Automation of Furnaces for Metal Heat Treatment: Cases of Vacuum Furnace and Conveyor Belt Furnace with Protective Atmosphere

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Automation of Furnaces for Metal Heat Treatment: Cases of Vacuum Furnace and Conveyor Belt Furnace with Protective Atmosphere

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***Abstract*— Sustainability, one of the most important aspects of every production plant, can be enhanced through retrofitting. In this paper, retrofitting of two furnaces for metal heat treatment, namely vacuum furnace and conveyor belt furnace with protective atmosphere, are presented. The goal of the revitalization of the furnaces is modernization through the digital transformation of technological process variables as a new form of data availability in the context of Industry 4.0. The application of a modern control system based on a programmable logic controller ensures optimal control of the technological process which significantly extends the useful life of the machine. For the vacuum furnace, the replacement of a dilapidated vacuum system is also performed.**

***Keywords*— PLC, process sensors, PI regulation loops**

I. Introduction

Industry 4.0 is a broad industry initiative that became a driving force towards a fundamental industry change and improvement of industrial systems [1]. It represents the digital transformation of production through factory automation digitalization and provides a guiding vision towards the realization of smart, connected factories as opposed to traditional systems that continue to function as a discrete autonomous solution [1]. Industry 4.0 principles lead to an increase in equipment efficiency and connectivity, and to the reducement in production costs [2].

Retrofitting implies the integration of new technologies in combination with the reuse of old equipment, and consequently it represents an opportunity to provide a transition to a new concept of technological innovation applied to industrial processes, but with lesser investments. As a result, using the concept of retrofitting migration to Industry 4.0 can be less expensive.

In the case of furnaces for metal heat treatment, precise temperature regulation is of the greatest importance. If the temperature rate is too high, the quality of the heat-treated material can be severely impaired. Practical challenges within the identification of slow processes cause insufficient precision in modelling. For this reason, there is limited application of analytical methods in temperature control and the application of practical techniques for adjusting the parameters of PID controllers based on experience gained in operation [3]. On the other hand, optimal control of the technological process of the metal heat treatment furnace significantly improves the quality of heat treatment and extends the useful life of the machine. Additional benefits include increasing the production efficiency and energy efficiency of the production line.

In order to achieve quality heat treatment results, control systems of metal heat furnaces have to use a variety of process variables. In this sense, taking principles of Industry 4.0. paradigm into account, and given the high price of flow and vacuum metal heat treatment furnaces, the revitalization and modernization of old furnaces by the means of application of state of the art control unit replacement proved to be a reasonable choice [4-5]. Herein, the old control cabinets (based on analogue and relay technology) are replaced with a new control cabinet with PLC (Programmable Logic Controller) with the development of new control functions.

In this paper, revitalization of the two different types of furnaces for metal heat treatment, vacuum furnace and conveyor belt furnace with protective atmosphere, is described. Shared user requirements for furnace revitalization, besides specifics for the two systems that are given separately, are listed bellow:

- Control system modernization including the development of protocols for all of the heat treatment operating regimes.
- The ability for the user to predefine the heating recipes for each material and their storage.
- More accessible and facilitated operator work and easier maintenance.
- Increased safety and reliability in operating.

The paper is divided into four sections. In Section 2, technical details of the vacuum furnace and furnace for metal heat treatment discussed in this paper are provided. In Section 3, modernization and controlling concepts for the two types of furnaces are described. Hardware and software aspects of the control system chosen for both furnaces are presented, and implementation specifics are discussed separately. Discussion on the revitalized systems and the improvements obtained by introducing such systems into the technological processes is briefly given in Section 4, while the conclusions is given in Section 5.

II. Description of the furnaces

A. Vacuum furnace

Competition and market demands encountered by manufacturers of vacuum furnaces have the consequence of constant development and innovation expanding the possibilities of metal heat treatment in vacuum [5]. A vacuum furnace is the type of furnace that heats materials, most often metals, to very high temperatures in which different thermal treatments characterized with high stability and a small number of impurities are conducted. The vacuum inside the furnace protects the metal workpiece as the metal is not subjected to the oxidation process, and there are no particles that would form harmful compounds. Furthermore, existing oxides decompose during the heating to the processing temperature. The consequence is a great purity and metallic luster of the processed material [5].

Fig. 1 Appearance chamber vacuum furnace

Heat treatment processes that are carried out in the reconstructed vacuum furnace are hardening and annealing. For the hardening process, the metal workpiece is heated by the requested temperature slope to the requested temperature (up to 1350°C) and held at the temperature for the given time period. At the end of the heating process, the cooling process begins by charging from the heating chamber with the help of appropriate carts transferred to the cooling chamber. The metal cooling process can be done with gas, within an oil bath, or by a combination of the two methods. The annealing process, which involves only metal heating, is used in the processing of various metals and their alloys in order to achieve specific technological properties.

Process control instrumentation in vacuum furnaces for metal heat in the industry is very diverse, due to the fact that its useful life varies from 20 up to 50 years. The existing vacuum system consisting of a mechanical vacuum pump, diffusion pump and vacuum valves was in use last thirty years.

Herein, in addition to shared control system requirements presented in the previous section, the list of requirements for vacuum furnace control system includes as well as the possibility of continuing the heat treatment process in case of interruption of any kind; recording and storing data on each batch; modernization of the vacuum system with the state of the art components; compliance with IEC standards.

B. Conveyor belt furnace

Conveyor belt furnaces are furnaces in which heat-treated parts move through temperature zones using a conveyor belt. A protective atmosphere prevents oxidation of the metal during annealing. The conveyor belt furnace in this paper consists of three control zones, and the protective atmosphere is obtained using an ammonia dissociator. The annealing process in a protective atmosphere is carried out by heating the furnace to the setpoint value (up to 1150 °C), while the ammonia dissociator is heated to the temperature of 935 °C. At an operating temperature of 935 °C, the ammonia flows into the cracking insert (catalyzer) via the pressure-reducing valve. The process of obtaining of protective gas atmosphere achieved in the furnace is described in [1] in more detail. The length of the furnace is 8000 mm, while the usual speed of the conveyor belt, depending on the material to be annealed, is in the range of 200-400 mm/min.

Fig. 2 Appearance protective atmosphere at the entrance to the furnace

III. Control system design and implementation

Programmable logic controllers, sensors, and other process instrumentation enable real-time monitoring of process parameters and optimal system control [6]. Using PLC enables the prediction of possible system failures through the acquisition of process data obtained from various types of sensors that measure process variables of interest, analysis of the data, and tracking of their trends.

A. Control system specifications

For both furnaces, the following components form the basis of the control system: 1) Programmable logic controller (PLC), ABB series AC500, CPU PM583 with integrated ethernet communication port and corresponding modular digital/analog inputs and outputs; 2) Operator programmable panel (OP) with touch screen, WEINTEK TFT COLOR LCD TOUCH, with ethernet communication port; 3) Application software implemented on the PLC and operator panel. Data exchange between PLC and OP is realized via the Ethernet communication port and MODBUS TCP/IP protocol. Moreover, the system is provided with the possibility to upgrade monitoring by using SCADA (Supervisory Control And Data Acquisition) applications.

PID algorithm control is the most common control algorithm used in the metal furnace industry due to its simplicity and robust performance in a wide range of operating conditions. Today's PLC controllers contain a PID in discrete form as a standard program module. The PLC, with its A/D and D/A converters, receives analogue inputs from the controlled process (temperature, pressure, etc.), processes the received data, and sends the control signal to the actuating devices. The processing of the obtained data is carried out using PID algorithms integrated into the PLC executable program. With the correct sampling period, the digital controller behaves comparably to the analogue one, and satisfying controller performance will be obtained [7].

The PLC application program was created in the CODESYS programming environment [8]. For the program implementation of the PID controller within the CODESYS development environment, a standard library is used, within which there are functional blocks in which the PID algorithm is implemented.

For the PID block control to be implemented in a PLC, it can be represented in discrete form by using appropriate mathematical approximations for differentiation and integration as shown in the following equation:

$$CV(k) = CV(k-1) + K_p \begin{bmatrix} \left(1+\frac{T}{2T_i}+\frac{T_d}{T}\right)e(k) \\ -\left(1-\frac{T}{2T_i}-\frac{2T_d}{T}\right)e(k-1) \\ \frac{T_d}{T}e(k-2) \end{bmatrix}. \quad (1)$$

where $CV(k)$ is the control variable, index k denotes the number of cycles, $CV(k\text{-}1)$ is the value of the control variable from the previous execution cycle, $e(k)$ is the value of error in the cycle k, i.e. the difference between the setpoint value and the measured value of the process variable, K_p is the controller gain, T_i is the integration time constant, T_d is the differentiation time constant, and T represents the sampling time. In the PLC program, the PID block is placed in a particular program that is executed cyclically, and T is the time interval between the two executions.

B. Design and implementation of the controller for the vacuum furnace

Heating of vacuum furnace is performed via single-stage control transformer apparent power 37 kVA, rated voltage primary 400 V, 50 Hz and secondary voltage in the range 0–40 V. The transformer secondary is by means of a copper rope (braid) of very small resistance ($\approx 0.04\,\Omega$) connected to graphite heaters in the heating chamber so that the value of the derived current can go up to 1000 A. Feedback control of the secondary voltage is realized using a thyristor voltage power controller located in the primary transformer circuit. Via analog PLC output that is configured as a current signal with a range of 0–20mA, setpoint value is sent to analog input of thyristor power controller which controls the effective value of the alternating voltage at primary of the transformer in the range 0–400 V.

The nominal temperature of the heating chamber is 1350 ° C, the temperature in the heating chamber is measured using thermocouples type S (90% Pt-10% Rh). Control and supervision system for vacuum furnace is placed in the electrical cabinet (Fig. 3). Operator terminal with touch screen and implemented application of screen displays are the central part of the system for control and supervision of vacuum furnace. Supervision is achieved by light and audible signaling. On screen, all relevant elements for the control and monitoring system are shown by using active graphics symbols and/or textual information. Through the operator panel, supervisory staff can obtain all relevant information on the state of the process through process variables in graphical and/or textual form.

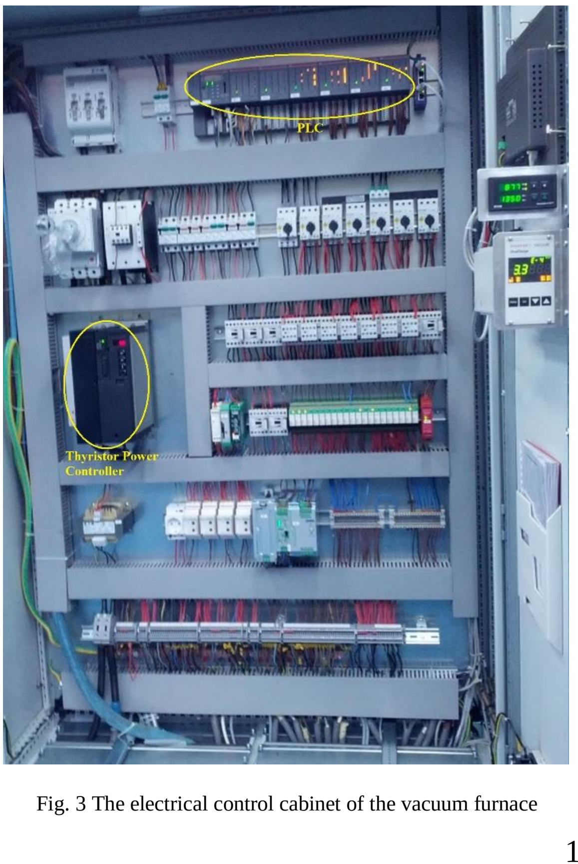

Fig. 3 The electrical control cabinet of the vacuum furnace

The previous vacuum system consisting of a mechanical vacuum pump, diffusion pump and vacuum valves was replaced with new and contemporary components designed according to the previous electromechanical project and current environmental standards. In a new system, a mechanical vacuum pump directly pumps out the system up to a maximum negative pressure (rough vacuum) [9] that allows the operation of a diffusion pump [5]. The diffusion pump is switched on when the mechanical pump reaches operating pressure of 10^{-1} mbar and when the diffusion pump warms to a temperature higher than 200 °C by using the heater. Separation of individual pumping cycles is performed using vacuum valves, while control and measurement of the pressure in the chamber is done by vacuum pressure meters. This way, by combining mechanical and diffusion pumps a high vacuum of up to 10^{-5} mbar is achieved. By appropriate control algorithm written in PLC application program, efficient control of mechanical vacuum pump, diffusion pump and angular electro-pneumatic and electromagnetic vacuum valves is achieved, with the purpose of reaching a vacuum level of values depending on the applied technological procedure. The usual values of the vacuum that were achieved during the thermal processes were in the range of 10^{-4}-10^{-1} mbar. Automatic pump control is activated using the operator terminal. In addition, it is possible to activate separate pumps and valves. The state of the pumps and valves is displayed by suitable symbols on the symbolic scheme placed on the operator terminal (Fig. 4).

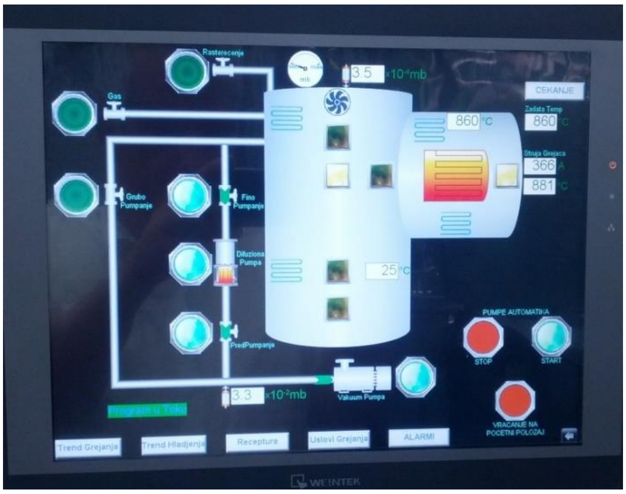

Fig. 4 The appearance of the main screen of the vacuum furnace monitoring system

Given that PI controller is chosen for the heating process control, the derivative action is turned off by setting $T_d = 0$. Proportional gain is set to value $K_p = 1$, while the integral time constant is $T_i = 100$ s. The cyclical time of PI algorithm execution is $T = 1$ s. Special emphasis should be placed on the quality adjustment of the PI controller, which, in addition to its simple structure, also meets the strictest control criteria. For chosen controller parameters, the system was stable and satisfactorily managed to eliminate the disturbances. Trend diagram during the heating process in the heating chamber for desired heating curves satisfactory control results are achieved, Fig. 5.

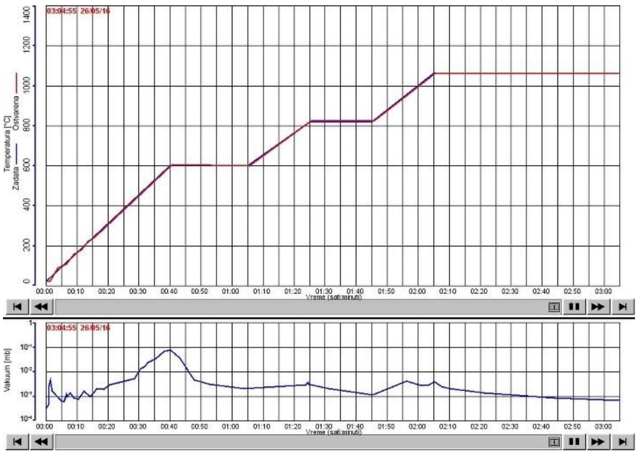

Fig. 5 Reference and obtained heating curves and vacuum trend during the heat treatment process

C. Implementation of PI- PWM controller for the conveyor belt furnace

Furnace heating is performed by electric heaters made of FeCrAl alloy, which are arranged by segments of the furnace housing. Heater power is controlled via appropriate solid-state contactors with a built-in "zero-cross" function. In this way, the occurrence of electromagnetic interference is significantly reduced, because by turning on the contactor at some point where the voltage is closer to the maximum value, sudden voltage/current jumps would occur, which would affect the occurrence of high frequencies. The conveyor belt drive consists of a DC gear motor that is continuously regulated by a DC controller.

Since the heater power is controlled via a solid-state contactor, a pulse (ON-OFF) control method is implemented using pulse width modulation (PWM). It is commonly called "time proportional control". Using the PI controller, the control variable output is calculated and expressed as a percentage of 0-100%, which represents the required averaged power of the heater. Based on the control variable and sampling time, using the PWM, the pulse and pause time durations are generated, i.e., the duration of switching ON-OFF periods of the solid-state contactor via the corresponding digital outputs. In this way, the combination of PI control and PWM enables temperature control with high precision without a significant jump in the regulated temperature due to the inertia of the heating element itself.

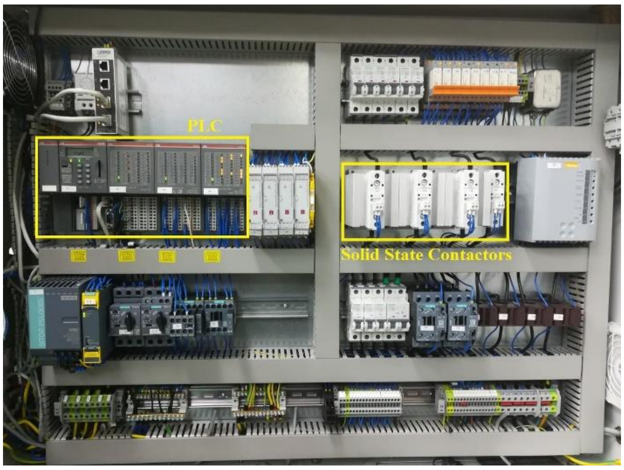

Fig. 6 The electrical control cabinet of conveyor belt furnace

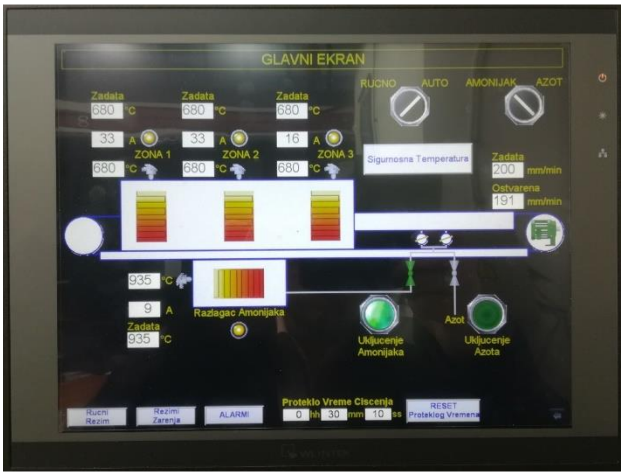

Fig. 7 The appearance of the main screen of the conveyor belt furnace monitoring system

A total of four control loops have been implemented, one for each of the three temperature zones in the furnace and another one to control the temperature in the ammonia dissociator. Heat (temperature) coupling, i.e. the mutual temperature impact of the temperature zones is characteristic of multi-zone temperature control. The influence of the temperature value of a zone to another depends on the structure of the plant and the selected operating points of the temperature zones.

As the PI controller is used to control the heating process, the differential effect was switched off by setting T_d =0 s. In order to avoid oscillations of controlled temperatures in the temperature zones and the ammonia dissociator, the integral time constant must be higher than the processing time constant. Also, the cycle time of PWM must be short enough to allow the thermal mass of the load to smooth out the switching pulses. Systems with a small thermal mass will need shorter cycle times than can be provided with a relay, and in these cases, a solid-state relay is commonly used. The proportional gain for the implemented PI controllers is set to the value K_p =5, while the integration time constant is T_i =100 s, the cycle execution time of the PI algorithm is T =1 s. For the given parameters of the controller, satisfactory temperature control results were obtained for the given temperature regulation of the heating regime with a deviation from the setpoint value temperature of less than ±1 °C. The cycle time for PWM generation is set to 5 s, and the obtained PWM signal represents the D/A conversion of the control variable for each individual control loop. This means that if in some control loop, the value of the control variable at the output of the PI controller is 70%, the switching ON time of the solid-state contactor will be 3.5 s (duty cycle), and the switching OFF duration is 1.5 s. The cycle time must be short enough to allow the thermal mass of the load to smooth out the switching pulses.

Temperature measurement in the conveyor belt furnace zones and the ammonia dissociator is performed using thermocouples type K (NiCr-NiAl). Linearisation of the measured value is performed within the PLC controller.

Like in the case of the vacuum furnace considered in this paper, the operator terminal with the application of screen displays is the central part of the system for monitoring the conveyor belt furnace's operation and control (Fig. 7). The screen displays of the application include all relevant elements of the monitoring and control system represented by the use of active graphic symbols and/or textual information. All relevant information on the state of the process is obtained, in graphical and/or textual form through the operator panel.

IV. DISCUSSION

PLCs have become an integral part of control systems in industrial processes, characterized with great reliability and easy and less time-consuming reconfiguring of the control algorithm, compared to controllers based on relay technique and discrete electric circuit.

The temperature control of the vacuum furnace is implemented by using the software PI feedback integrated within the PLC controller. The presented temperature control method has given efficient, reliable and robust setpoint regulation. In order to avoid the oscillations of the output temperature, the integration time constant has to be greater than the processing time constant.

The project of automation of the conveyor belt furnace for metal annealing based on combination PI feedback controller and time proportional control has given the efficient, reliable, and robust set value regulation.

For both cases, future system upgrades are anticipated regarding the provided possibility to upgrade the system monitoring by using SCADA applications.

After the completed revitalization of the control system for considered furnaces, obtained improvements can be concluded to include the following:

- Increase of product quality,
- Reduction of the time of the heat treatment cycle and thus the increase of the production level,
- Optimization of energy consumption,
- Less machine wiring and easier maintenance,
- More accessible diagnostics of faults on the machine,
- Increased safety and reliability in operating.

V. Conclusions

The concept of retrofitting an old machine is the quickest and usually the most cost-effective way to migrate to Industry 4.0 and increase connectivity in the industry. In this paper, revitalization of the temperature control units of the two cases for metal heat treatment plants, namely vacuum furnace and conveyor belt furnace is presented. Developed control units based on PLC controllers, PI and time proportional control laws are described in detail. Obtained improvements include an increase of product quality, an increase of the production level, optimized energy consumption, easier maintenance and diagnostics of faults on the machine, as well as increased safety and reliability in operating. Taking goals of Industry 4.0. into account, control unit development considered future upgrades future system upgrades, such as SCADA applications, etc.

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