Design Calculation and Performance Testing of Heating Coil in Induction Surface Hardening Machine

Soe Sandar Aung, Han Phyo Wai, and Nyein Nyein Soe

Abstract**—**The induction hardening machines are utilized in the industries which modify machine parts and tools needed to achieve high ware resistance. This paper describes the model of induction heating process design of inverter circuit and the results of induction surface hardening of heating coil. In the design of heating coil, the shape and the turn numbers of the coil are very important design factors because they decide the overall operating performance of induction heater including resonant frequency, Q factor, efficiency and power factor. The performance will be tested by experiments in some cases high frequency induction hardening machine.

Keywords**—**Induction Heating, Resonant Circuit, Inverter Circuit, Coil Design, Induction Hardening Machine.

I. INTRODUCTION

THE principle of induction heating is shown in Fig. 1, there an electric conductor such as iron or steel placed in the inductor is heated rapidly by induced eddy current caused by electromagnetic induction, and hysteretic heat loss, which is generated by vibration and friction of each molecule in magnetic material under AC magnetic flux.

In induction heating, as the frequency of the heating current tends to concentrate close to the metal surface (work piece).This is referred to as the skin effect. The skin effect is the phenomenon, which electric current flows only in the limited area near surface of conductive material, and proximity effect is the phenomenon, which the primary current in the inductor and the secondary current in the conductive material pull each other because the direction of current is opposite each other, and flows in the limited area near surface where distance is nearest each other. The depth depends upon the frequency and as the frequency is higher, the depth becomes smaller. [1]

The penetration depth δ is calculated as follows;

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \text{ (m)} \qquad (1)$$

Where, δ = penetration depth, m
μ = specific permeability
f = frequency, Hz

This formula shows that as the frequency is higher, δ will be smaller and the heating will be concentrated as the surface in case the materials are same. However in actual heating, the heated tends to become bigger because of heat conduction in the heated material.

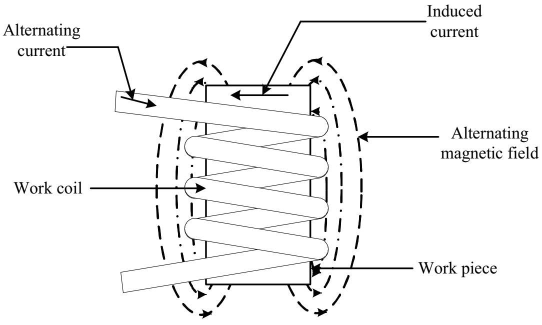

Fig. 1 Basic Induction Type Heating System

II. SYSTEM CONFIGURATION

Fig. 2 shows the general block diagram of the induction heating system. The AC power source is single phase and it applies line frequency and line voltage. The non controlled rectifier converts the AC voltage to the DC values and applies the desired DC current to the inerter circuit. The inverter changes the DC signals to the AC signals with desired frequency to apply the work coil. When the work piece has been heated for a time, the quenching system is applied to the work piece.[2]

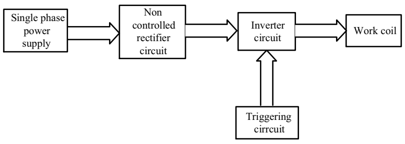

Fig. 2 General Block Diagram

III. SYSTEM ANALYSIS

A. Equivalent Circuit

The work coil and work piece have the special property of resistance and reactance values due to their resistivity and inserted flux. Using Wheeler's formula, the inductance of the work coil can be calculated as follows.

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$$L_c = \frac{r_{out} N^2}{0.0254\left(9r_{out} + 10l_{wc}\right)} \qquad (2)$$

Where L_c = inductance of work coil, µH
r_{out} = outer radius of work coil, m
l_{wc} = length of work coil, m

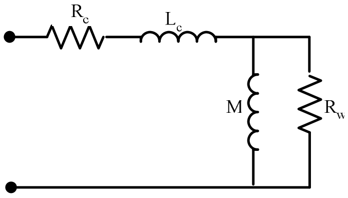

Fig. 3 Impedance Circuit of Work Coil and Work Piece

The work coil and work piece can be represented by an equipment series inductance and resistance model as shown in Fig. 4.

$$L_{eq} = L_c + M \qquad (3)$$

$$R_{eq} = R_c + R_w \qquad (4)$$

Where M = magnetizing inductance, H
L_{eq} =equivalent inductance of work coil and work piece
R_{eq}= equivalent resistance of work coil and work piece

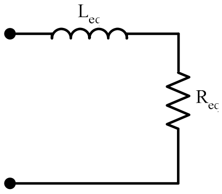

Fig. 4 Equivalent Circuit of Work Coil and Work Piece

B. Resonant Circuit

As shown in Fig. 4, the equipment inductance and resistance of work coil and work piece are in series connection. To resonate the circuit a capacitor is connected in parallel resonant circuit and it is shown in Fig. 5.

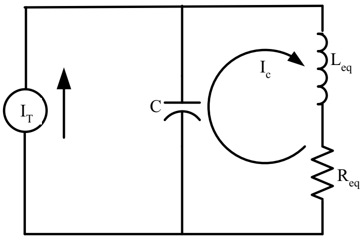

Fig. 5 Resonant Circuit for the Load

If the capacitor is charged to a supply voltage, the energy stored in $CV_T^2/2$. And this energy transfer to the inductance L_{eq} and returns again to the capacitor so the frequency of the oscillation depends on the values of inductance and capacitance. In the circuit, the dissipated energy in resistance R_{eq}, and after each cycle of oscillation the store of energy in the capacitor is reduced.

C. Series Parallel Resonant Inverter

This configuration has the desirable characteristics of series and parallel resonant inverters. The load short circuit and the no load regulation are possible. High part-load efficiency is possible with the proper choice of resonating components.

A resonant inverter can be operated either below or above resonance frequency. This inverter contains impedance matching system. The tank circuit incorporating the work coil (L_w) and its capacitor (C_w) can be though of as a parallel resonant circuit

This has a resistance (R) due to the loss work piece coupled into the work coil due to the magnetic coupling between the two conductors. In practice, the resistance of the work coil, the resistance of the tank capacitor and the resistance of the work piece all introduce a loss into the tank circuit and damp resonance. Therefore, it is useful to combine all of these cases into a single loss resistance. In the case of parallel resonant circuit this loss resistance appears directly across the tank circuit. This resistance represents the only component that can consume power and therefore it can be though of resistance as the load that it is being tried to drive power into as efficiently as possible.

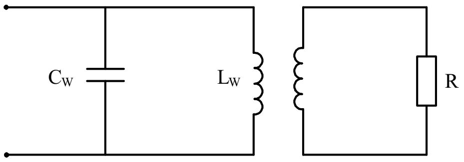

Fig. 6 Circuit Diagram of Tank Circuit

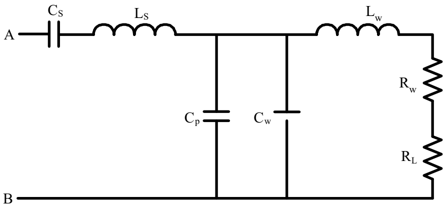

Fig. 7 Diagram of Matching Network

IV. REQUIRED SPECIFICATIONS FOR INDUCTION SURFACE HARDENING MACHINE

The specifications for operating are the ambient temperature is assumed 300.15 K, the desired hardened temperature is 1116.48 K, the duration of hardened time is 10 sec, the output power is 5 kW and the use of apply frequency is 35 kHz. Table I is for the specifications of conductor used as work coil.

TABLE I
SPECIFICATIONS OF CONDUCTOR

Unit	Specification	value
-	material	copper
Ωm	resistivity	1.7×10^{-8}(at 293.15 K)
Hm	permeability	1
kg/m^2	density	7861.13

TABLE II
SPECIFICATIONS OF WORK PIECE

Unit	Specification	value
-	Material	1040 carbon steel
Ωm	Resistivity	1.7×10^{-8}(at 293.15 K) 115.6×10^{-8}(at 1253.15 K)
Hm	Permeability	1
J/kg.K	Specific heat	434 (at 300 K) 1169 (at 1000 K)
K	Melting temperature	1794.26
K	Hardened temperature	1116.48 _ 1172.03
kg/m^2	Density	7861.13

V. CALCULATIONS OF INDUCTION SURFACE HARDENING MACHINE

A. Calculation of Work Coil

The number of turns of work coil is mainly based on the length of work piece and the pitch of coil windings. Thus,

$$N=\frac{l_W}{d_c+C_p} \tag{5}$$

Where,

N = number of turns of work coil
L_w = length of work piece to be hardened, m

And the inner diameter of work coil is

$$D_{in}=d_W+2C_p \tag{6}$$

The outer diameter of work coil is

$$D_{out}=D_{in}+2d_c \tag{7}$$

Where,

d_w= diameter of work coil, m
d_c = diameter of conductor, m

The total length of conductor for work coil is

$$l_c=2l_{lead}+N\sqrt{(2\pi\times\times_m)^2+(1.5\times d_c)^2} \tag{8}$$

Where,

l_c = length of conductor, m
l_{lead} = length of work coil lead, m
r_m = inner radius of work coil, m

The minimum thickness of conductor must be at least two times of depth of current penetration in conductor itself. Therefore, the minimum thickness of conductor is

$$t_c=2\delta_c$$

Where,

t_c = minimum thickness of conductor, m
δ_c = depth of current penetration in conductor, m

The depth of current penetration in conductor is

$$\delta_c=\frac{1}{\sqrt{\pi f\mu_c\mu_o\sigma_c}} \tag{9}$$

Where,

μ_c = permeability of conductor, H/m
μ_o = permeability of free space, H/m
σ_c = electric conductivity of conductor, mho/m
f = applied frequency, Hz

B. Calculation of Impedance Matching System

$$Q=\frac{\sqrt{L_S/C_S}}{R_L} \tag{10}$$

$$F=\frac{\omega_s}{\omega_o} \tag{11}$$

From Equation (10) and (11),

L_S = 0.033185 mH
C_S = 0.753953 μF
C_P = 0.753953 μF

The capacitor in the matching net work (C_P) and tank capacitor (C_w) are both in parallel. In practice, both of these functions are usually accomplished by a single capacitor.

$C_{pw} = C_p + C_w$
$= 1.796509$ μF

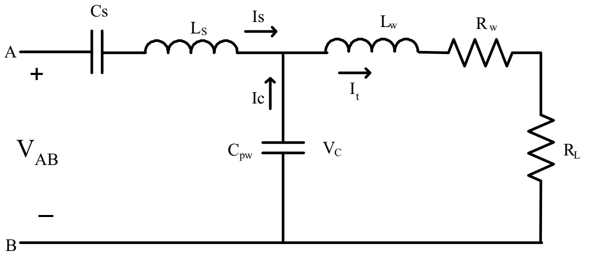

Fig. 8 Circuit Diagram of Matching System

$$Z_{cpw}=R-jX_{cpw}=-j\frac{1}{\omega C_{pw}}=-j2.531178$$

$$I_c=\frac{V_c}{Z_{cpw}}$$

$$=\frac{119}{-j2.531178}$$

= j47Amp

$I_t - I_s = I_c$
= 16.042916 + j22.655880
= 27.760837(θ =54.70°)

$$V_{AB}=I_sZ_s-V_c$$

$$Z_s=jX_{ls}-jX_{cs}$$

$$=j\omega_sL_s-\frac{1}{j\omega_sC_s}$$

= j7.297822 –j6.0312583
= j1.266564

V_{AB} = -147.696106 +j20.317976
=149.087088(θ =172.17°)

Required voltage for matching system is
V_{AB} = 149.087088Volt
Required current for matching system is
I_s = 27.760837Amp (θ =54.70°)
The selected series capacitor C_S is 0.8 μF, 600 Volt.
The selected series inductor L_S is 0.03 mH, 600 Volt, 2 Amp.

The selected parallel capacitor C_{pw} is 1.796507 μF, 600 Volt.

C. Calculation of Voltage and Current Ratings for Inverter

Device voltage and current rating must to be satisfied supply bus voltage and the load impedance so that power can be delivered to the load.

The required voltage for the load is

V_{AB} =149.087088 Volt.

The supply dc voltage is 149.087088 volt.

$$\text{Peak of supply voltage} = \sqrt{2} \times 149.087088$$
$$= 210.840982 \text{ Volt}$$

The inverter is driven high frequency switching. This is supplied by inductance load.

D. Calculation of Single Phase Rectifier Circuit

Inverter input voltage E_d = 149.087088 Volt

Inverter input current I_d = 27.760837 Amp

So, required dc voltage $E_d = 149.087088 \approx 149$ Volt

Required dc current $I_d = 27.760837 \approx 28$ Amp

Average load voltage $V_{0(avg)} = 0.636\ V_m$

V_m is peak load voltage.

$$V=\sqrt{2}V_{RMS}$$

V_{RMS} is supplied voltage RMS value.

$E_d = V_{0\ (avg)}$

$V_m = V_{0(avg)}/\ 0.636$

$= 149.087088\ /\ 0.636$

$= 234.276730$ Volt

$$\text{Supply voltage for system} = 234.276730 / \sqrt{2}$$
$$= 165.658664 \approx 166 \text{ Volt}$$

Required supply voltage is 166 Volt to 220 Volt

RMS value of load current = average load current

= 27.760837 Amp

Average current in each diode $I_{D(avg)} = I_{0(avg)} / 2$

$= 13.880419 \approx 14$ Amp

$$\text{Peak load current,}\quad I_m = \frac{I_{o(avg)}}{0.636} = 43.649115\text{Amp}$$

Supply current for system,

$$I_{rms} = \frac{43.649115}{\sqrt{2}} = 30.864585 \approx 31Amp$$

Required power $=VI=5.11597$ kW

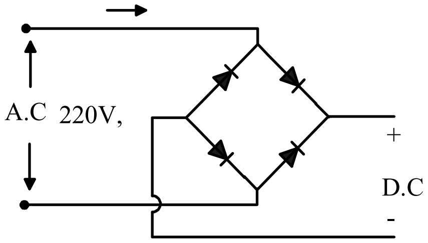

Fig. 9 Circuit Diagram of Rectifier Circuit

VI. DESIGN RESULTS

The results for work piece, conductor, work coil and electrical properties of the system are calculated. The results are shown in table respectively.

TABLE III
RESULT FOR WORK PIECE

Unit	Specification	Design Value
-	Material	1040 carbon steel
-	shape	cylindrical
-	Nature of surface	uniform
m	Depth of hardness	0.0009587
m	Diameter	0.067008
m	Length	0.033504
m^2	Cross sectional area	0.000199
m^2	Surface area	0.007053
μm^3	Volume	6.665071

TABLE IV
RESULTS FOR WORK COIL

Unit	Specification	Design Value
-	shape	round
-	number of turns	4
m	inner diameter	0.070184
m	outer diameter	0.082884
m	Length	0.0381
m	coil pitch	0.003175
m	coupling distance	0.001588

TABLE V
RESULTS FOR CONDUCTOR

Unit	Specification	Design Value
-	material	copper
-	shape	round
m	thickness	0.000702
m	diameter	0.00635
m	length	1.282781

TABLE VI
RESULT FOR ELECTRICAL PROPERTIES OF THE SYSTEM

Unit	Specification	Design Value
Ω	Resistance of work coil	0.003114
Ω	Resistance of work piece	0.121220
μH	Inductance of work coil	1.434858
μH	Magnetizing inductance	0.551223
μF	Resonated capacitance	1.0411355
-	Power factor	0.273791
-	Quality factor	3.512809
Ω	Total impedance	1.658596
A	Supply current	71
V	Supply voltage	119

VII. PERFORMANCE TESTING

A. Testing of Control Circuit

Wave shape, frequency and voltage values at the input and output of control circuit are measured with oscilloscope. Resulting waves are square wave and the wave shapes are shown in Fig. 10.

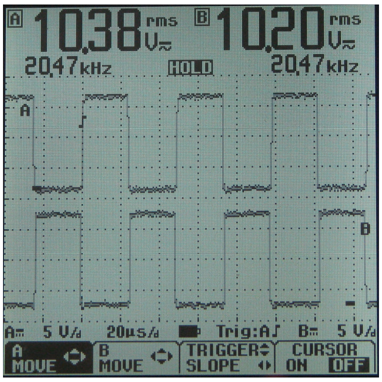

Fig. 10 IGBT gate driver circuit (for start heating)

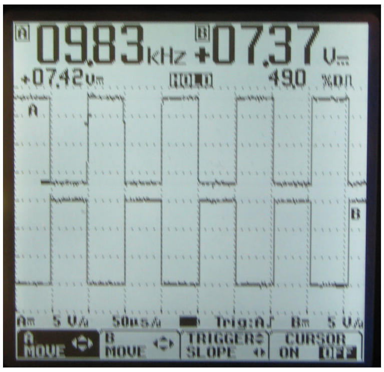

Fig. 11 IGBT gate driver circuit (after heating)

B. Performance Testing of Inverter

First, the inverter output is measured without tank circuit as shown in Fig. 12 and resulting wave shape is square wave with spite.

Then, the inverter is concerned with tank capacitor and measured. The resulting wave shape is pure sine wave. The wave shapes are shown in Fig. 13.

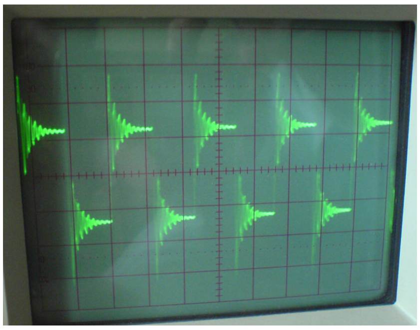

Fig. 12 Wave Shape of Inverter Output without Tank Circuit

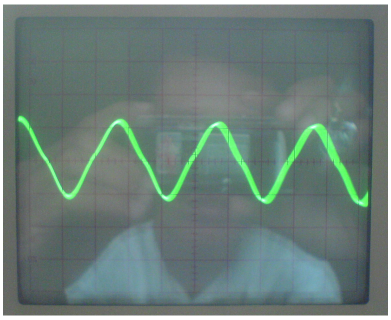

Fig. 13 Wave Shape of Inverter Output with Tank Circuit

ACKNOWLEDGMENT

Firstly, the author would like to express her deepest great thank to her parents. The author deeply wants to express her special appreciation to Dr. Ni Ni Win, Department of Electrical Power Engineering Department, Mandalay Technological University, for her invaluable support and advice.

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