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# Heating systems with PLC and frequency control

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ABSTRACT

In this work, medium capacity controlled heating system is designed and constructed. The programming method of control of heating process is achieved by means of integrated programmable logic controller (PLC) and frequency inverter (FI). The PLC main function is to determine the required temperatures levels and the related time intervals of the heating hold time in the furnace. FI is used to control the dynamic change of temperature between various operating points. The designed system shows the capability for full control of temperature from zero to maximum for any required range of time in case of increasing or decreasing the temperature. All variables of the system will be changed gradually until reaching their needed working points.

An experimental study was performed to investigate the effect of tempering temperature and tempering time on hardness and fatigue resistance of 0.4% carbon steel. It was found that increasing tempering temperature above 550 °C or tempering time decreases the hardness of the material. It was also found that there is a maximum number of cycles to which the specimen can survive what ever the applied load was.


## 1. Introduction

Heat treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape. Heat treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, and restore ductility after a cold working operation. Thus it is a very enabling process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics [1,2].

A new single-switch parallel resonant converter for induction heating was introduced in [3]. The circuit consists of an input LC-filter, a bridge rectifier and only one controlled power switch. The switch operates in a soft communication mode and serves as a high frequency generator.

A voltage-fed resonant LCL inverter with phase shift control was presented in [4]. It was seen that the control strategy offered advantages in the megahertz operating region, where a constant switching frequency is required. The inverter steady state operation is analyzed using fundamental frequency analyses.

A cost-effective high efficiency inverter with phase-shifted pulse modulation scheme was proposed for medium power (5–30) kW induction heating applications is discussed in [5]. The proposed inverter accomplishes soft switching operation over a wide power regulation range. The actual power conversion efficiency reached was 96.7%.

A control method of reducing the size of the dc-link capacitors of a converter–inverter system was presented in [6]. The main idea is to utilize the inverter operation status in the current control of the converter. This control strategy is effective in regulating the dc-voltage level. Even the dc-link capacitor is arbitrarily small and the load varies abruptly.

In [7] a method was proposed to accurately predict the minimum required temperature recovery considering repeatability and accuracy of the leak detector by investigating the relation between temperature recovery time and theoretical thermal time constant for various test volumes and applied pressures using PLC system.

In [8] a methodology was demonstrated to design a PLC program that organized the relation between the physical inputs and outputs of the pumping tools in manufacturing systems.

In [9] an experimental study was performed to investigate the effect of using two axes tracking with PLC control on the solar energy collected. The two axes tracking surface showed better performance with an increase in the collected energy up to 41% compared to the fixed surface.

The PLC main function is to control the required temperature levels and the related time intervals of the heating hold time in the furnace [10]. Frequency inverter is used to control the dynamic change of temperature between various operating points [11,12].

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This integration of the PLC and frequency control shows the capability for full control of temperature from zero to maximum in dynamic and static conditions, in case of increasing or decreasing the temperature.

The properties and microstructure as a function of tempering time at intercritical temperatures in HY-80 steel castings were evaluated by [13]. They varied the time for which the steel was held in the intercritical temperature range. An important finding of this study is that, contrary to normal behavior during tempering HY-80 steel tempered in the intercritical range demonstrates a severe loss of toughness; which can be exaggerated for longer hold times and higher temperatures.

A fractography survey on high cycle fatigue failure in Fe–C–Cr–Mo–X alloys was made by [14]. They found that various parameters are likely to influence high cycle fatigue failures, the most significant one dealing with the nature and location of embedded precipitates and the forging reduction ratio.

The ageing effect on cyclic plasticity of a tempered martensitic steel was studied by [15]. They carried out specific isothermal cyclic deformation tests on a tempered martensitic steel 55NiCrMoV7 at four hardness levels in the temperature range 20–600 °C. They found that the cyclic stress response generally shows an initial exponential softening for the first few cycles, followed by a gradual softening without saturation, hardness dramatically decreases when the specimen is simultaneously subjected to ageing and fatigue at elevated temperature, cyclic softening intensity increases with testing temperature from 300 to 600 °C, but the maximal softening intensity occurs at room temperature.

Back-propagation neural networks were used by [16] to optimize the heat treatment technique of high-vanadium high-speed steel including predictions of retained austenite content, hardness and wear resistance according to quenching and tempering temperatures.

A novel concept for the heat treatment of martensite, different to customary quenching and tempering was proposed by [17]. This novel treatment has been termed 'quenching and partitioning' (Q&P), to distinguish it from quenching and tempering and can be used to generate microstructures with martensite/austenite combinations giving attractive properties.

Reversible martensitic transformation, ageing and low-temperature tempering of iron–carbon martensite were studied by [18]. In this study, reversible martensitic transformation was observed in Fe-based high-carbon alloys at temperatures when none lattice defects (including divacancies) could diffuse. Formation and behavior of carbon-vacancy clusters was studied and discussed. Chemical composition of hexagonal ε-carbide was determined as Fe3C. The effect of particle size and ε-carbide/martensite orientation relationship on the ε-carbide → cementite transformation was discussed.

## 2. The heating system design and control

In this work, the design of PLC and frequency controlled heating system were performed using an open loop and programming method of control in which stored instructions in memory of PLC was used to control the actuation of heating process. The block diagram of the hardware components of the automatically controlled heating system is shown in Fig. 1.

Personal computer is used to write the control program then download it to the PLC [19,10] through communication cable. The PLC is S7-200 type, which has 12 inputs, 8 outputs and 220 VAC supply voltage.PLC S7-200 uses ladder logic diagram programming language describes in Refs. [19,10]. The PLC main function is to instruct the analog unit to go on or off and to state the required percentage output and the related hold time intervals.

The digital output of PLC is ranging from zero to 32,700 quantization levels. The analog unit function is to transfer the digital output value at the output of PLC into analog value, which ranging from zero to 10 VDC at the output of analog unit. In the program a different percentages of output voltage is supplied to the furnace by the frequency inverter which is originally stated by the analog unit output where 0 DVC equals 0% at the output of the frequency inverter and 10 VDC equals 100% at the output of frequency inverter. Frequency inverter is a single phase input, three phase output, 220 VAC rated output voltage, 50 Hz rated output frequency and 3 kW power.

In this work a frequency inverter of type SINAMICS G110 is used [11]. Frequency inverter according to the different incoming instructions of PLC through analog unit operates the three phase heater with the required percentage of voltage and frequency. Parameter unit is a type of programmers used to program the ramp up and ramp down time between each two controlled levels. So, frequency inverter has two types of commands: (1) Type of commands which is supplied by the PLC to the analog unit then to the frequency inverter to state the hold time intervals. (2) Type of commands which is supplied by parameter unit td control the ramp up and ramp down time to make a soft transition conditions between various operating levels [20].

The furnace consists of a three phase heater in a room which is 3 kW rated power, with 220 VAC rated input voltage, 50 Hz rated frequency and star connection.

## 3. Mathematical description of frequency controlled heating system

The main important parts of the PLC and frequency controlled three phase heating system are the frequency inverter and the three phase furnace.

### 3.1. Modeling of the frequency inverter

From all types of frequency inverters for regulation of AC motors, the more important is thyristor frequency inverter with clear dc part as shown in Fig. 2. This type of frequency inverter has high technical and economical specifications.

The equation of the frequency control channel can be written as

$$F = k_F u_F \tag{1}$$

where $k_F$ is the inverter amplification coefficient by frequency control channel and $u_F$ the input voltage of frequency generator.

The equation of the voltage control channel will be

$$u = k_v u_u \tag{2}$$

where $u_u$ and $u$ is the output and input voltages of the inverter. $k_v = 2/(\pi\sqrt{3})$.

The dc circuit of thyristor frequency inverter contains LdC-filter, where Ld is the inductance of the filter and C is the capacitance of the filter condenser.

The equation of the dc circuit will be

$$u_u = E_d - R_d i_d - L_d \frac{di_d}{dt} \tag{3}$$

where

$$\begin{aligned} i_d &= i_u - i_c \\ i_c &= C(du_u/dt) \end{aligned} \tag{4}$$