Power and Frequency Control in a 60 kW Induction Steel Heating Furnaces through PLC

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Abstract

Magnetic permeability (μ) and resistivity (ρ) of the materials experience large variations during heating in induction steel heating furnaces (ISHF). Power unit operating at mid frequencies is expected to observe these variations and keep the output power constant and in the active region. It is not easy to obtain heat, pressure and position control while controlling other units, by using microcontroller based systems in power units. These require a separate control unit, such as Programmable Logic Controllers (PLCs). New generation PLC systems are equipped to provide all the necessary control functions needed in an ISHF, as well as a PWM signal generator that can drive the switches of a dc/ac inverter. This provides the necessary tools for various control techniques such as classical control, artificial intelligence, fuzzy logic and adaptive control. In this work, controlling of an ISHF through classic control methods and PLC, and simplification of the system structure has been attempted.

Keywords: Induction heating, Inverter, PLC, PID control, Power and frequency control

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1. Introduction

Induction furnaces are used to heat metals by using the principles of induction. A nice feature of these furnaces is to create heat on the surface of the material. The furnace is designed by considering which part of the material will be heated and how long it will be heated. Since this is a very clean heating process no deterioration is made in quality.

Induction furnaces have found a wide range of application area in the last decades including heating, melting, welding, shrink fitting, forming, soldering, hot forming, hardening, cooking and plasma physics [1-3]. They can heat in the frequency range of 10 Hz to 60 MHz. Several different types of power supplies operating at different frequencies have been developed and used depending on the type of the application. Switching power losses have been reduced, safety at high frequency operation has been increased and weight has been reduced in the course of development of these supplies. In parallel to the developments in the power semiconductor technology, applications utilizing Insulated Gate Bipolar Transistors (IGBT) have become very common. Low conduction losses and low gate power requirement of IGBTs have made them the primary switching device.

Although ISHF have several advantages in practical applications, their design is not simple, and several inherent problems are met. Two serious problems especially become important when the material starts heating up in induction heating. The first problem is that increasing temperature leads to increased resistivity and thus the total resistance (R) of the material increases. This, in turn, causes a significant drop in the power drawn from the supply. The second problem occurs when the material temperature approaches to Curie point. Magnetic permeability (μ) decreases as this point is being approached and becomes unity at this temperature. This results in reduced inductance (L) value, and the resonance frequency changes. The active power transfer from the supply, again, decreases and heating time increases. Also, thermal losses occurring during this process extends the time to reach the desired temperature point.

Modern PLCs have large memory capacities, special functions such as PWM, data communication facility as well as attractive features like being modular and economically affordable.

Due to the PLC utilization in ISHF, position, temperature, pressure control and overvoltage and overcurrent protection become easier. Also, power unit can be controlled in any desired way. All these features of the PLC may help faciliate the production, control and automation of induction furnaces.

In this work, a PLC control system has been designed for an ISHF. Heating at constant power and proper resonance frequency have been achieved with the implemented system.

2. Developing a Simple and Reliable Technique to Determine Resonance

When the system is based on parallel resonance concept, it has been suggested by several researchers that the resonance frequency be determined by a phase locked loop (PLL) [4-7]. However, these systems are complicated, difficult to calibrate, and sensitive to noise. Therefore, researchers sought simpler and more reliable ways of implementing the system.

In parallel resonance circuits, inductor current (I_L) is larger than the capacitor current (I_C) when the operating frequency is below the resonance frequency. On the other hand, inductor current (I_L) is lower than the capacitor current (I_C) when the operating frequency is above the resonance frequency. The currents are equal at the resonance frequencies. This case is pictured in Figure 1. In this figure, amplitudes of the inductor and capacitor currents are drawn as functions of frequency.

A simple control scheme to achieve the desired output is modeled by using MATLAB Simulink software. Figure 2 depicts the operation of the controller as follows: Initially, the switching frequency (f_s) is higher than the resonance frequency (f_o). Therefore the capacitor current is higher than the inductor current. Therefore the controller acts to decrease the switching frequency to catch the resonance frequency. In order to simulate the real system as close as possible, the inductor value has been allowed to change linearly during the simulation. As seen in the figure, after some point, the controller decides to increase the switching frequency so that the system is kept in resonance.

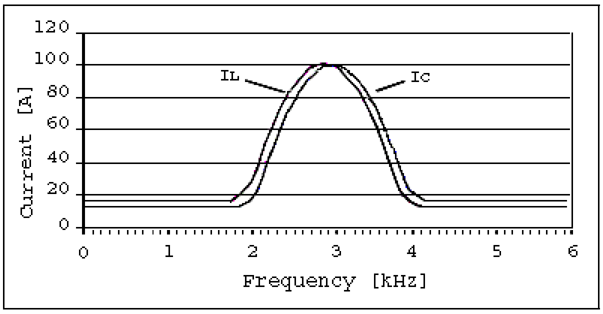


Figure 1. Current variation of the parallel branches depending on the frequency

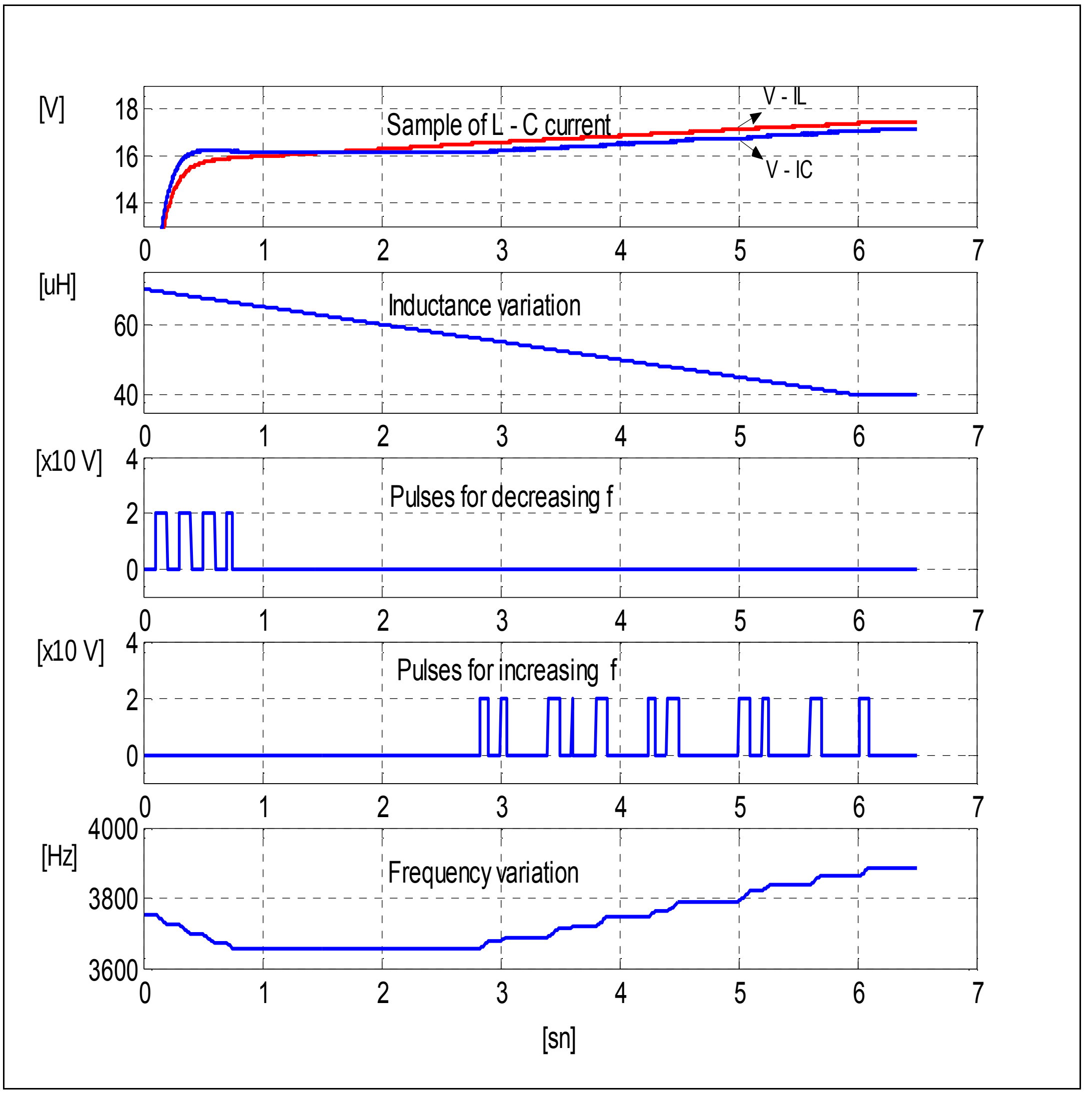


Figure 2. Resonance frequency adjustments (Simulation results in MATLAB Simulink)

3. PLC Program

Siemens's S7-200/ CPU 214 model PLC has been chosen for the hardware implementation based on benefit/cost criteria. This PLC has 14 inputs, 10 outputs and, PWM and PTO (Pulse Train Out) generators. These generators can be directed to Q0.1 and Q0.2 outputs. It also has the input-output capability to perform certain functions such as placing and removing the work piece, temperature, pressure and position control. Arrangements to respond to overcurrent, overvoltage and short circuit protection signals are also available. The written program has two main components: The first part generates the necessary pulses for the inverter, while the second one is responsible for the control of the induction furnace.

I0.0 and I0.1 inputs of the PLC can be used as interrupt inputs. Depending on the status of these inputs a four-bit region is defined in the M memory. With this definition, transferring the commands of increasing or decreasing the PWM pulse periods or duty cycles to PLC is aimed.

Since there are only two interrupt inputs in the PLC system, another input (I0.3) is also used to determine on which one of the two parameters, duty cycle or frequency, will be operated. Period and duty cycle adjustment selection of the PWM generator is done through the electronic switch enabling input to I0.3. An electronic circuit has been designed to determine the position of the electronic switch that inputs to I0.3, depending on the signals generated by PI control units. The priority is given to resonance frequency adjustment in this process.

The program can automatically determine the period and the duty cycle depending on the feedback signals sent by PI control units. It also allows manuel operation. Furthermore, pressure, temperature, overcurrent, overvoltage and short circuit protection as well as system turn-on and turn-off operations can easily be performed with very simple adaptations.

The flowchart of the program is given in Figure 3. Structural programming technique has been used in programming. Transfer to interrupt modules is done through the definitions on the main program and subroutines.

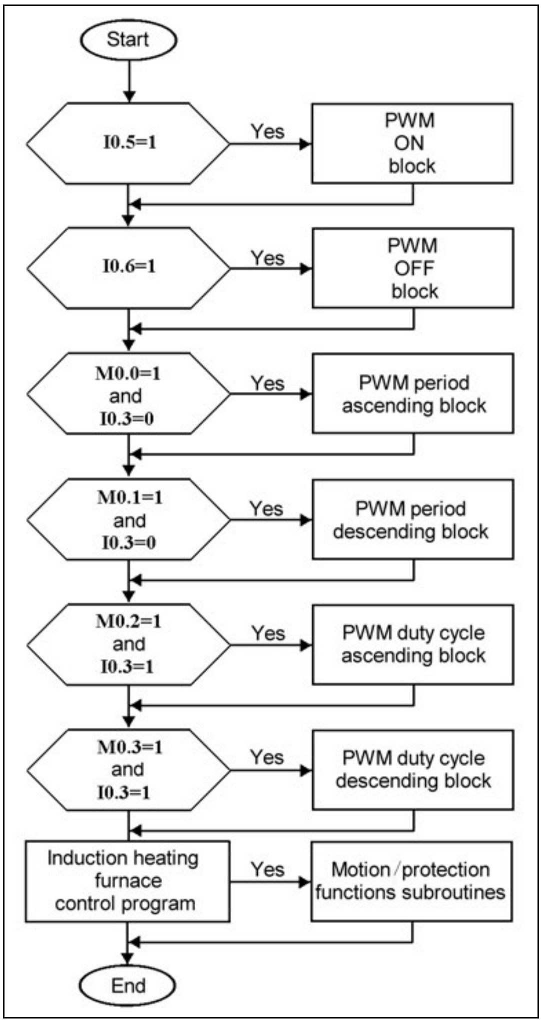


Figure 3. Flow Chart for the PLC Program

4. System Structure

The block diagram of the system is seen in Figure 4. It consists of a control unit, a power unit, a high frequency transformer (MFT), and a resonant tank containing a capacitor and heating inductor.

4.1 Power Unit

The power unit is an AC/DC/AC converter. It can provide up to 60 kW output power at any frequency between 5 Hz and 10 kHz. At the front of the converter is a three-phase uncontrolled rectifier, and the output is taken from an inverter with voltage and frequency control.

4.2. Rectifier

100 A, 1200 V Semikron SKKD100/12 three-phase half-bridge diode modules have been used in the rectifier section.

4.3. Inverter and Control Unit

The single-phase inverter utilizes two Semikron SKM 200 GB123D half-bridge IGBT modules. The rated values of the modules are 200 A, 1200 V. Siemens S7 214 CPU has been used as the PWM generator. The outputs of the PWM generators are applied to Semikron SKHI26/W gate drives after separated to positive and negative alternances [8,9].

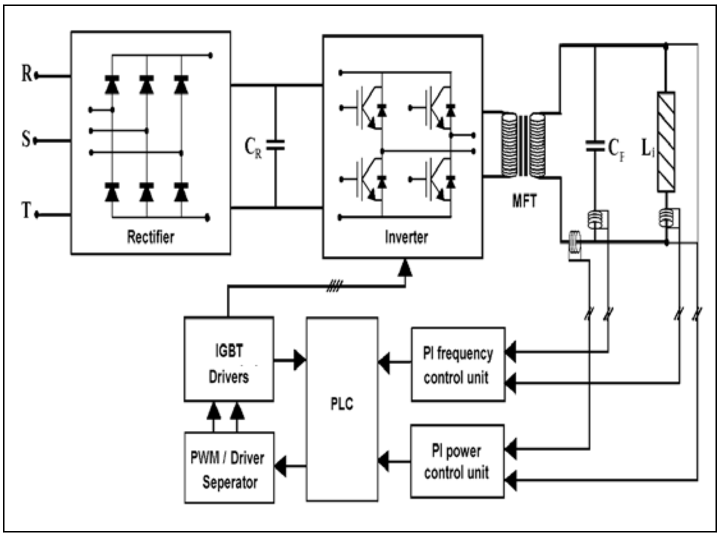


Figure 4. Block Diagram of the Designed Induction Steel Heating Furnace.

PI controllers are used in the frequency control unit. Current samples received from the inductor and capacitor are separately converted to voltage and filtered. Each signal, then, is passed through a PI regulator. PI regulator outputs are applied to a differential amplifier. The bandwidth of the amplifier can be adjusted. Finally, the output of the differential amplifier is used to control the PLC drive.

Power control unit also has a PI regulator. Load voltage and current are sensed, rectified, filtered and multiplied. The result, then, is passed through a PI regulator. A differential amplifier amplifies the difference between the output of the regulator and the reference value. This amplified signal is used to control the PLC driver.

4.4. Mid Frequency Transformer

The Mid frequency transformer has a turn ratio of 10/25, and rated values of 500 V/ 1250 V, 55 kVA. A 0.1mm thick, 35000 Gauss laminated steel is used to build the transformer [10,11].

5. Experimental Results

5.1. Power Analysis

Computations performed on the pipe material showed that cold value of the inductance is 67.8µH, and it drops down to 63.17µH when heated. Similarly resistance value increases from the cold value of 16.3 µΩ to 13 mΩ when heated. A capacitor with a value of 28.82µF was used to be in the neighborhood of 3 kHz resonance frequency. The initial resonance frequency with these conditions is given as

$$f_0 = \frac{1}{2\pi\sqrt{L.C}} = \frac{1}{2\pi\sqrt{67{,}8.10^{-6}.28{,}82.10^{-6}}} = 3600 \quad Hz \tag{1}$$

(A resonance frequency of 3730 Hz is obtained when the material temperature is 1250 °C.)

Figure 5 shows the secondary side voltage and current information at the frequency obtained from (1) when there is no power or frequency control. Numerical values of the curves seen in Figure 5a are given in Table 1. The increase observed in the curve following the minimum point should not be misinterpreted as a power increase. As seen in Figure 5b, the phase difference between the voltage and current is as high as 60° and the system is operating in the inductive region. As the power drawn in this region is very low, instead of the expectation that the temperature settles at 1250 °C in 25 seconds, it takes 160 seconds to reach 900°C.

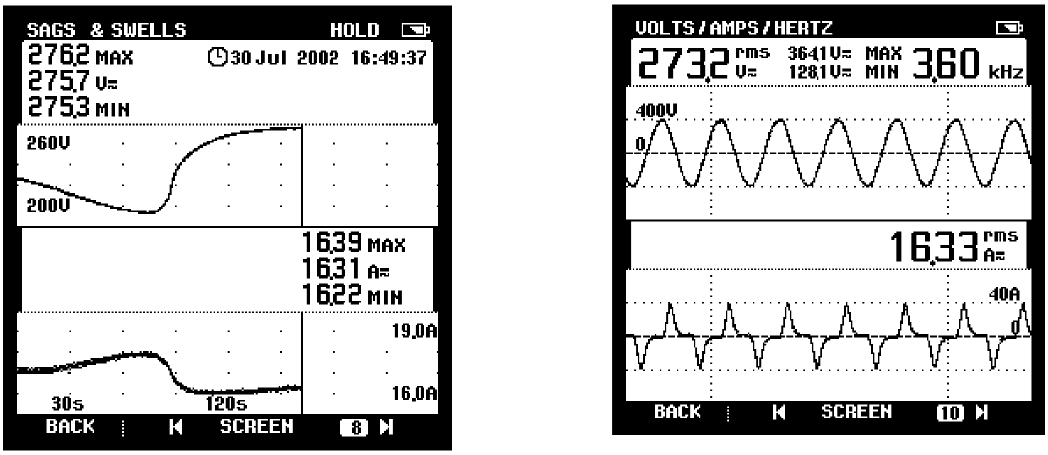
Figure 6 shows experimental results when the control unit is used. The system was used to heat a pipe and a solid cylindrical material. In figure 6a, ac input line current and voltage variations are shown. Power factor (PF) at the input was measured as 0.89 (pipe) and 0.93 (solid). The power (P_p) in the pipe heating was calculated as follows:

$$P_p = U.I.Cos\,\phi = 400.4x55.5x0.89 = 19777.758 \cong 19.8 \quad kW \tag{2}$$

The power for the solid cylindrical material case (P_s), on the other hand, is

$$P_s = U.I.Cos\,\phi = 398.3x65.5x0.93 = 24262.445 \cong 24.3 \quad kW \tag{3}$$

Figure 6a-b proves that current and voltage variations are with in the acceptable limits (±%3).



(a) (b)

Figure 5. Secondary voltage and current in uncontrolled operation (a) RMS value variation (b) waveforms

Table 1. Numerical Values for the Variations Seen in Figure 5a

Time [s]	0	15	30	45	60	75	90	105	120	135	150	160
V [V]	226,9	220,7	212,0	209,2	197,8	194,6	233,8	258,6	268,8	273,2	275,0	275,7
I [A]	17,10	17,19	17,35	17,64	18,85	17,88	16,62	16,10	16,09	16,15	16,26	16,31
S [KVA]	3,88	3,79	3,68	3,69	3,73	3,48	3,89	4,16	4,32	4,41	4,47	4,50

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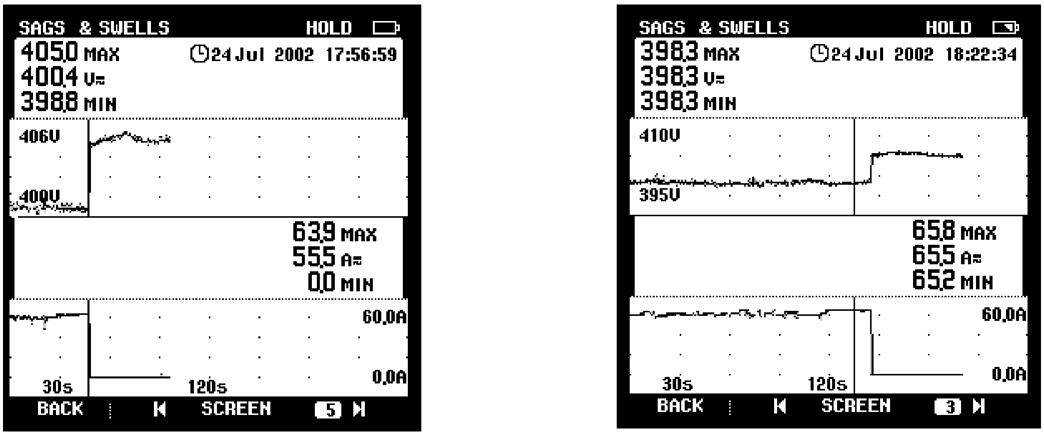


(a) (b)

Figure 6. AC Line voltage and current variations with controlled operation (a) pipe (b) solid cylinder

5.2. Frequency Analysis

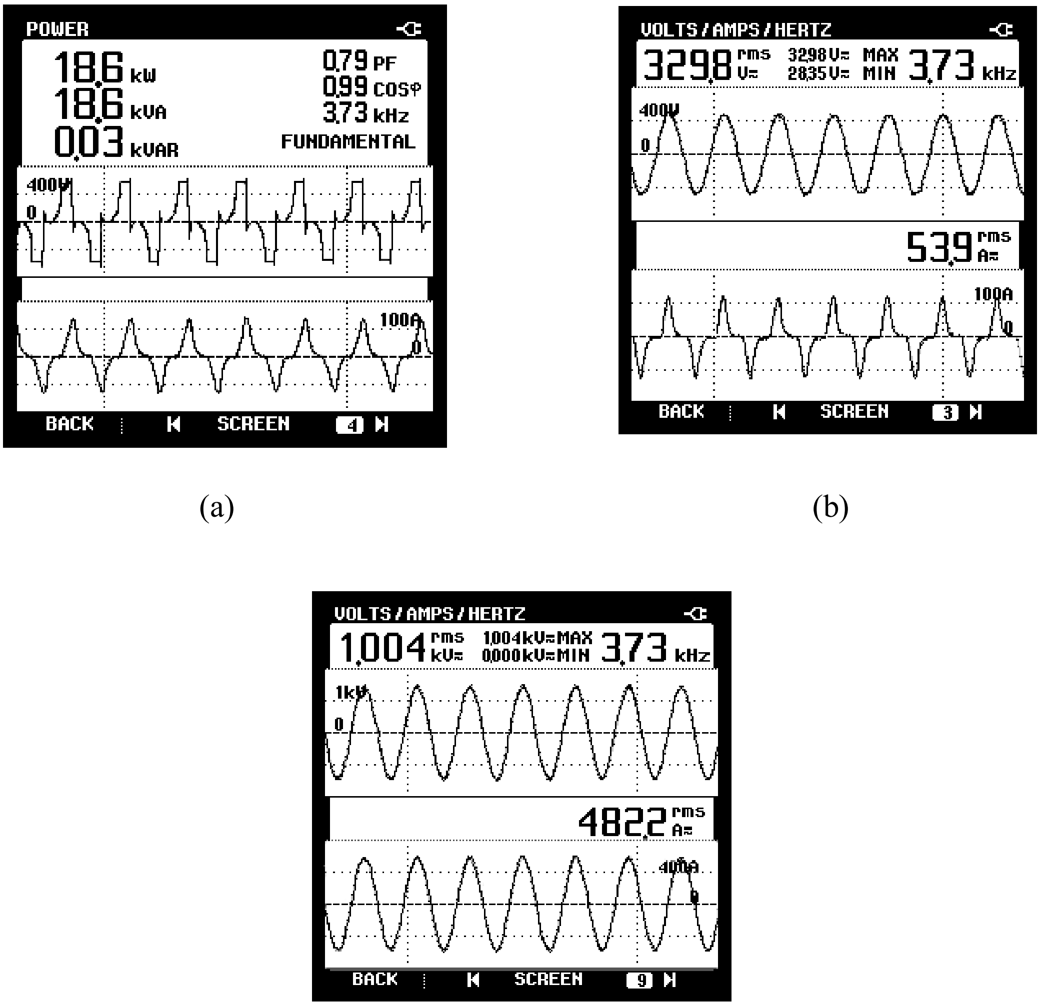
One picture from the primary and two pictures from the secondary side of the high frequency transformer were taken for frequency analysis. These waveforms are given in Figure 7a-c.

Figure 7a shows the primary power variation. It is seen that primary power is 18.6 kW at 0.79 power factor (with 0.99 displacement factor). The instantaneous resonance frequency of the system is 3.73 kHz.

Figure 7b shows the secondary side voltage, current and frequency. Again, a measurement of ~330V and ~54 A is read at 3.73 kHz. From the figure, it is seen that voltage and current waveforms (fundamentals) are in phase, and thus resonance condition exists. By considering that the power factor is 0.79, the total power is found as

$$P_i = U.I.\mathrm{Cos}\,\varphi = 329.8\mathrm{x}59.9\,\mathrm{x}0.79 \cong 15.6\mathrm{kW} \qquad (4)$$

The power difference between the input and output is mainly due to the loss mid frequency transformer. By designing and building a more efficient transformer this loss can be reduced. Figure 7c shows the secondary voltage, current and frequency data when the system is operating at an input power level of 55 kW. The secondary power at this case is 48.4 kW.



(a) (b)

(c)

Fig. 7. MFT data of (a) primary side power (b) secondary side voltage and current at reduced power (c) secondary side voltage and current at full power (with 1/10 current probe)

Figure 8. and 9. show the cold and heated materials used in the tests.

Fig. 8. Cold material inside the inductor

Fig. 9. The material at 1250°C

6. Conclusion

A system has been designed and built for induction steel heating furnace. It has been tested with a pipe and solid cylindrical steel material, with various capacitor and inductor values. During all these tests, the system has been able to follow the resonance frequency and power variations.

In this work, a system suitable for PLC control with modular and very flexible structure has been built. The next stage in the work is to use analog input/output ports to achieve PID control inside the PLC so that the other control cards can be removed from the system. Also, it is possible to use adaptive control, fuzzy logic and artificial intelligence techniques in this system. Now the system enables one to control several processes such as material loading, material selection depending on time of the day, responding to fluctuations on the ac line voltage, and interactions between the units following the heating.

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