State-of-the-Art of an Induction Furnace: Design, Construction and Control

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***Abstract*— As a result of energy crisis, there is large innovation in heating and the electrical systems have progressed from low voltage to high voltages or multilevel to multiphase system. Induction furnaces employed for the melting metals can be well implicit and optimized electromagnetically. Still a novel challenge ascends, when the entire device is considered. The vibrations and the acoustic noise are of predominant importance, as the frequency of operation and the rated power of the devices are rapidly rising. A clean, energy-efficient and well-controlled melting process is advantage when the induction furnace is compared with other melting processes. It uses high frequency electricity to heat up the materials that are electrically conductive in nature. As it is non-contact heating process, it does not pollute the material being heated. It is also very efficient as the heat is actually produced within the work-piece. This leads to differ with other heating methods where heat is produced by either a flame or heating element, which is then supplied to the work-piece. Hence an induction heating offers itself some unique applications in industry. In this manuscript, a finite-element analysis of the furnace is presented and compared with the results from the experimental furnace in order to design the induction furnace. Power supplies can be in ranges from 10 kW to 42 MW, with melt sizes of 20 kg to 65 tonnes of metal respectively.**

Keywords*— Induction furnace, Resonant tanks, Impedance matching network, work coil, power controller.

I. INTRODUCTION

Currently, there is huge progress in heating because of energy crisis [1]-[3] and the electricity systems are improving from low voltage to high voltages or multilevel to multiphase system [4]-[9]. Due to converters, these days the electrical systems are easy-going in control [10]-[20]. Heating process without any contact is the principal attribute of induction heating. It encompasses high frequency supply through conductive part. This high alternating current is allowed to circulate through a coil called as work coil [21]-[22]. Rapidly varying field is formed inside coil. The work piece is heated by locating it inside the work coil. The alternating magnetic field induces a current through work-piece. This arrangement of work piece inside work coil bears a resemblance to an electrical transformer. The work coil is believed as a primary side where energy is supplied. The work piece is believed to be secondary side with single turn shorted triggering high value current to flow through work-piece. This current can be stated as eddy current. Furthermore, a phenomenon of skin effect is too presented for the reason of utilizing high frequency in induction heating and impacts the alternating current to flow in a thin layer towards the surface of the work-piece. The effective resistance of the metal for passing enormous current is amplified by skin effect which leads for increase in the heating effect instigated by the current induced in the work-piece.

For ferrous metals like iron and certain varieties of steel, mechanism encompassing eddy currents is unveiled. This is called as Hysteresis loss which is maximum for materials having a large area under their B-H curve [1]-[3], [21]-[22]. The magnetic field formed inside the work coil effects into rapid magnetization and demagnetization of iron crystals causing substantial resistance and heating inside the material. And so ferrous materials contribute themselves further effortlessly for heating by induction than non-ferrous materials [1]-[3].

The substantial element to be discussed about steels is their behaviour of losing its magnetism when heated above 700°C temperature (Curie temperature) as a result of hysteresis losses. Surplus heating of the material is due to induced eddy currents only, leading as a challenge for the induction heating systems. The non-magnetic and good electrical conductors like copper and aluminium too results into a challenge of efficient heating. In this research, the best course of action for these materials is to uphill the frequency to exaggerate losses caused by the skin effect [21]-[22]. The three foremost requisites for designing and construction of induction furnace are a High Frequency electrical power supply, a work coil for production of the varying magnetic field and an electrically conductive work-piece for heating.

Induction heating systems are quite complex systems requiring certain impedance matching networks between high frequency source and the work coil for secure power transfer. But there is difficulty in this circuit. For removing waste heat through work piece, water cooling systems are necessitated. Ultimately some semiconductor technology is frequently involved for regulating the intensity of the heating action, and instant of heating cycle for consistent results. There may be different contradictory circumstances for passing on account of high frequency alternating power supply. The semiconductor technology safeguards the system from being damage. Still, the basic notion of operation of any induction heater remains the same as illustrated previously

II. SYSTEM DEVELOPMENT

An induction furnace is an electrical furnace in which the mode of heat application is by way of induction heating of metal. This method is clean, energy efficient and well controllable and thus it is one of the preferred heating practices. Due to absence of arc or combustion, the temperature of the material is not higher than required to melt it preventing the loss of valued alloying elements.

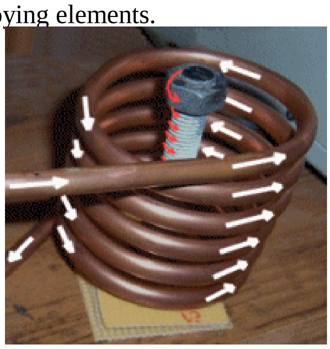

Fig. 1. Induction coil

In this manuscript the commissioning frequency ranges from utility frequency (50 or 60 Hz) to 400 kHz or higher. This operating frequency is primarily reliant on melting material, capacity of furnace (volume), and required melting rate. In induction heating, volume of furnace and frequency of supply are inversely relative.

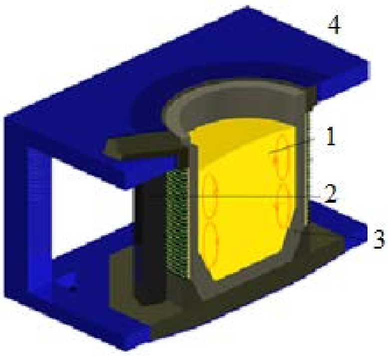

Fig. 2. Cross section of Furnace

1-Melt 2-Water-cooled coil 3- Crucible 4- Yokes

Two sorts of induction furnace are crucible induction furnace and coreless induction furnace. Hitting a granular refractory between the coil and hollow internal former results into the formation of crucible which is melted away with the first heat leaving a sintered lining.

The power crucible delivers the necessary voltage and frequency of main supply for electrical melting. Frequencies used in induction melting vary from 50 cycles per second (mains frequency) to 10,000 cycles per second (high frequency). The increase in operating frequency intensifies the amount of power supplied to furnace of given capacity and lessens the amount of turbulence induction.

When the charge material is smelted, a stirring action within the molten metal is produced as a result of interface of the magnetic field and the electrical current through induction coil. This stirring action reasons the molten metal to actually rise upwards. The magnitude of stirring action is affected by the power and frequency applied moreover the size and shape of the coil and the density and viscosity of the molten metal. The stirring action in the interior of the bath is of extraordinary significance as it aids with mixing of alloys as well as retaining equal temperature all the way through the furnace. There may be an unnecessary stirring which can become reason of gas pick up, lining wear and tear, oxidation of alloys, etc.

The coreless induction furnace is ordinarily used furnace than the crucible furnace, particularly when melting point of alloys to be heated is high. The coreless induction furnace is commonly used to melt all qualities of steels and irons as well as many non-ferrous alloys. The furnace is ultimate for re-melting and alloying because of the absolute control over temperature and chemistry.

Refractory lined steel casing can be considered as the channel induction furnace comprising the molten metal. The steel shell and connecting throat forms melting component of the furnace. This is called as an induction unit. The induction unit is made up of an iron core prominently in the ring form around which a primary induction coil is wounded. This assembly bears a resemblance to a simple transformer in which the molten metal loop is the secondary component. The heat generated within the loop leads to the circulation of metal into the main well of the furnace.

Here a Power supply is ranging from 10 kW to 42 MW, with melt sizes of 20 kg to 65 tonnes of metal respectively. Induction motor more often does not produce the hums due to varying magnetic forces becoming identification to operator regarding operating circumstance of furnace and its power level.

The resonant tank circuit forms an important part in induction furnace. The work coil is usually integrated into a resonant tank circuit incorporating different advantages comprising sinusoidal current and voltage waveform, minimization of losses by letting either zero-voltage switching or zero current switching depending on exact assembly. The attained sinusoidal waveform from work coil characterizes a pure signal and thus less radio frequency interference occurs to nearby equipment. When this system is deliberated with other systems, this point becomes very important in high power applications. Numbers of resonant scheme are applied so that designer of an induction heater has choice for the work coil. Circuit diagram for induction furnace is shown below which includes parallel resonant tank circuit, impedance matching circuit, and the LCLR work coil.

Parallel resonant tank circuit: Here the capacitor is positioned parallel to work coil with the intention of resonating at intended frequency. This leads to the amplification in current through work coil. This is very noteworthy since there are low power factors in induction heating applications. In the parallel resonant tank circuit, the work coil can be assumed as an inductive load with a "power factor correction" capacitor connected across it. The work coil comprises few turns of thick copper but with large currents flowing of value hundreds or thousands of amps.

Conduction losses are in reality reliant on square of current. In this manner, decrease in conduction losses takes place as full circulating current is not passed through coil. There is constant dielectric loss existing because of capacitor and skin effect bringing about resistive losses in work coil. A small current has been drawn by the circuit despite the fact of absence of work coil. There is damping of resonant circuit resulting to additional losses from system if faulty work piece is implanted in work coil. So there is rise in current drawn by parallel resonant tank circuit whenever work piece is placed in work coil.

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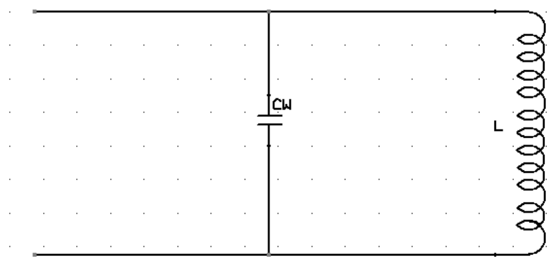

Impedance Matching Circuit: This circuit is positioned between high frequency power source and the work coil. Very high value of current has to be passed through work piece while dealing with solid piece heating by means of induction furnace. This becomes contradictory with inverter circuit operated for high frequency generation. The functioning of inverter can be considered superior, if operated at high voltage but at low current thereby matching impedance between source and work piece.

The work of the matching network and the work coil is to change over the high-voltage/low-current from the inverter to the low-voltage/high-current necessitated to heat the work piece efficiently. The work coil (Lw) and its capacitor (Cw) is encompassed in circuit as a parallel resonant circuit.

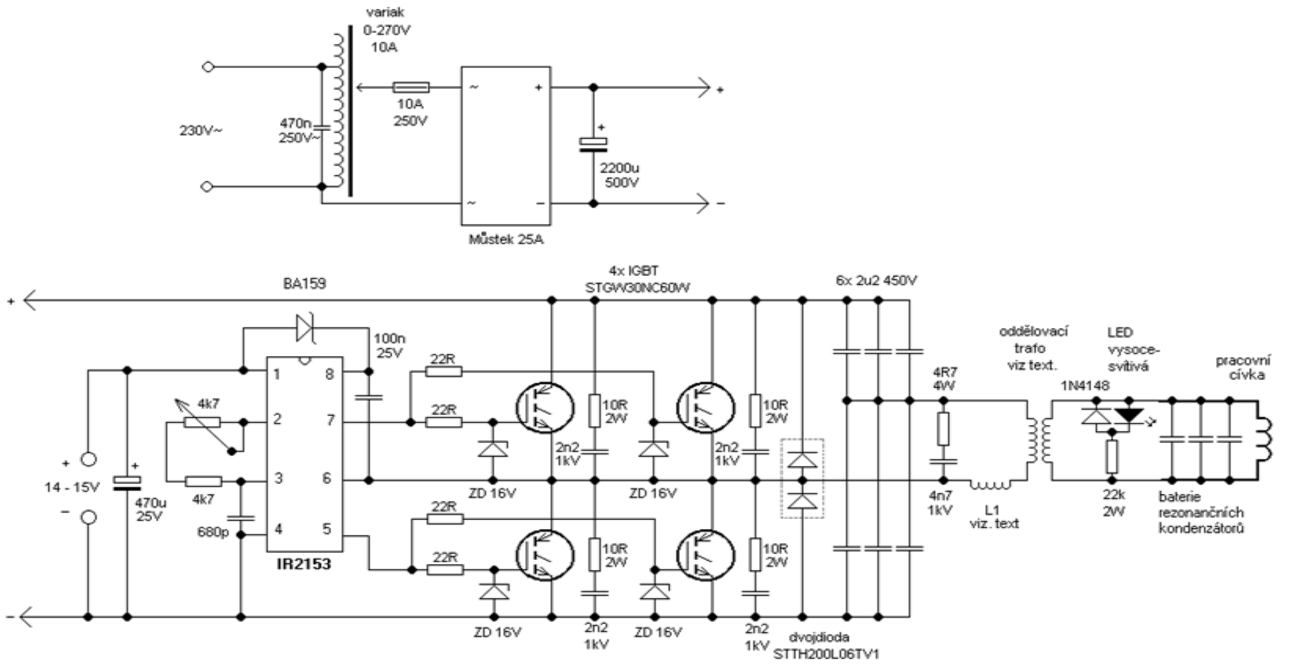

Fig. 3. Parallel resonant tank circuit

Fig. 4. Circuit Diagram

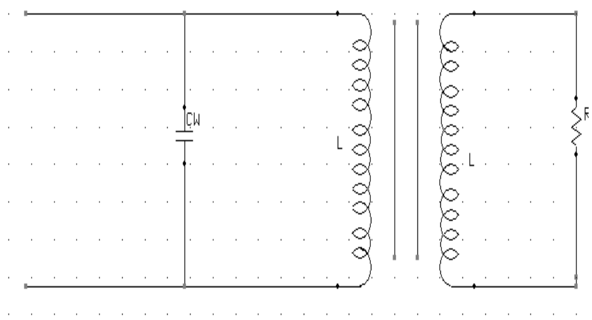

Fig. 5. Impedance Matching Circuit

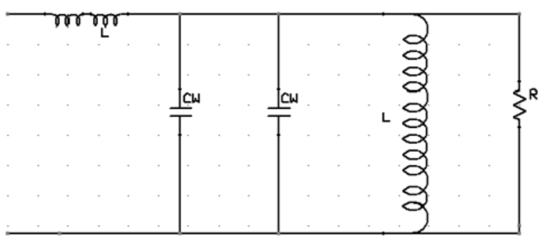

Fig. 6. L Match Network

A resistance (R) is connected as a result of the lossy work-piece is connected to the work coil and the magnetic coupling between the two conductors. Due to resonance, the current of almost same magnitude but with opposite phase is drawn by tank capacitor and work coil thereby canceling out each other. The resistance across tank circuit only provides opposition. This loss resistance is simply restored down to lower value suitable to inverter circuit by matching impedance circuit

The impedance transformation can be recognized in many other means such as using tapping to work coil, use of capacitive divider circuit as a substitute to tank circuit capacitor and using ferrite transformation. L-match network is usually applied to drop down the tank resistance up to 10 ohms suitable for inverter operation.

For performing switching operation of MOSFETs, the voltage is maintained at several hundred volts while current down to medium level. Due to L-Match network the required power is delivered to work piece from inverter. The increased inductive reactance to high frequency harmonics leads to secure operation of inverter.

The LCLR work coil: In this circuit, parallel resonant circuit consists of work coil which is between capacitor and resistor. L- Match network is located between tank circuit and inverter. Some desirable properties of LCLR work coil are the incorporation of the L-match network into the LCLR work coil arrangement helps in removal of a transformer to match the inverter to the work coil resulting in cost saving and simplified design. This offers sinusoidal load current to facilitate benefits from ZCS or ZVS to reduce its switching losses.

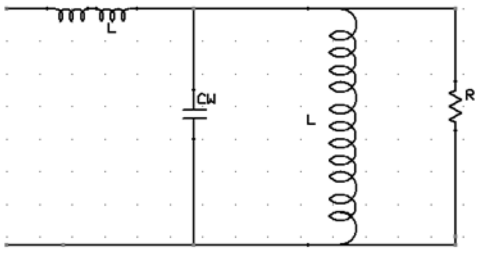

Fig. 7. LCLR Work Coil

III. DEMONSTRATION PROTOTYPE

The schematic shown below demonstrate the inverter driving the LCLR work coil arrangement.

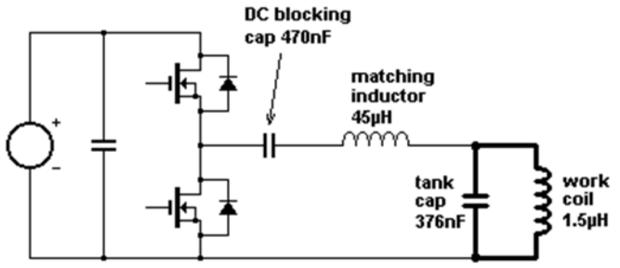

Fig. 8. Half Bridge induction Heater Using LCLR Work Coil.

The half bridge inverter was employed in this demonstration including two MTW14N50 MOSFETs and smoothed DC supply is provided to inverter. For maintaining AC current demand of inverter, capacitor is connected across the rails. DC blocking capacitor is applied to prevent DC output from half bridge inverter resulting in flow of current through work coil and does not participate in impedance matching.

In high power application full bridge inverter mainly H-bridge inverter involving four or more switching devices can be designed. In this case the drive voltage needs to be balanced with respect to ground thereby matching inductances usually split between two bridge legs equally. Although implementation of number of separate inverters effectively is possible but to satisfy the high current demand it has to be connected in parallel. However these separate inverters are not directly coupled in parallel at output terminals of H- bridge inverter.

The impedance between any two inverter outputs equals to double the value of the matching inductance is merit of this circuitry. If switching instants are unable for perfect synchronization, this inductive impedance restricts the "shoot between" current flowing between paralleled inverters.

Power Control Methods: For determining the rate at which heat energy is transferred to work piece, control of power processed by an induction heater is often desirable. Some methods applied to control power flow are:

A. Varying the DC link voltage:

The power processed by inverter can be regulated by increasing or decreasing power supply to inverter by supplying a variable voltage DC supply. Varying the DC link voltage allows full control of the power from 0% to 100%. However, the accurate power throughout in kilowatts depends not only on the DC supply voltage to the inverter, but also on the load impedance that the work coil presents to the inverter through the matching network.

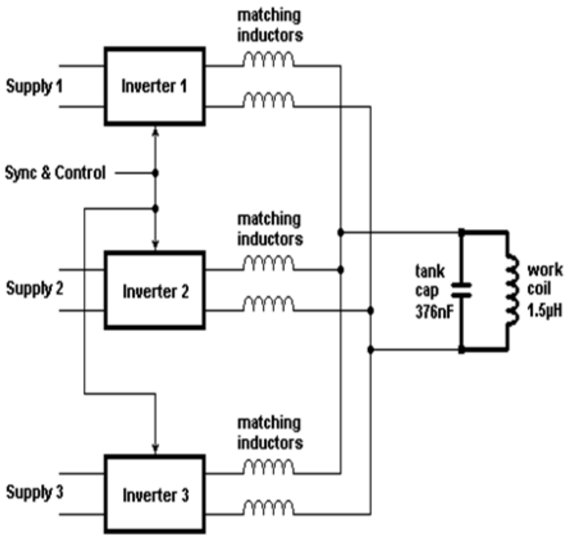

Fig. 9. LCLR Induction Heater Using Multiple Distributed Inverters

B. Varying the duty ratio of the devices in the inverter:

The power can be controlled by changing duty ratio of switches. When the devices are switched on, power is supplied to the work coil. The commutation of heavy currents between active devices and their free-wheel diodes is key problem of this method. On account of this reason, duty ratio control is not frequently used in high power induction heating inverters.

C. Varying the operating frequency of the inverter:

The inverter is normally detuned on the high side of the tank circuits by natural resonant frequency to reduce the power. This triggers dominant inductive reactance at the input of the matching circuit with the increase in frequency. Therefore the current drawn from the inverter by the matching network lags in phase lowering the amplitude. Both of these factors participate for reduction in the real power through output.

D. Varying the value of inductor in the matching network:

Matching network normally converts load impedance from work coil to suitable load impedance that can be driven by the inverter. In fact, the work coil impedance decreases as value of inductance is reducing ultimately lessens the power to be supplied from inverter.

E. Impedance matching transformer:

RF power transformers with tapings can be utilized in circuit to coarse step the work coil impedance. The duty of electrical isolation and performing impedance transformation to set the power throughput is also provided by ferrite power transformer. The transformer should be designed in such a manner that they have minimum inter-winding capacitance and high insulation at the rate of high leakage inductance.

F. Phase-shift control of H-bridge Inverter:

There is alternative method of attaining power control when the work coil is operated by a voltage-fed full-bridge (H-bridge) inverter. There is possibility of controlling power if independent switching of both the bridge legs is feasible by adjusting the phase shift between the two bridge legs. When both bridge legs switch exactly in phase, same voltage is offered as output. This connotes that no voltage and no current is appearing in the work coil. On the contrary, when both bridge legs switch in anti-phase, maximum current is flowing through the work coil and maximum heating is accomplished. When compared to the drive of other bridge leg, power between 0% and 100% can be attained by changing the phase shift of the drive to one half of the bridge between 0 degrees and 180 degrees.

This technique proves to be extremely effectual as power control can be achieved at the lower power control side. Since the inverter is not detuned from the resonant frequency of the work coil, the good power factor is always noticed by the inverter; hence reactive current flow through free-wheeling diodes is diminished.

IV. CONCLUSION

In this study, application of induction furnaces for the melting metals is discussed. Clean, energy-efficient and well-controlled melting process is benefit of the induction furnace when compared with other melting processes. As inductions furnaces are non-contact heating process, they never contaminate the material being heated. Due to actual heat generation inside the work-piece, very high efficiency is obtained. A finite-element simulation of the furnace is also exhibited in comparison with the results from the experimental furnace.

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