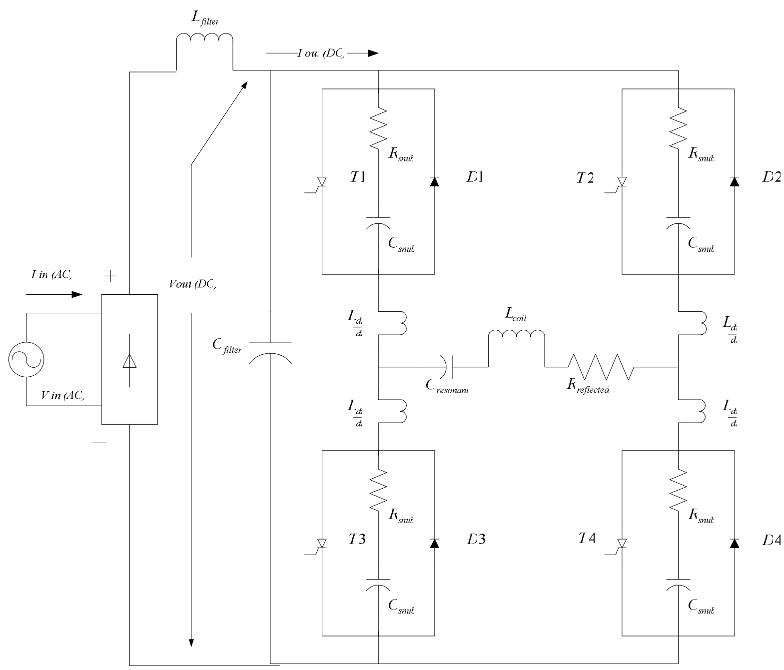

Figure 3: Full bridge high frequency resonant inverter for induction heating.

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Table 1 Resonant Frequency = 10 KHz

Test Piece	**: 1**
Diameter	:0.5cm
Resonant Frequency	:10 KHz
Vin (AC)	:210 V(AC)
Iin (AC)	:14A
Power Factor	:0.77 lagging
Power Consumed from AC Source	:1.5 KW
KVAR consumed from AC Source	:1.5 KVAR
Vout (DC)	:170 V (DC)
Iout (DC)	:7.3 A
Intial Temperature	:25 ^{o} Celsius
Final Temperature	:850^{o}Celsius
Time to heat up	:05 seconds

Table 2 Resonant Frequency = 5 KHz

Test Piece	**: 1**
Diameter	:0.5cm
Resonant Frequency	:5 KHz
Vin (AC)	:210 V(AC)
Iin (AC)	:6.6A
Power Factor	:0.755 lagging
Power Consumed from AC Source	:1.4 KW
KVAR consumed from AC Source	:0.933 KVAR
Vout (DC)	:192 V (DC)
Iout (DC)	:6.7 A
Intial Temperature	:25^{o}Celsius
Final Temperature	:850^{o}Celsius
Time to heat up	:11 seconds

Table 3 Resonant Frequency = 3 KHz

Test Piece	**: 1**
Diameter	:0.5cm
Resonant Frequency	:3 KHz
Vin (AC)	:210 V(AC)
Iin (AC)	:7.7A
Power Factor	:0.745 lagging
Power Consumed from AC Source	:1.2 KW
KVAR consumed from AC Source	:1.125 KVAR
Vout (DC)	:200 V (DC)
Iout (DC)	:6 A
Intial Temperature	:25^{o}Celsius
Final Temperature	:850^{o}Celsius
Time to heat up	:13 seconds

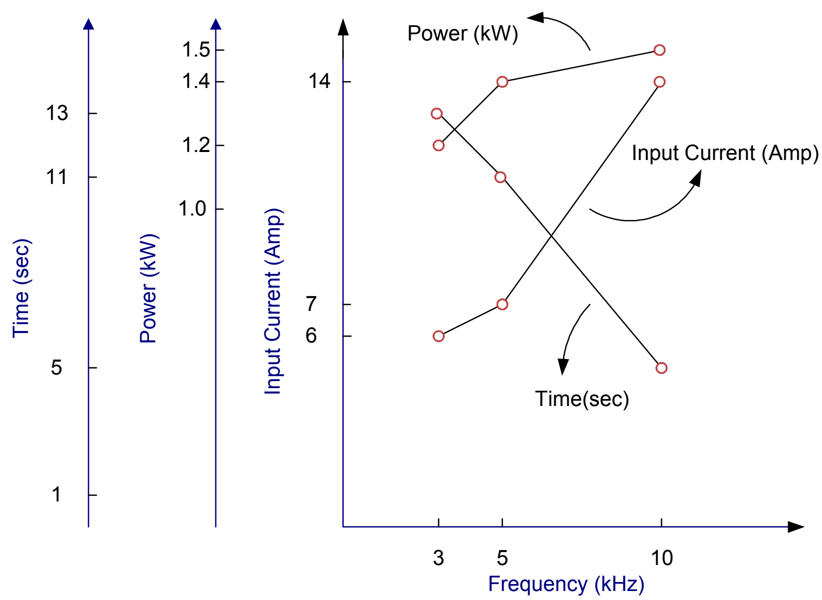

Figure 4: Measurements of Power, current etc as a function of frequency.