Air-cooled Induction Heating Solution for Heat Treatment of P91 Grade Steel in Welding Applications

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ABSTRACT

To have long operating life and to withstand high temperature and pressure of steam, now a days, the standard material used in power industry is the P91 Grade steel. It has high creep resistance. In a fabrication process when arc welding is used for joining this material the high energy density of arc heat makes strong influence on its microstructure. Moreover, the prospect of hydrogen cracking increases if pre-heating is not properly done. Therefore, for long term quality of P91 Grade steel, detailed heat treatment operation must be performed before and after the welding. For heat treatment operations, the induction heating method is ideally suitable. This article proposes to use air-cooled system to improve the efficiency of power delivery to the requisite area of pipe in high power applications.

Keywords: Post weld heat treatment (PWHT); programmable logic controller (PLC); self-tuning controller; wide range induction heating; zero voltage and near zero current switching (ZVS-n-ZCS).

1.0 INTRODUCTION

Engineering processes evolve continuously to achieve better productivity and quality at improved energy efficiency to reduce the cost of production of end items. To boost the efficiency of thermal power plants the pressure and temperature of modern power plants are increased appreciably. For reliable operation of power plants the materials used for such system should have long service life. The materials used for such extreme conditions need to have high creep resistance and low thermal expansion coefficient and their physical properties should not change over time. P91 grade steel is preferred for these applications [1-4]. It contains 9% Chromium, 1% Molybdenum and small percentage of Nickel and Manganese.

For fabrication of pipes and other structures the high energy density arc welding process [5] is used. P91 Grade material has great affinity to hydrogen. Naturally, the prospect of hydrogen cracking in P91 grade steel is high. Therefore, prior to welding the moisture content around the joint is removed through pre-heat treatment procedure. Pre-heating, maintaining inter-pass temperature and post weld heat treatment (PWHT) are pre-requisite for P91 Grade steel. Following are the benefits of heat treatment process:

1. Improving the diffusion of hydrogen out of the weld metal
2. Softening the heat affected zone (HAZ)
3. Improves ductility
4. Increase creep resistance
5. Remove residual stress, and,
6. Hardness level is reduced, etc.

For heat treatment of steel, to achieve temperature profile similar to **Fig. 1**, the induction heating principle [6-16] is most suitable. The pre-heating, inter-pass and sub-profiles p, q, r an s depend on material and applications. Here, an energized induction coil supplies heat energy to a specified zone accurately in a non-contact mode. The delay in power actuation is negligible. The source does not need any cooling time either as the coil itself does not get heated up. Accurate feeding of quantum of heat or energy is possible as the efficiency of power transfer from source to the specified area, when compared with other means of heating, is maximum. Moreover, the heat energy can uniformly be transferred throughout the desired periphery of a pipe. By changing the frequency of coil current and with proper coil design the distribution of heat can be altered. It is a clean and energy efficient method. It does not need any start up time. The process is environment friendly. Its arrangement is also simple. Two arrangements of pre-heating of welding pipes are shown in **Fig. 2** and **Fig. 3**. **Fig. 4** shows PWHT arrangement using two number of 40 kW controllers.

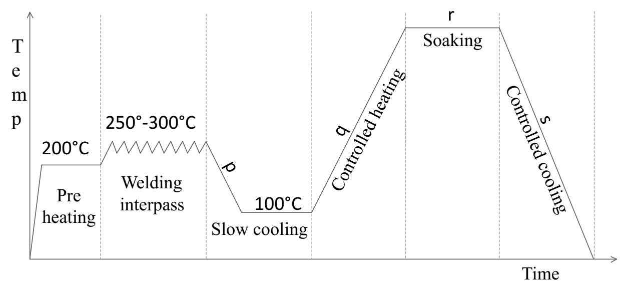

Fig. 1 : Typical temperature profile during different heat treatment phase of P91 grade material

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Fig. 2 : Arrangement of induction heater for pre-heating of circular welding joint of pipe

The quantum of energy to the pipe depends on inductance value L1 of coil and current i_s passing through it. It also depends on frequency. Generally, the induction coil carries large current. Normally, the coil is water cooled because large power loss takes place in it. It is contributed mostly by high-frequency skin and proximity effects. The impact of proximity effect on loaded coil is, however, much reduced. The large usable current density makes the water cooled coil compact. However, the coil needed for heat treatment of pipes is more spatial where litz wire based air cooled coil is preferred [10]. The power loss in air-cooled coil is much less [11]. But its current density is moderate. It needs large value of L1 to feed the requisite power to the welding section. Air-cooled coils are flexible as well. For power enhancement either more coils could be added or separate converters could be deployed. Either parallel or series resonant topology [16], could be suitable for heating of pipes. Parallel resonant topology is complex and needs more power components. It is costly as well. In this article, series resonant inverter with separate power control circuit is proposed. The rest of the article is organized as follows: Section 2 briefly discusses heating mechanism of P91 Grade Steel. Section 3 details the control structure of pipe heating system. Section 4 proposes the suitable induction heating system for pipe welding applications. Finally Section 5 details the implementation of the system and a few experimental results.

2.0. HEAT TREATMENT OF P91 GRADE STEEL

A typical temperature profile for complete heat treatment process of P91 Grade steel is shown in **Fig. 1**. The basic aim,

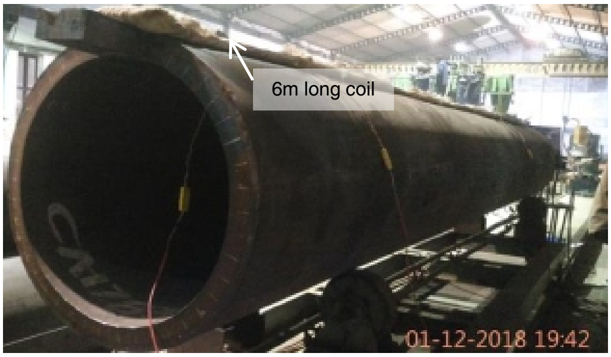


Fig. 3 : Arrangement of induction heater for pre-heating of longitudinal welding joint of pipe

Fig. 4 : Two inter-locked controllers feeding two coils for PWHT at 750 deg C

for example, in the first case of pre-heating of pipe, is to achieve the desired temperature to remove any moisture content in it. The pre-heating is done in such a manner that the temperature just prior to welding around the zone where welding to be performed remains at least more than 100 ^{o}C. Post heat-treatment needs to be followed meticulously. The parameters such as rate of temperature rise or fall during heating and cooling cycles depends on thickness and diameter of the pipe, and so is the soaking period. For a particular diameter if temperature during soaking period is changed then its duration needs to be changed. For geometry of coil design and its layout the width (W) of the heating zone is decided by the formula [3].

$$W = 5\sqrt{R_{in} t_{sh}} \quad (1)$$

R_{in} and t_s respectively are inside radius and thickness of the pipe, their unit is in mm.

The power rating of the induction coil P_L is decided by the cumulative effect of three parameters, they are

1. Energy needed to raise the temperature of heating zone
2. Excess mass heated by conduction effect
3. Wastage of energy by convection and
4. Wastage of energy by radiation

The controlled temperature of the desired section of the pipe depends on the highly nonlinear dynamic equation of energy balance, it could be expressed as

$$P_L = mC_p \frac{dT}{dt} + hA(T - T_{amb}) + \varepsilon\sigma A(T^4 - T_{amb}^4) \quad (2)$$

A (m^2) is area of heated zone and ε is emissivity of steel and σ is Stefan-Boltzmann constant, and m is mass of steel to be heated to T (in ^{o}K), C_p is specific heat and P_L is power transferred to the specified area of the pipe. The temperature of job increases the power loss at high temperature increases exponentially. Proper shielding arrangement is needed.

Considering that there is no loss by radiation and convection then the minimum time t (in hour) required to take the temperature to T^{o}C of specified area of pipe or slab is

$$t = \frac{mC_p (T - T_{amb})}{3600 P_L} \quad (3)$$

The mass m may be expressed as

$$m = k_0 \pi W t_p \rho_p \frac{(d_1 + d_2)}{4} \quad (3a)$$

Where d_1 and d_2 respectively are the inner and outer diameter of the pipe of density ρ_p and t_p is its thickness. The parameter k_0 (>1) depends on operating temperature, dimension of the pipe and desired temperature slew rate.

The heat flow rate or power P_L deliverable onto the pipe depends on too many factors of the inverter system because

$$P_L = k_1 V_{L1} i_S \quad (4)$$

V_{L1} is voltage induced across inductance L1 of coil, i_S is coil current and k_1 depends on coupling between coil and job.

Heat treating applications of welding pipes ideally need through heating. However, it is avoided as it requires bulky power source and coil dimension would be large. The effective approach is to transfer the power uniformly throughout the periphery with certain depth of penetration. Then, thermal conduction takes care. For heating large surface the nature of distribution of P_L in the pipe is important design consideration. The requisite power density (W/mm^2) is moderate. In induction heating the heat is uniformly dissipated on the surface of the pipe in the form of annular ring around the landscape of coil whose depth or thickness δ at inverter frequency f_s is expressed as

$$\delta = \frac{1}{\sqrt{4\pi^2 X 10^{-7}}}\sqrt{\frac{\rho}{\mu_r f_s}} \quad (5)$$

Where μr and ρ respectively are relative permeability and resistivity of the parent metal of pipe. The value of δ mostly depends on μ_r and f_s. Extremely thin surface heating would lead to overheating of thin annular surface. Therefore, design of induction heating means compromised choice of L_1, i_s and f_s, the value of f_s is not kept large.

3.0 SELF TUNING CONTROLLER

The basic structure of the controller for pipe heating application is shown in **Fig. 5**. The control is executed in two loops. The outer loop executes temperature control algorithm. For most pipe heating applications the response time for temperature control loop is large. The output of outer loop control is used as power reference to achieve the desired temperature profile. The actuation in inner loop is through excitation of the coil L1 at requisite frequency and current. Its response time is small. It is aimed to achieve the requisite power control through use of induction heating equipment.

The control of desired temperature profile is the primary objective. The expression of PI control using self-tuning control algorithm the control function u_{STC} of the outer loop, with dynamic reference $T_{ref}(t)$, is expressed as

$$u_{STC} = K_P(T_{ref}(t) - T_{act}) + K_I\int(T_{ref}(t) - T_{act})dt \quad (6)$$

K_P and K_I are gains of the system and T_{act} is the actual temperature of the pipe. Depending on the value of temperature error and its derivative the gains (6) are selected automatically through use of self-tuning controller. Self-tuning controller is needed to achieve accurate temperature profile for highly non-linear system (2). The profile could change with

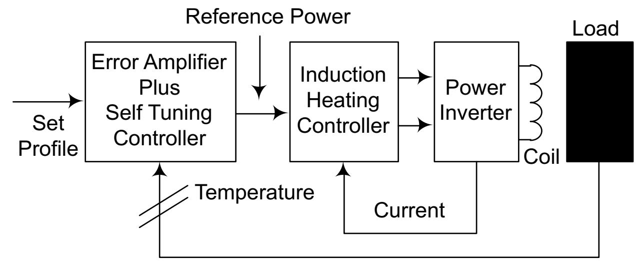


Fig. 5 : Block diagram of a typical two-loop control system of induction heating systems

material used, application and physical dimension of the job. The output of outer loop controller u_{STC} is used as dynamic reference of the inner loop induction heating controller. The inner loop provides the necessary actuation of controller heating for control of temperature. Multiple temperature sensors are deployed at different places to verify the temperature profile. For control purpose only one temperature feedback is used.

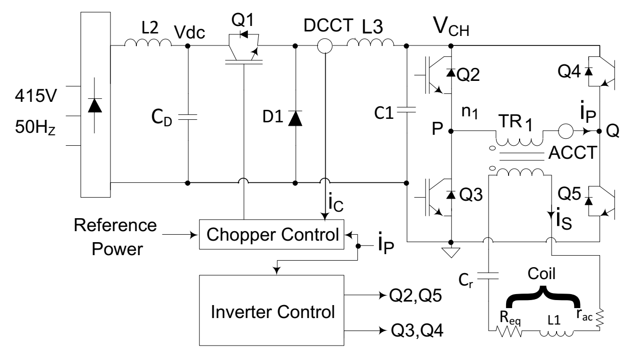


Fig. 6 : Full-bridge SRI for induction heating system

4.0. AIR COOLED INDUCTION HEATER

Induction heating can affect heating profile of metal surface in multiple ways (4). Number of topologies, either in series or in parallel resonant configurations, exists [16]. Due to simple configuration and easy availability of high-frequency active and passive power components at low cost the series resonant topology (see **Fig. 6**) is preferred [11]. For efficient power delivery to load the controller involves control of both frequency and power. For efficient use of inverter, the resonant frequency f_r is tracked closely by driving the gates of Q2-Q5 under zero voltage switching condition (ZVS) using phase lock loop (PLL). The switching frequency f_s is kept larger than f_r. For high power application, proper power control feature is needed for efficient actuation. Large number of topologies exists for power control to series resonant inverter SRI. To feed requisite power to wide range load, separate chopper circuit is preferred. It along with PLL ensures the inverter switches turn on at zero voltage and turn off at near zero current (ZVS-n-ZCS). Its circulating current is near zero. It helps optimize the utility of tank circuit where major power loss takes place. The resonant frequency fr of tank circuit at no-load [10] is

$$f_r = \frac{1}{2\pi\sqrt{L_1 C_r}} \tag{7}$$

C_r is capacitance of series resonant tank circuit. Upon application of load the value of f_r increases as the effective inductance value L_{eq} is less than L1.

The quantum of power needed for heat treatment applications is large. For efficient energy transfer the coupling between pipe and large spatial coil head should be good. To achieve uniform temperature rise the coil design for large spatial coil is complex. A thick layer of insulating compound with very high temperature withstand capability is placed, between the pipe and the coil assembly, primarily, to protect the coil as well as to reduce energy waste by radiation, etc. The newly emerged water-less induction heating system [3], [8] have made the heating system compact and inherently energy efficient as auxiliary power otherwise needed to maintain and circulate cold water to remove system's heat loss is eliminated. Air cooled coils are constructed using litz wire to further reduce power loss as skin and proximity effects both in L_1 and TR_1 are reduced. As the current density of air-cooled (≤5A/mm²) coil is much less, just to ensure the requisite power available for heating purpose the value of inductance of coil L_1 is kept large. For much higher power applications the litz-wire coil could as well be made conduction cooled.

For proper distribution of power and power density the value of f_r is kept fixed. Therefore, for litz wire based coil, when the value of L1 is increased the value of C_r needs to be proportionately decreased. At resonant condition the stored energy of tank circuit per cycle is zero, or,

$$\frac{1}{2} L_1 i_S^2 = \frac{1}{2} C_r V_C^2 \;\Rightarrow\; V_C \approx V_{L1} = \sqrt{\frac{L_1}{C_r}}\, i_S \tag{8}$$

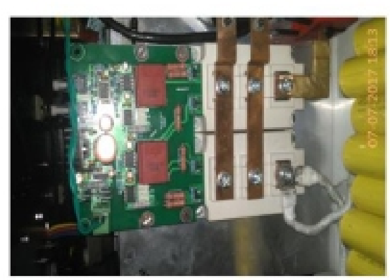
Where i_S is coil current. For a fixed value of resonant frequency, when L1 is increased, the characteristics impedance Z_0 of tank circuit increases. The voltage drop across resonating tank circuit components is large.

Under ZVS-n-ZCS condition ($f_s \approx f_r$ and fs > fr) the power transferred to load, at a particular coil current i_S, is nearly optimized as switching loss in Q1 and Q2 is negligible. Total conduction loss is minimized because the circulating current is small. Considering negligible drop in Q1 and Q2 the output power P_{inv} of half-bridge inverter at primary current i_P is

$$P_{\text{inv}} = \frac{2\sqrt{2}}{\pi} V_{PQ} i_P \cos\phi \approx \frac{2\sqrt{2}}{\pi} V_{CH} i_P \tag{9}$$

(a) Chopper controller

(b) The complete system



(c) Resonant inverter

Fig. 7 : Details of 40 kW Induction heating system

ϕ is phase angle between V_{PQ} and i_P. The power to load with equivalent effective load resistance R_{eq} is expressed as

$$P_L = i_S^2 R_{eq} \tag{10}$$

As the actuation is related to current in tank circuit, the output of outer-loop control of controller (see **Fig. 5**) is used as reference of the induction heater. **Fig. 7** shows the details of industry grade 40 kW pipe heating system.

4.1. Induction Coil

The coil is the heart of any induction heating system. It facilitates the requisite power transfer to the metallic load or the joint area. The coil could be either water cooled or air-cooled. Separate water cooling arrangement makes conduction cooled system. Moreover, apart from more power loss in coil, it consumes extra power power and should be avoided for outdoor applications. The cooling requirement is primarily decided by the maximum power loss taking place in the tank circuit at rated output power. The power loss depends on coil current and effective high-frequency current density in it and winding pattern. Litz-wire based air-cooled arrangement is preferred in pipe heating applications because:

1. The power density (W/mm^2) needed is small to moderate
2. The coil area is large
3. Coil should be flexible for wide range use
4. Power loss in the coil is much reduced

However, the construction of air-cooled for heat treatment applications is complicated because:

1. The ambient temperature is high
2. Means of heat removal from coil is poor
3. More problematic for PWHT applications as ambient temperature is large, and,
4. Generating uniform thermal insulation between the coil and job over large coil area is complicated.

Most of the no-load power loss P_{NL} takes place in ac resistance of coil r_{ac}. P_{NL} is approximated [11] as

$$P_{NL} \approx i_S^2 r_{ac} \approx \frac{2\sqrt{2}}{\pi n_1} V_{CH}(NL) i_S \tag{11}$$

$V_{CH}(NL)$ is the chopper output voltage at no-load. The value of r_{ac} depends on following factors:

1. DC resistance value
2. Resistance caused by skin effect of high frequency current
3. Caused by proximity effect by the fellow strands
4. Caused by magnetic field of other turns of the coil

The expression of high frequency resistance r_{ac} of coil [14] is

$$r_{ac} = r_{dc} + r_{ac}(\text{int}) + r_{ac}(\text{ext}) \tag{12}$$

Where r_{dc} is dc resistance and r_{ac}(int) is contributed by skin and proximity effect of the bunch of strands and r_{ac}(ext) is contributed by external magnetic fields, by current carrying conductors of other turns and layers.

The heating area of pipe is large and wide. The coil is spatially placed. Moreover, it should be flexible to cater wide range applications. Litz-wire based air-cooled coil improves the energy efficiency of heat treating solution. The current density allowed in naturally cooled coil is moderate. Still, air-cooled coil is more suitable because it provides flexibility where long flexible coil could comfortably fit the job. The skeleton of a typical air-cooled coil is shown in **Fig. 8**.

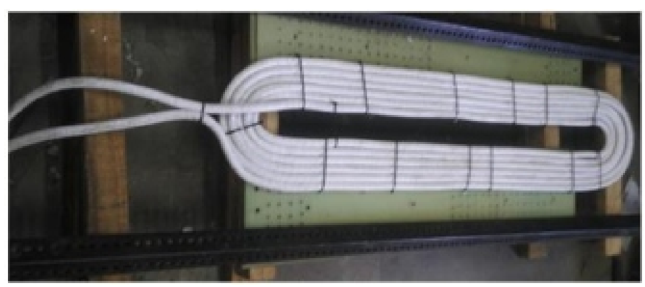


Fig. 8 : Winding pattern of a typical air-cooled induction heating coil

5.0 EXPERIMENTATION AND PRACTICAL RESULTS

Multiple experiments were conducted using 40 kW, 11 kHz inverters. Here, one pre-heating cycle is detailed. The outer diameter, thickness and the length of the pipe were 1.0m, 9.5mm and 12m respectively. **Fig. 9** shows the output waveforms of the inverter when the coil was loaded. **Fig. 10** shows the temperature profile of pre-heating a long-seam joint. **Fig. 11** shows the snap of recorder of temperature reading of six thermo-couples during the heating cycle. The temperature difference between the outer and inner layers was within 15 deg C. In pre-heating, it was ensured that each thermo-couple recorded the desired temperature, say, 250 ^{o}C.

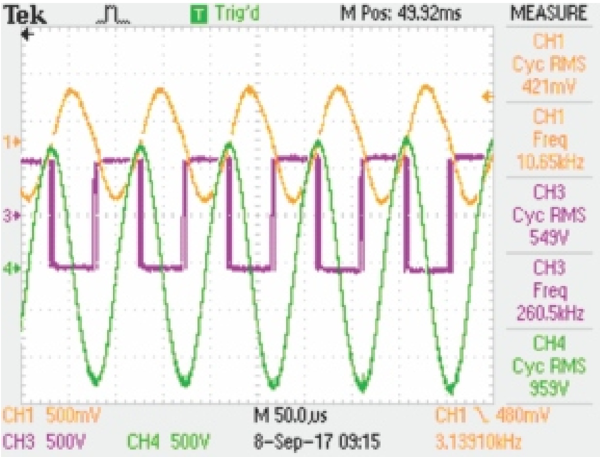


Fig. 9 : Major waveforms of induction heating controller in pre-heating application. [CH1:- coil current i_s: 250A/div.; CH3:- Inverter output V_{PQ}: 500V/div.; CH4:-Tank capacitor voltage V_c: 500V/div.]

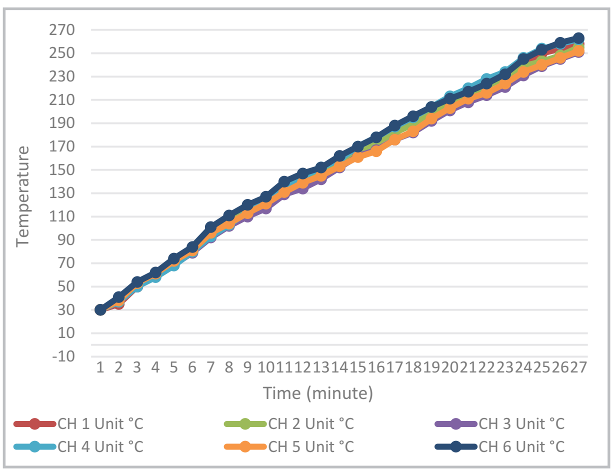


Fig. 10 : Recorded temperature in pre-heating cycle set at 250 °C.

Fig. 11: Calibrated temperature reading indicates good temperature profile through reading of six thermocouples. Top row indicates temperature of inner side of pipe of depth 50mm

For PWHT phase two inter-locked inverters were preferred to feed two separate coils. Each They together achieve superior power distribution to achieve uniformity in temperature over the job. **Fig. 12** shows the temperature profile in soaking period during post weld heat treatment. The temperature profile was accurate within 10 °C.

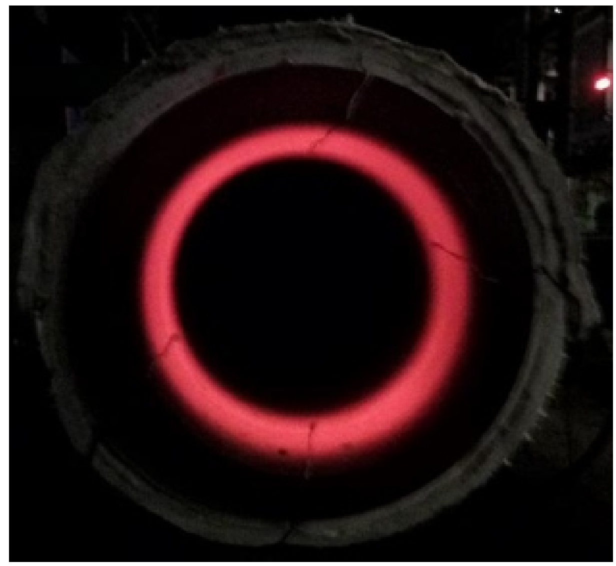


Fig. 12 : The high temperature annular ring is for post weld heat treatment of pipe at 750 deg C.

6.0. CONCLUSION

This article has practically demonstrated a flexible, energy efficient and cost effective engineering solution for complete heat treatment of P91 Grade steel being used in modern power plants and several critical piping applications. It practically demonstrated that the use multiple dedicated inverters could be used to meet different applications of PWHT for P91 Grade steel. Moreover, being air-cooled the flexibility of the equipment is high as the same coil can be configured for many applications.

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