Automation a conveyor belt furnace for annealing metals in a protective atmosphere

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Abstract— **The paper presents the revitalization of a conveyor belt furnace for annealing metal, which included the design and implementation of a control system based on a programmable logic controller. The goal of the revitalization of the furnace is its 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 ensures optimal control of the technological process and thus significantly extends the useful life of the machine.**

Keywords-PLC, process sensors, PI regulation loops.

I. Introduction

Conveyor belt furnaces are furnaces in which a piece moves through temperature zones. The heat-treated parts are moved using a conveyor belt. A protective atmosphere is used to prevent oxidation of the metal during annealing. The revitalized conveyor belt furnace 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 first heating the furnace to the setpoint value (maximum up to 1150°C), while the ammonia dissociator is heated to the temperature of 935°C required for ammonia dissociation. At an operating temperature of 935°C, the ammonia flows into the cracking insert (catalyzer) via the pressure reducing valve. This inserts being filled with a nickel-containing catalyzer, and it cracks into 75% hydrogen and 25% nitrogen. After reaching the set temperatures in the annealing channel, the decomposed ammonia into nitrogen and hydrogen is fed into the furnace where the hydrogen burns along its entire length. In this way, a protective gas atmosphere is obtained in the furnace, which burns at the inlet and outlet of the channel (Fig. 1), and it is allowed to place the piece in the annealing channel. The length of the furnace is 8000mm, while the usual speed of the conveyor belt, depending on the material to be annealed, is in the range 200-400mm/min. By revitalizing the annealing furnace, it was necessary to achieve the following:

- modernization of the control system with the development of protocols for all operating modes of heat treatment,
- the ability to predefine the annealing recipes for each material and their storage,
- more accessible operator work and easier maintenance,
- safety and reliability in operating.

Due to the high price of flow furnaces, the revitalization and modernization of old furnaces and the replacement of old control cabinets with analogue and relay technology with a new control cabinet with PLC (Programmable Logic Controller) with the addition of new functions proved to be a reasonable choice [1-2].

Figure 1. Appearance protective atmosphere at the entrance to the furnace

Retrofitting of old machines, which implies the reuse of old equipment and the integration of new technologies, is an opportunity to provide a transition to a new concept of technological innovation applied to industrial processes with lower investments. Migration to Industry 4.0 can be cheaper by using the concept of retrofitting because it represents an upgrade and adaptation of industrial equipment to new technologies. Industry 4.0 increases equipment efficiency, reduces production costs and increases industry connectivity [3]. Industry 4.0 is a broad industry initiative aimed at providing huge potential for improving industrial systems and driving us towards a fundamental change in the industry. In other words, it represents the digital transformation of production through the digitalization of factory automation and provides a vision to guide us towards the realization of a smart, connected factory as opposed to traditional systems that continue to function as discrete autonomous solutions.

The paper is divided into four sections. Section 2 provides details of modernization and conveyor belt furnace controlling concepts. The implementation of proportional-integral control for temperature control in temperature zones and ammonia dissociator is presented in section 3. Finally, section 4 presents the appropriate conclusions about the revitalized system and the improvements obtained by introducing such a system into the technological process.

II. Details of Conveyor Belt Furnace Modernization

Today's conveyor belt furnaces use a variety of process variables and that variables must be monitored and controlled in order to achieve quality heat treatment results. PLC process status information is obtained from various types of sensors that measure process variables of interest and convert them into a suitable electrical form. The PLC then compares the received data with the setpoint values and, through algorithms and calculations, sends the appropriate signals to the actuators in order to obtain the desired responses of the controlled variables. Programmable logic controllers, sensors, and other process instrumentation enable real-time monitoring of process parameters and optimal system control [4]. It is possible to predict possible system failures through the acquisition of process data, analysis, and tracking of their trends.

The existing control system with relay technology and analogue temperature controllers has been replaced by a new control using PLC (Fig. 2). The basis of the system for monitoring and control conveyor belt furnace make:

- programmable logic controller (PLC), ABB series AC500, CPU PM583 with integrated ethernet communication port and corresponding modular digital/analog inputs and outputs,
- operator programmable panel (OP) with touch screen, WEINTEK 12.1 "TFT COLOR LCD TOUCH, with ethernet communication port,
- 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. As a possible upgrade of the system is provided for monitoring via the SCADA (Supervisory Control And Data Acquisition) applications. From a remote computer with a SCADA application, it will be possible to view all system states and process measurements with the possibility of their historical review and printing.

The functions that the control system provides are:

- acquisition of state data in the process obtained through digital input signals and analogue measurements,
- appropriate processing of accepted data,
- issuing control orders actuators via the digital and analog output signals,
- protection of conveyor belt furnace technological equipment through detection of equipment failures,
- realization of conditions and blockades,
- setting heat treatment recipes and displaying process signals, values of analogue measurements, operating parameters, alarms, and messages on the operator terminal.

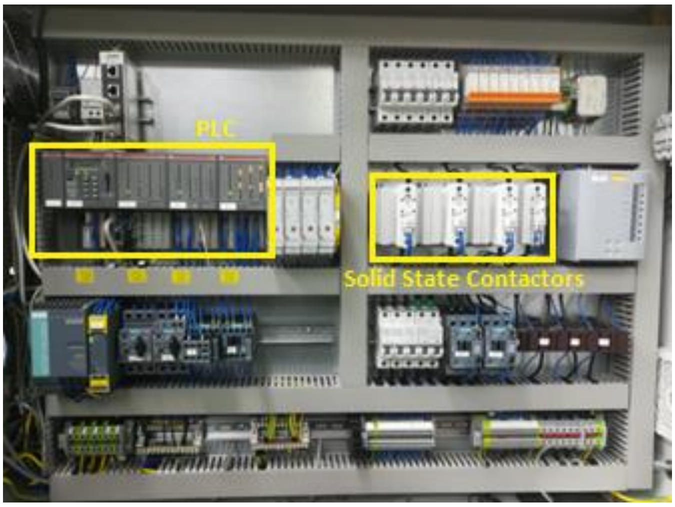

Figure 2. The appearance of the electrical control cabinet

The place of control and supervision is the operator panel with a touch screen (Fig. 3). The control is performed via appropriate buttons and other control elements located on the electrical cabinet's doors, and the control is achieved by light and sound signalling. 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 will be performed within the PLC controller. The operator terminal with touch screen and implemented application of screen displays is the central part of the complete system for monitoring the conveyor belt furnace's operation and control from the electrical cabinet door. The screen displays of the application include all relevant elements of the monitoring and control system, which are represented by the use of active graphic symbols and/or textual information. Through the operator panel, all relevant information on the state of the process and the state of process variables are obtained, in graphical and/or textual form.

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.

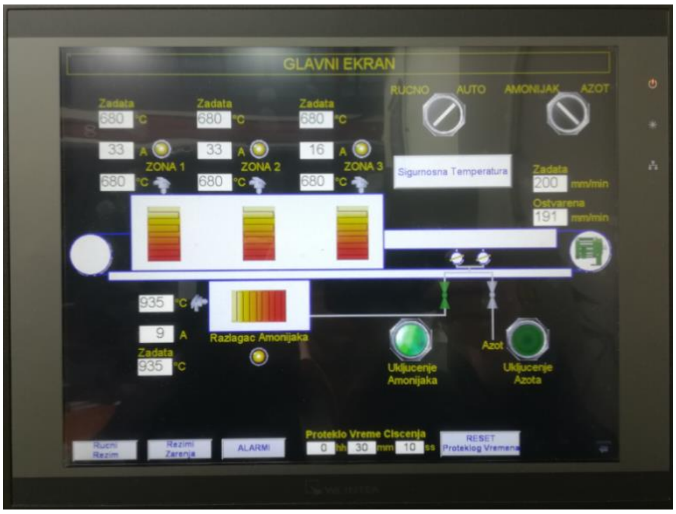

Figure 3. The appearance of the main screen of the conveyor belt furnace control

III. Implementation of PI Regulators in Temperature Zones and Ammonia Dissociator

PID algorithm control is the most common type of control accepted and used in the furnace industry. These regulators are used due to their robust performance in a wide range of operating conditions and simplicity. Today's PLC controllers contain a PID in discrete form as a standard program module. The PLC, with its A/D converters, can receive analogue sizes from the controlled process (temperature, pressure, etc.), process the received information, and finally send the analogue control variable to the process using the D/A converter. This processing of the obtained data is carried out using PID algorithms integrated into the PLC executable program. The correct choice sampling period, the digital controller will behave similarly to the analogue one, and good controller performance will be obtained [5].

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 proportioning control". Using the PI controller, the control variable is calculated, which is expressed as a percentage of 0-100%, which represents the required averaged power of the heater. Based on the control variable and cyclic time, using the PWM, the pulse duration is generated, i.e., pause, i.e., the duration of switching on/off 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. It prevents a significant jump in the regulated temperature due to the inertia of the heating element itself.

The PLC application program was created in the CODESYS programming environment [6]. 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. The PID block is executed according to the following algorithm:

$$CV(t) = K_p \left[e(t) + \frac{1}{T_i} \int e(t)\,dt + T_d \frac{de(t)}{dt} \right], \qquad (1)$$

where $CV(t)$ is the control variable, $e(t)$ is 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. It is clear that the above expression cannot be directly implemented in a PLC, but by using appropriate mathematical approximations for differentiation and integration it can be represented in discrete form, as shown in equation (2):

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

The new variable T introduced in equation (2) represents the sampling time. In practice, this actually represents the refresh time of the control variable, i.e., how often the algorithm is executed. 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. The index k denotes the number of cycles so that $CV(k-1)$ $e(k-1)$ and represents the values of the control variable and the control error from the previous execution cycle.

A total of four control loops have been implemented. One control loop is implemented for each of the three temperature zones in the furnace. Also, another control loop is implemented to control the temperature in the ammonia dissociator. The mutual impact on the temperature zones by thermal coupling is characteristic for multi-zone control. This means that the actual value of a zone can influence the actual value in another zone by heat coupling. It depends on the structure of the plant and the selected operating points of the zones how heavily the zones influence each other. As the PI controller was used to control the heating process, the differential effect was switched off by setting T_d=0. The proportional gain for the implemented PI controllers is set to the value K_p=5, while the integration time constant is T_i=100s. The cyclic execution time of the PI algorithm is T=1s. 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 5s, 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 3.5s (duty cycle), and the switching OFF duration is 1.5s. The cycle time must be short enough to allow the thermal mass of the load to smooth out the switching pulses.

Precise temperature regulation is of great importance in the operation of flow furnaces for metal annealing. If the temperature increases or decreases too quickly, the quality of the heat-treated material can be severely disturbed, and the final product will have significant degrading properties. Problems due to insufficient precision in the identification of slow processes have led to the limited application of analytical methods in temperature controlling and the application of practical techniques for adjusting the parameters of PID controllers based on experience gained in operation [7].

IV. CONCLUSION

Temperature control in the three temperature zones of the conveyor belt furnace and ammonia dissociator is implemented using a software PI controller integrated into the PLC controller. A total of four control loops were performed. In combination PI regulation and time proportioning control this method of temperature control given the efficient, reliable, and robust results. In order to avoid oscillations of regulated temperatures in the temperature zones and the ammonia dissociator, the integration time constant must be higher than the process 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 concept of retrofitting an old machine is the fastest and most cost-effective way to migrate to Industry 4.0 and increase connectivity in the industry. The project of automation of the conveyor belt furnace for metal annealing enabled the reduction of the time of the heat treatment cycle and thus the increase of the production level. The improvements obtained after the automation of the conveyor belt furnace are less wiring of the machine and easier maintenance, more accessible diagnostics of faults on the machine, optimization of energy consumption, increase of product quality.

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