Energy Efficiency Model for Induction Furnace

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Abstract. In this paper, a system of a solar induction furnace unit was design to find out a new solution for the existing AC power consuming heating process through Supervisory control and data acquisition system. This unit can be connected directly to the DC system without any internal conversion inside the device. The performance of the new system solution is compared with the existing one in terms of power consumption and losses. This work also investigated energy save, system improvement, process control model in a foundry induction furnace heating framework corresponding to PV solar power supply. The results are analysed for long run in terms of saving energy and integrated process system. The data acquisition system base solar foundry plant is an extremely multifaceted system that can be run over an almost innumerable range of operating conditions, each characterized by specific energy consumption. Determining ideal operating conditions is a key challenge that requires the involvement of the latest automation technologies, each one contributing to allow not only the acquisition, processing, storage, retrieval and visualization of data, but also the implementation of automatic control strategies that can expand the achievement envelope in terms of melting process, safety and energy efficiency.

1. Introduction

Energy source and energy efficiency are the two main aspects for a sustainable growth of foundry sector. Renewable energy module of the foundry industry needs to develop up and implement sustainable practices based on Environmental adaptability. Energy resource constraint is an area which also needs to be focus, foundry industry depends on natural resources directly and indirectly PV solar is one of such best resources. To meet energy efficiency target, we need to utilize data acquisition technology to deliver castings at the desired quality level:

- Optimum heat losses from furnace.
- Reduce time delay during the process operation.
- Become Effective (productive), functional and fully perfect Castings process control.
- Linking sensor data from monitoring physical processes with analysis data.
- Alarm and emergency acknowledgements via the internet.
- At the lowest cost process.

To success in highly competitive global markets, foundry sector need to employ modern PV solar power source, heat preservation and data acquisition system that included energy enhance, supervision integrate process and concurrent engineering.

2. Methodology

Data acquisition, Solar energy source and heat preservation system can be a fundamental element in the modern foundry sector towards a sustainable energy future. Data acquisition system can contribute to improving the energy efficiency of foundry industry furnace heating system plants in different ways. Implementing better supervision, control and optimization strategies improves energy performance directly and indirectly, through better process control system practices that help to prevent and increase in energy use due to operation downtime and start up-shutdown process. The block diagram (Figure 02) shows to physique an induction heating furnace that produces efficient heat than the equivalent amount of electricity with modified source. Practically induction heating process required an impedance matching system which essential between the high frequency source and the output coil in order to ensure decent power flow. A control block diagram of monitoring system algorithm employed to control heating action and time heating cycle to ensure consistent output [1].
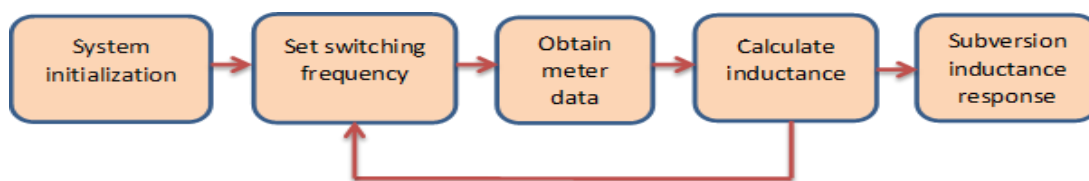

Figure 1. Block diagram for inductor characterization process.

A frequency control system is developed that automatically search for and operate at the natural load resonant frequency and continuously track this resonant frequency during the heating cycle as shown in figure1. This is accomplished by data acquisition system monitoring the load phase angle and altering the inverter operating frequency accordingly. Frequency is very important parameter in the design of induction heating power supplies because power components must be rated to operate at the critical frequency. In order to heat a solid piece of metal via induction heating require an incredible current to flow in the surface of the metal. However this can be contrasted with the inverter that generates the high frequency power. The inverter generally works better if it operates at fairly high voltage but a low current. Increasing the voltage and decreasing the current allows common switch mode MOSFETs to be used. During power MOSFET turn-off, voltage rise time is controlled by the ability of the gate drive circuit to sink the current being delivered to the gate by the gate-drain multi-capacitor as the drain voltage increases and thus charges the gate-drain capacitor. If the driver current exceeds the power MOSFET gate-drain feedback current during voltage switching, power MOSFET transistor will be off during the capacitive charging of the power MOSFET output capacitance. This charging is performed by an inductive element and charging is thus lossless. During power switched turn-on, the store capacitive charge in the power MOSFET output capacitor is however dissipated in the power MOSFET channel. At higher voltage levels or high switching frequencies such as in off-line applications, voltage switching losses can become a dominant loss factor.

During power MOSFET current turn-off, the negative current slop created by the decaying drain-source current, induces a negative voltage across the common source inductance. Since the common source inductance is also in series with the gate-source loop, the negative voltage induced across the common source inductance appears as a positive gate-source voltage on the power MOSFET. When power MOSFET gate-source voltage reaches the voltage level required to conduct the drain-source current, the system will be operating in its active linear mode having high drain-source voltage. Due to the negative feedback, the power MOSFET will effectively limit rate-of-current decay i.e. negative di/dt (DS) to a fixed upper limit. Any tendencies to exceed this upper limit will increase power MOSFET gate-source voltage further, causing power MOSFET to reduce the slop of the negative di/dt (DS), thereby effectively controlling maximum current switch off speed. In this mode, switch voltage levels never reach clamp voltage levels and converter current commutation is therefore controlled by power MOSFET maximum current turn-off di/dt. That maximum current turn-off speed in a power MOSFET is controlled by the common source inductance. Thus the lowest losses is obtained when converter current commutation is limited only by the power MOSFET maximum turn-off di/dt. The

comparatively low currents make the inverter less sensitive to layout issues and stray inductance. This is the main work for matching inductor and working coil itself to transform the high-voltage/low current from inverter to the high current/low voltage required to the heat the workpiece efficiently.
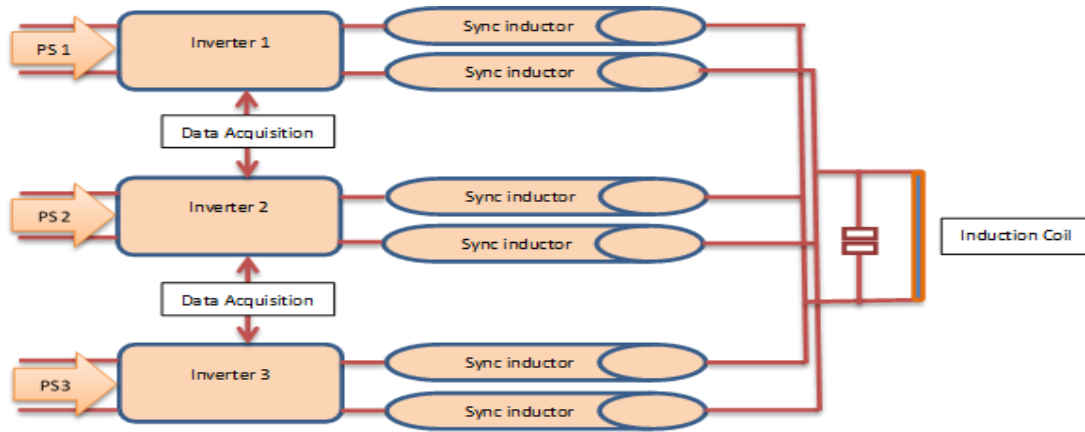

Figure 2. Induction furnace multiply power source (PS: power source)

Software outline: The main deal of the project is design and implementation of a Data Acquisition system for furnace efficient heating system of foundry, as shown in figure 3.
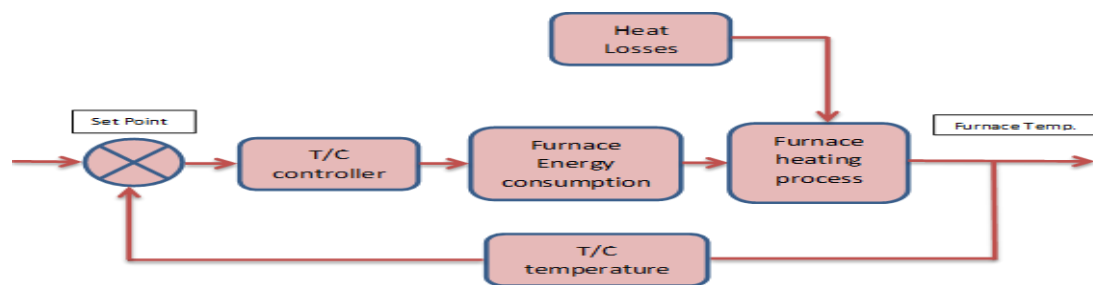

Figure 3. Process diagram for energy losses-heat control.

The system engaged with Schneider IGSS software and SICK sensors which is ideal for heat & frequency control monitoring system. It is use for reading data from over 1000 Analog and digital sensors, display synoptic images in a hierarchical structure, display events and alarms(over heating acknowledgement), command field devices, system diagnostics under user permission concept. Also allows web-based monitoring and command through Object linking embedding process control and web server by using the existing communication infrastructure. When the Manager of the acquisition system runs with different application; it should select the furnace number from overall system to read status of individual furnace, as shown in figure 4. Then manager sets the tolerance value and to calculate energy optimization according to heating conventional value. After that the data acquisition application provides the manager in the network result to make a decision based on outcome [2].

The total Energy consumption, $P(t)$, of a solar induction furnace can be defined as: $P(t) = V(t) I(t)$.

Where $V(t)$ and $I(t)$ are the solar source DC voltage and current respectively. With the voltage defined as: $V = RI(t) + Kv \, \omega(t)$

The power $P(t)$ can be described as a function of the electrical current (I), and the angular velocity ω such as

$$P(t) = [RI(t) + Kv \, \omega(t)]I(t) = R I^2(t) + Kv \, \omega(t)I(t). \tag{1}$$

R is the resistance, Kv the electrical (back emf) constant, where this power implements by the voltage multiplier device [3].These analytical expressions are therefore very useful in designing and optimizing high input current converters for high conversion efficiency.
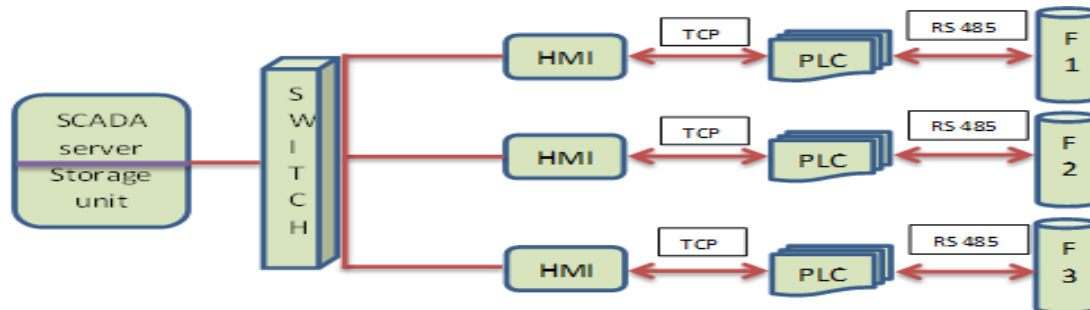

Figure 4. Hardware design of furnace control.

Voltage Multiplier Method: Here we are presenting an inductor-less solar power management system for induction furnace. A device is used some form of switching component to control the connection of voltages to the capacitor. Under low light intensity, the PV voltage is low and the voltage multiplier device steps up the voltage either for charging the battery or powering the induction furnace. At the same time, the optimal power tracking unit monitors the voltage multiplier device output power and determines the adjustment of the system operating parameter. Based on the adjustment decision, the PLC unit tunes the operating frequency of the device in order to maximize the system power output, shown in figure 5. Under a certain light intensity, the output of the PV cell behaves like a current source with a voltage limiter [4]. For different loadings, the PV cell will operate at different points, either in current source region or in voltage source region, where the output current or voltage almost keeps a constant. The procedure for regulating the converter output power via sustaining resonance is more convenient with annulling the phase difference the output voltage and current through the inductor than the procedure for correcting the phase between the output voltage and inductor voltage. Inductor voltage sensing results in a more significant phase error and also higher harmonic components are present in the inductor voltage.

The converter output power control with correcting the phase angles between the output voltage and current through the inductor. The presented phase control algorithm for the resonant converter shows that by supervision the output voltage or output current phase difference, for a particular resonant frequency, the converter output power can be controlled. Any deviation from the resonant frequency is structured by changing the phase angle between voltage and current of the converter. The voltage multiplier method proves that the iteration procedure is possible to perform adaptive regulating on the phase difference between output voltage and current of the converter and thus indirectly to achieve a new resonant frequency which corresponds to the changes for the resonant circuit values. Due to the effect of regulation, output current can affect the voltage stresses on multiplier's diodes and capacitors. Since regulation is directly proportional to output current, and as input voltage is usually increased to compensate for regulation, the diodes and capacitors near the input side of the multiplier will be subjected to higher voltage stress at the higher output current [5]. The programmable logic controller maintain constant output current. The controller essentially consists of an operational amplifier based proportional integral controller. The pulse width modulator generates the switch duty circle in response to the output voltage received from the controller. The current feedback circuitry consists of the necessary sensing and signal conditioning circuits required for closed loop control. The power controller also functions as a protection system for the voltage multiplier output stage, allowing the maximum current level and multiplier peak switching voltage to be set independently [6].

Load resonant converters allow for higher voltage multiplier switching frequencies to be achieved efficiently and also enable lower power rated switches to be employed due to the reduction in

switching power losses. Due to the dynamic nature of induction heating loads, a considerable change in natural resonant frequency of the load circuit can occur during the heating cycle.
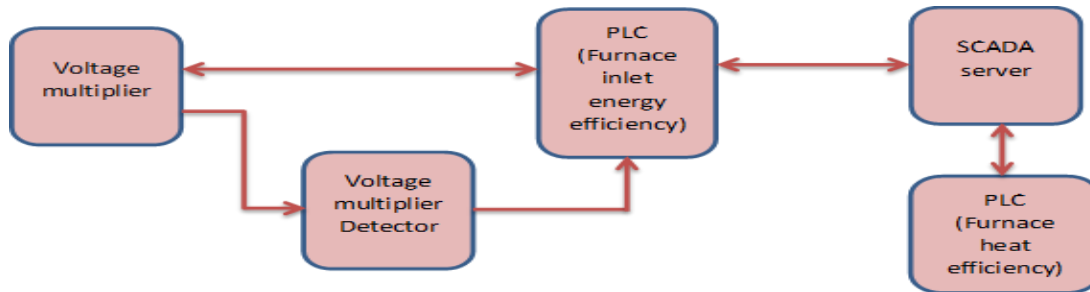

Figure5. Diagram for PLC control Voltage multiplier.

The PV output power also varies with loadings and the maximum output power point exists at the crossing point of the two regions. The voltage multiply device is a step-up voltage converter which consists of only capacitors and switches, as shown in figure 6. In order to prevent the reverse current through the switches of voltage multiplier when they are turned off, the switches size should be made small, and the driving capability of the gate control inverters should be strengthened [7]. At the same time, the size of the switches should guarantee the charge on the capacitors can be fully shared even when the device is operating at high frequencies. To supply maximum power to charge the battery or to directly drive the computation circuit, the data acquisition unit is used to monitor the amount of power flowing out of the device.
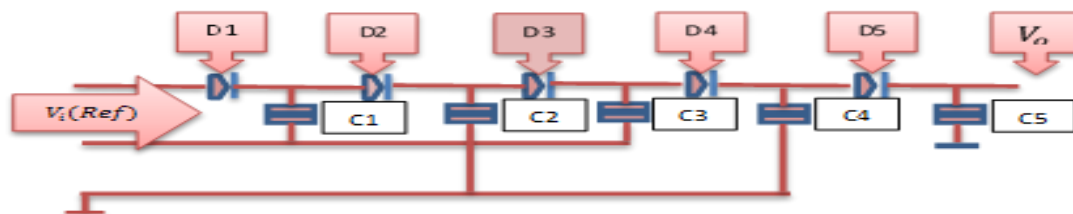

Figure 6. voltage multiplier diagram

The control unit is used to adjust the system operating parameters based on the decision from the programmable logic control unit in order to maximize the output power from the voltage multiplier device. Usually the period capacitors C_P are much smaller than the output capacitor C_o. Then, the output voltage changes very slowly and the circuit can be regarded as operating in the steady state. Here, steady state means that during each switching cycle, the charge being transferred into each period capacitor as well as the output is the same as the charge flowing out of them during the discharge period, and we denoted it as Q. In each switching cycle, let the voltage at the ith period capacitor be V_i after it is charged by the previous stage. At the second clock phase, the switch between the ith and $i+1^{th}$ stage capacitors is on and charge sharing occurs. After that, the voltages on both sides of the switches equals to V_{i+1}. At the same time, the voltage at the other plate of the ith stage capacitor, which is driven by the clock buffer equals to the voltage control oscillator power supply voltage V_{ph}. The voltage across the ith stage capacitor thus equals to (V_{i+1} -V_{ph}). For the ith capacitor:

$$C_p (V_{i+1} - V_{ph}) + Q = C_p V_i, \ i = 1,2,.. \ n.$$
$$Q = C_p V_i + V_{ph} C_p - C_p V_{i+1} \tag{2}$$
$$I_o = f_{clk} Q$$

There are Q amount of charge being transferred to the output, the input to the voltage multiplier device has to provide Q charge to each stage capacitors either directly or through the clock (f_{clk}) buffers. So total power feeding to the induction furnace is:

$P(t) = R\{f_{clk}Q\}^2 + Kv\,\omega(t)\,f_{clk}Q$. Where $Q = C_p V_i + V_{ph} C_p - C_p V_{i+1}$. (from equation no. 2).

The actual V-I characteristic of the PV cells is different from the ideal voltage and current source. The output current will increase with the decrease of the PV voltage, even at the current source region [8]. We can see in figure no 5 that in order to increase the voltage multiplier device output current, we should increase the PV cells output current i_{ph}, and reduce the frequency dependent current loss. The system output voltage is regulated by the battery and the voltage of the battery changes very slowly; we can assume that maximizing the system output power is equivalent to maximizing the system output current. Here, we use the current sensor to measure the voltage multiplier output current. Based on the measured current value, the data acquisition units check whether the system is at the optimal point. An inductor-less voltage multiplier device was used to step up the PV voltage for the battery charging. In order to maximize the power outputted from the system, the system operating behavior was theoretically analyzed.

3. Conclusions

In this project design was divided into two different section. Voltage multiplier use for operating frequency of the device in order to maximize the system power output. And additional circuits were used to link the generated control signals to the MOSFET transistors of the inverter circuit. The paper refereed to control of the manufacturing processes in foundry with aid of systems belonging to the data monitoring system. Application of a system in the foundry requires a special approach. Three main areas present the future evolution of this design: Heating optimization, energy efficiency and data acquisition system. A Circuit model for the optimal power control algorithm was discussed where low power techniques are employed to avoid the power deficiency and utilizes a converter topology from other applications to create a unique contribution to the induction furnace of foundry. Data acquisition system is very useful for foundry sector when it is necessary to control and supervise heating system, being able not only to work items in the system, but also to warn about various warnings. The use of this system enables constant power converter operation, energy saving and technological processes effectuating.

References

[1] Gandhewar, V.R., Bansod, S.V., Borade, A.B.(2011).Induction Furnace-A Review,International Journal of Engineering and Technology Vol.3 (4), 277-284.

[2] Sika, R., Ignaszak, Z., Rogalewicz, M. (2014). In Polska Metalurgia 2011-2014, Świątkowski, K. (Eds.), Specificity of application of the spc methods in complex manufacturing process on example of foundry (357-371). Krynica Zdrój: Akapit.

[3] Bala, K.C. (2005). Design Analysis of an Electric Induction Furnace for Melting Aluminum Scrap, AU J.T. 9(2): 83-88.

[4] Ignaszak, Z. & Sika, R. (2012). Specificity of SPC procedures application in foundry in aspect of Data Acquisition and Data Mining. Archives of Foundry Engineering. 12(4), 65-70. DOI: 10.2478/v10266-012- 0108-8.

[5] Yin Y., Regan Z.: Digital Phase Control for Resonant Inverters, IEEE Power Electronics Letters, Vol. 2, June 2004.

[6] K. Agbossou, J. L. Dion, S. Carignan, M. Abdelkrim and A. Cheriti, "Class D Amplifier for a Power Piezoelectric Load", IEEE Trans. On Ultrasonics, Ferroelectrics and Frequency Control, July 2000, vol. 47, no. 4, pp. 1036- 1041.

[7] Anaidhuno, P. U. (2014). Construction of an Electric Heat Treatment Furnace, M. Eng Thesis; Mechanical Engineering Department; Anambra State University, Nigeria

[8] A.I. Martinez and H. Calleja, "A simple, high-quality output PV system aimed at peak demand reduction," in Conference Publication of the VII IEEE international Power Electronics Congress, CIEP 2000, 15-19 Oct. 2000, pp.301-306.