DESIGN AND SIMULATION OF A SPECIAL MEDIUM POWER INDUCTION HEATING SYSTEM FOR OXYGEN FREE COPPER PRODUCTION

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Abstract: For sustainability purposes this project is studying the recycling of copper scrap. It is intended to melt a copper in oxygen free environment to achieve a highly conducting copper suitable for electrical installation and bus-bars manufacturing. Such a project must be started by a design and simulation step. Since the furnace composed of two main parts, the power supply and the induction coil, the power supply is a current fed inverter (CFI) simulated using Matlab, and the induction coil simulated by Finite Element Method (FEM) using ANSYS computer package. The induction coil design of this project is a special task due to the limitation of the maximum output voltage of the available power supply. The results approve the visibility of the system to be implemented in near future.

Keywords: *Induction Furnace, Current Fed Inverter CFI, FEM, ANSYS.*

1. Introduction

The production of Oxygen Free Copper from scrap copper is a very useful technology. The copper produced in such environment is of very low resistivity. This property makes it a candidate as a conductor for electrical installations, cables, bus-bars, etc. This type of copper can be produced from copper scrap in condition that it must be melted in a special environment. Such melting process can easily be done using induction furnace, since it doesn't need Oxygen gas like the traditional furnaces.

The induction coil (including the scrap copper to be melted) must be occupied in a container does not contain oxygen. This is can be done by replacing the air inside the chamber by any available Nobel gas like Argon.

This work deals with the design of an induction coil for this purpose. In this work the design suffers from a restriction of the limitation of the output voltage of the available power supply because it is supplied by 220V, 3-phase, 50Hz mains. This restriction leads to make this coil design a complex task.

It is well known [1] that the coil design can be done through an electromagnetic-thermal coupled analysis using (FEM). This analysis able to determine the current magnitude, the frequency, the coil self-inductance, equivalent resistance, and the time elapsed for melting. The induction coil of such a system is connected in parallel with a tank circuit such that they resonate at the required frequency. Then the terminal voltage across the induction coil can be determined. So, this explains the difficulty of matching these variables with the available voltage.

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A special condition must be considered in this process, because it occurs in a closed chamber, and this means the absence of heat dissipation due to convection and emissivity. Also, the effect of the existence of the crucible must be considered. The simulation results of this system assists the designer to determine the required power and the components ratings.

It has to be mentioned here that, in melting process, the simulation results are an approximation due to the truth that; a change in the geometrical shape of the scrap copper when it is melted.

Since, the system to be implemented is a melting furnace, the most suitable power supply is the current-fed inverter (CFI) [2]. Hence, the block diagram of the power supply is shown in fig. (1).

The system is composed of the power supply and the induction coil. The power supply is fed mainly by 3-phase, 380 V, 50 Hz source. This power feeds a thyristorized (Fully controlled full wave rectifier) (FCFWR). The DC voltage of this rectifier fed to the inverter through a specially designed smoothing reactor [3]. The self-tuned single phase inverter must follow the change in the resonance frequency of the parallel tank circuit. This is done by a feedback current transformer (CT).

Figure 1. The proposed System

2. The Proposed System

The power supply is simulated and studied in [4]. It is found that this power supply is suitable for this process, but its external characteristics is as shown in fig. (2).

Since this type of rectifiers suffers from current distortion, the Total Harmonic Distortion (THD) factor shown in fig. (3) illustrates the relation of this factor with the load current. It is found that the operation of this power supply at full-load will reduce the THD to an acceptable limit.

Figure 2. The external characteristics of the power supply at a triggering angle ($\alpha = 0^\circ$)

Figure 3. The THD factor vs. load current at ($\alpha = 0^\circ$)

Hence, the coil design of this furnace must be done in this research, such that it must operate with the available voltage of this power supply, also it is better to design the load power as near as possible to the maximum load. Otherwise, a step-up transformer of higher power rating must be used. So this system is more economical because it does not need a step-up transformer. The load of this power supply is composed of the induction coil which is a cylindrical copper tube coil. Its core includes a crucible with the scrap to be melted. This coil is connected in parallel with a capacitor of low Equivalent Series Resistance (ESR) especially manufactured to achieve a high quality factor tank circuit. Fig. (4), represents an Argon filled chamber enclosing the induction coil in order to avoid the effect of the Oxygen on the melted copper.

Figure 4. A schematic diagram of the induction coil under study

3. Theoretical Background

Many researchers deals with induction coil design [5] to reach its requirements that make it able to perform the heating process efficiently, and determines its equivalent ($R - L$) circuit.

It is well known that ANSYS is a software computer package to solve Maxwell's partial differential equations numerically, using FEM by adopting the electromagnetic-thermal coupled analysis [1, 5, 6]. So, the theory of this part is fully mentioned in literature.

The FEM analysis leads to reach the best design parameters of the induction coil. The starting parameters can be estimated from the available literature and previous experience.

Since this design deals with copper melting, it is wealthy to mention the related theory as follows:

Let us consider a normal induction furnace as shown in fig. (5). With the following dimensions:

T_{ref} : the refractory thickness

T_{cr} : the crucible thickness

D_w : the workpiece diameter

D_c : the coil internal diameter

H_w : the workpiece height

H_c : the coil height.

Figure 5. Traditional induction coil

From experience the relation between the parameters H_w and D_w will be due to the empirical ratio [7]:

$$\frac{H_w}{D_w} = (1.6 \rightarrow 2) \quad (1)$$

Since the melt of the copper mass will be of cylindrical shape, then the workpiece volume V_m must be:

$$V_w = \frac{\pi D_w^2 H_w}{4} \quad (2)$$

Since the volume copper density is (ρ_{cu}), then the mass of the copper to be melted M will be:

$$M = \rho_{cu} \times V_w \quad (3)$$

And the relation between the mass of the workpiece M in kg and T_{cr} in mm is due to the empirical relation [8]:

$$T_{cr} = 2.66\sqrt{M} \quad (4)$$

Also, the relation between H_c and H_w is as shown in the empirical formula [11]:

$$H_c = (1.1 \rightarrow 1.2) \times H_w \quad (5)$$

Hence, from the available thermal constants the energy required to melt a precise quantity of copper can be determined as follows, refer to figure 5:

$$D_c = D_w + 2(T_{cr} + T_{ref}) \quad (6)$$

Then, since the initial and final temperatures of the melt are known, the energy required to melt this quantity of copper is [9]:

$$Q_s = MC_p(T_f - T_i) \quad (7)$$

M : the mass of the melt in kg.

Q_s : the specific heat energy in kJ.

C_p : the specific heat capacity in kJ/kg·°C.

T_f : the final temperature in °C.

T_i : the initial temperature in °C.

Also, the required energy due to the change in the chemical structure of the copper from a solid to a liquid material must be determined. This latent or this change in potential energy (enthalpy) for the melted mass is as:

$$Q_l = ML_f \quad (8)$$

Q_l : the latent heat energy of the molten metal in kJ.

L_f : the latent heat of fusion of the molten metal in kJ/kg.

The total thermal heat energy in kJ can be calculated from the equation

$$Q_{th} = (Q_{ch} + Q_{cr})_s + Q_l \quad (9)$$

Q_{ch} : the specific heat capacity of the charge.

Q_{cr} : the specific heat capacity of the crucible.

The required power in (kW) can computed from this equation

$$P = \frac{Q_{th}}{3600 \times t} \quad (10)$$

t : the heating process time in hours.

The choice of the frequency that is greater than or equal to the critical frequency (f_c) is dictated by [10]:

$$f_c = \frac{\rho_w}{0.0625\mu D_w^2} \quad (11)$$

All of these calculations are preliminary and can be used to estimate the approximate geometry and required power for melting certain quantity of copper. It is wealthy to mention here that these equations are not for the case of a closed chamber without Oxygen gas, but they are about an open furnace to the normal environment.

The actual and the most accurate design can be done by using FEM. The simulation can start with rough estimation design depending on the described empirical formulas, then it can be

refined in order to achieve the most suitable design of the induction coil. The simulation objective is to find the best dimensions of the coil, the crucible, the magnitude of the current, the frequency, and the elapsed time of the melting process. These parameters must provide the most efficient process and must be compatible with the power supply.

4. Induction Coil Simulation

A 2-D finite element model is done using the initial induction coil dimensions. The model mesh refined such that, the mesh is dense in the important regions. The elements area is minimized to a smaller area such that the most accurate results achieved. This is done taking into consideration the minimum number of element in the model is required, in order to achieve a moderate running time of the total run. Half of the 2D model is considered due to its symmetry. A harmonic (steady state) electromagnetic analysis done, to measure the energy of the induced eddy currents inside the copper and the crucible. These data will be as an input to the transient thermal analysis to determine the temperature distribution inside the specimen. The temperature effect on the physical characteristics of the heated materials taken into consideration in the new harmonic analysis. This update occurs each time step of the thermal analysis. This step is precisely determined to follow the heating progress inside the specimen. Fig. (6), shows the FE model of the designed coil and fig. 7, shows its mesh.

Figure 6. The FE model of the IC

The design of the coil optimized such that it will be compatible with the available power and terminal voltage. The achieved design able to melt the greater mass in a moderate time. The data of the furnace is shown in table 1. The range of current density (J) for water cooled tubing conductor is from (20 to 40) A/mm² [12]. So in this model can be used (20) A/mm².

The heating process continued until the average temperature of the copper mass reaches the melting degree of (1080 °C). Fig. (8) show the temperature vs melting time of about 35 minutes

Figure 7. The mesh of the FE model

Fig. (9), depicts the heat distribution inside the furnace at the end of the melting process.

The compatibility of the designed induction coil with the 60 kW, CFI [3], is explained by the following waveforms. These waveforms are

results of the Matlab simulation of the power supply described in fig. (1). Matlab results considering the furnace equivalent circuit values are shown in fig. (10-12). These are representing the induction coil current, the output voltage of the inverter, the line current, and its THD at this load.

Table 1. Mechanical And Electrical Parameters of Furnace.

Parameter	Value	unit
Mass of the copper to be melted	47.5	kg
The melting time	45	Min.
Operating frequency	10	kHz
Power required	47.5	kW
Voltage of coil	413	V
Coil current (I_c)	604	A
Outer diameter of the induction coil copper tube	10	mm
Inner diameter of the induction coil copper tube	7	mm
Number of turns (N_c)	10	-
Space between turns	2	cm
Diameter of induction coil (D_c)	20	cm
Height of induction coil (H_c)	30	cm
Diameter of crucible	15	cm
Full Height of crucible	35	cm
Thickness of the crucible	1.8	cm
IC equivalent resistance (R_{eq})	0.13	Ω
IC self-inductance (L_{eq})	13	μH

Figure 8. Temp. vs. Time curves of two nodes inside and at the periphery of the melt

Figure 9. The temp. distribution inside the furnace

Figure 10. The induction coil current

Figure 11. Tank circuit voltage

Figure 12. Line current and its THD factor

5. Discussion and Conclusions

The obtained design in this research can approve the validity of the proposed furnace to melt the specified quantity of copper. The implementation of this furnace is started to produce this high quality copper. Then, this furnace can be considered as a good choice for small investment projects. Also, it is very suitable for R&D laboratories due to its available rated power and productivity. It is suitable to melt other similar non-magnetic materials like Aluminum, Brass, ... etc. This system able to melt magnetic materials also, but another design of the coil is required due to the sever effect of such materials on the coil self-inductance.

Normally, the simulation of melting induction furnace has inherent drawbacks due to the nature of this process like:

- The resonance frequency of the tank circuit will be effected by the connection accessories of the induction coil and the capacitor bank. This means that the exact practical resonance frequency is not as that measured theoretically.
- The geometry of the scrap copper will be a mix of different dimensions, and different impurities, which cannot be simulated.
- The temperature increase, changes the properties of the specimen which leads to change the resonant frequency, and then the magnitude of the induction coil current.

Acknowledgment

The researchers appreciate Mustansiriyah University administration and the Dean of Engineering College to provide assistance and facilities, during this work. Also, they express their thanks to the Head of Elect. Eng. Dept. for here logistical support.

Conflict of interest

The authors declare that the publication of this paper does not include any conflicts of interest.

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