Modernization of interconnected multimotor drives of continuous annealing units

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Abstract
Based on the experience of the modernization of multimotors interconnected through the processed material or mechanical transmission of controlled electric drives of unique technological lines the methodology for implementation of such projects was proposed. The essence lies in the combination of experimental studies in the standard operating procedure of equipment with physical and simulation modeling for obtaining the adequate mathematical models, as well as in the development of new systems in the standard and emergency procedures on the simulation and physical models. Modernization raised the speed of metal heat treatment from 2.5 to 8 m/s with minimal dynamic loads in the strip.

Keywords: MULTIMOTOR INTERCONNECTED ELECTRIC DRIVE, HEAT TREATMENT, ELASTIC-PLASTIC PROPERTIES, THE PRINCIPLE OF DECOMPOSITION, SIMULATION MODEL, HIERARCHICAL MODEL

Introduction

Continuous annealing units (CAU) are used for the annealing of cold-rolled steel sheet at the largest metallurgical plants of the CIS countries, including Novolipetsk Steel, the enterprises of "Severstal", Karaganda Metallurgical Plant (JSC "ArcelorMittal Temirtau") and others. During annealing metal passes through the draw furnace of turret-type and is under various conditions of heating and cooling, when the local strip compression and stretching are taken place.

During the operation at the CAU on the JSC "ArcelorMittal Temirtau" there were long idle-hours most of which were due to the instability of the high-speed mode and strip tension, leading to metal bleeding. Start of the unit after stops was accompanied by strong oscillating motion and displacement of the strip from the unit axis. When design speed of the metal motion was up to 7.5 m/s, only speed of 2-3 m/s was achieved.

Modernization of interconnected CAU electric drives

The objective of the interconnected CAU electric drives modernization was to increase the performance (metal strip speed of the movement) to the project level without modification of the power unit.

Functional scheme of the middle part of the CAU process, which determines the basic dynamic processes taking place in the strip during the heat treatment, is shown in Fig. 1. The main mechanisms are pinch rollers No3 (PR3) and No4 (PR4), tension adjuster (TA) and the vertical tower-type furnace (TF1-TF4) for the strip annealing [1]. PR are designed for metal transportation. TA provides a strip tension.

TF is divided into four chambers providing heating, equalizing, controlled and accelerated metal cooling. Transportation of the strip in TF chambers is performed in groups by 15 rollers with individual electric drivers with capacity of 22 kW fed by the grouped SCR's controls for each chamber.

ANO electric drives use DC motors with separate excitation. The automatic control system (ACS) TF is designed as double-braking speed control systems are intended to compensate the frictional losses in the strip. The rate of furnace rollers is synchronized with speed of the strip in the middle part of the unit. ACS PR are double-braking and built by the method of subordinate regulation. The PR drivers have a capacity of 37kW and 55kW. To distribute the load between the upper and lower PR a system of subordinate regulation of the upper roller motor excitation current is used. Demand signal for the excitation current regulator is a signal proportional to the EMF. Single-braking ACS TA operates in current regulator mode. The motor with capacity of 640 kW is used.

Maintaining the constancy of the strip tension is the main task of control systems of the drives of the unit technological medium, for which modernization has been carried out.

On the first stage the collection and analysis of information necessary for modernization is made including information from the in-process sensors of the strip tension which are placed in the TF tambours.

The oscillograms of the all standard working modes of electric drivers units mechanisms were obtained, including drive-brake and steady state rating [2], which did not require undue experimentation influencing the operation of the line. A preliminary decomposition of the existing electromechanical structure was carried out with taking into account the possibilities of control the parameters of the electromechanical system. The electric drivers, systems of mechanisms automatic control, converters and elementary sections of mechanical linkages were accepted as the basic elements in CAU. The information about electric drivers rotation speed, currents, volt-

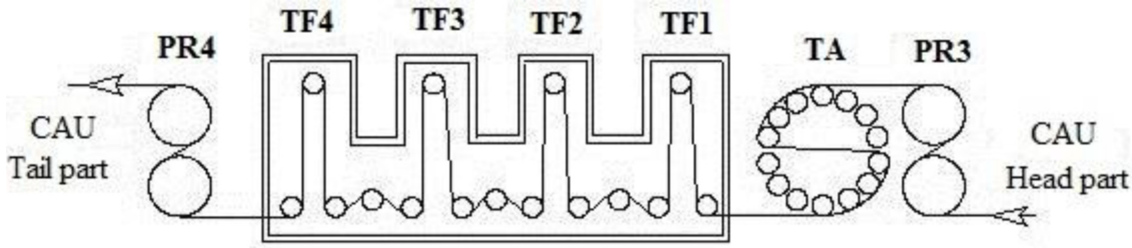


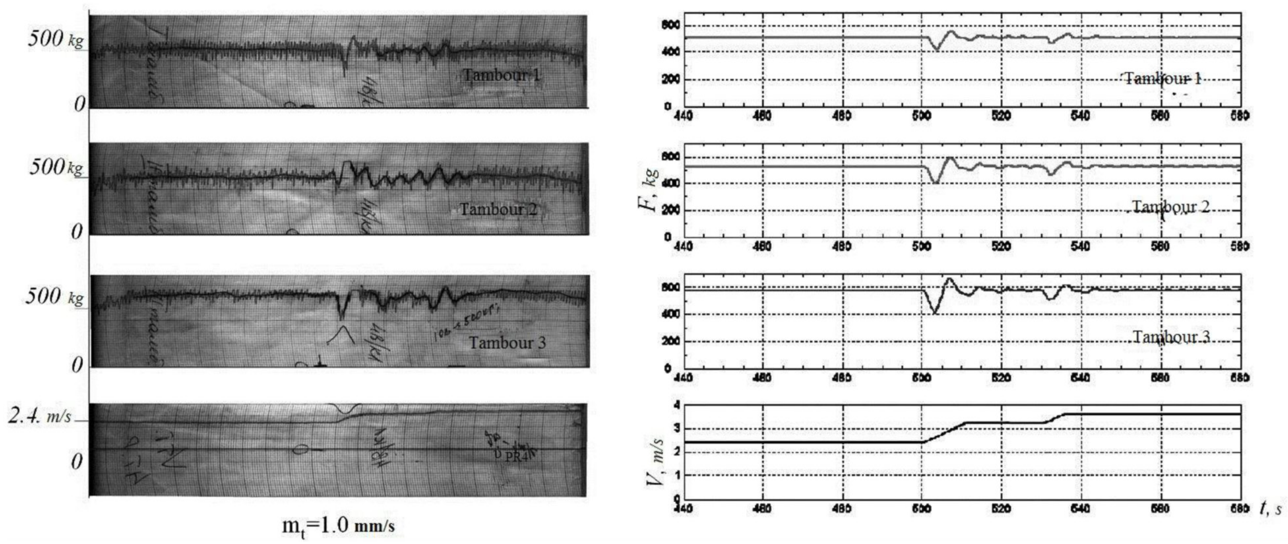
Figure 1. Middle technological part of CAU

ages, input, intermediate and output signals of control systems, converters, as well as the information about strip tension is available in CAU. Oscillographic testing in each of the design modes is performed repeatedly (at least 6 times for each implementation).

To estimate the dynamic modes in the metal strip to the electric drives of TF in inching mode, when threading and stretching the metal strip the excitations were introduced alternatively by changing the control influences and the force distribution along the strip from the tension sensors was recorded (Fig. 2a). It is established that the elastic deformation wave propagates not only in a forward, but also in backward direction (when propagating of elastic wave in the direction of strip movement the attenuation of the dynamic forces does not take place, and against the strip movement the attenuation is 70-80%). At the same time there was an increase in the amplitude of the force along the strip in the course of its movement, which was explained by an increase in the strip rigidity coefficient when reducing the heating temperature and its change during the passage of metal through different TF chambers [3]. The frequency spectrum of the force change is concentrated in the frequency range of 0.1-2.5 Hz. The forced and self-oscillations are presented in the strip. Forced oscillations contain components excited by the constant interaction of the rollers with the strip (their frequency is proportional to strip speed), as well as the components that arise when changing the speed. The time of the elastic waves propagation was 0.7 s in the course of strip, from the first to the third tambour, and 0.6 s - in the opposite direction. Also, it has been determined that it is necessary to take into account the elongations than appears due to the strip tension and the temperature influence [4].

The results of experiments and analysis of the CAU operating modes have shown that when designing the processes of propagation of the elastic deformation wave along the metal strip as along the course of movement as against it, as well as changes in its properties during annealing have not been taken into account. For this reason we could not reach the estimated output.

On the next stage the development of mathematical model of electromechanical system CAU has been carried out. For CAU distinctive is the repeatability of structural components of electric drives such as the elastic tension force of resistance modulus, the electric driver and ACS. Therefore, when developing the simulation model the decomposition method was used and the CAU model of the electric driver was represented by hierarchical structure. The first level consists of submodels of the elastic tension force in the strip F_f, resistance modulus M_R, electric drivers ED and ACS. Submodels of the first level are models of the basic elements in accordance with the preliminary decomposition conducted when oscillographic testing. They make up the submodels of the second level such as models of TF, PR and TA electric drivers. At the second level, there are three types of subsystems, and two of them (TF and PR) are similar. From four TF models, two PR models and TA model the model of the third level is collected, i. e. CAU electric driver model [5-7].



a) b)

a - on the operating unit; b - on the simulation model

Figure 2. Forces signals in the metal strip in the tower-type furnace chambers

Approximation of the model of metal strip is made by replacing the elements with distributed parameters of the multi-mass system with lumped masses and elastic elements of finite rigidity. Then multi-mass system was reduced to dual-mass with an accuracy of less than 5% [8]. Design scheme of CAU electromechanical system represented by a 13-mass system is shown in Fig. 3 where all interacting masses are designated by the order numbers in accordance with the direction of the strip movement in the unit.

Multimotor group electric drive of rollers in each of the chambers of the tower-type furnace (TF1-TF4) is replaced by the dual-motor equivalent. Equivalenting of the TF electric drivers was performed by the following equations [5]:

$$\left.\begin{aligned} u_a &= i_{aeq} \cdot R_{aeq} + L_{aeq} \frac{di_{aeq}}{dt} + C_t \cdot \Phi \cdot \omega \\ J_{eq} \frac{d\omega}{dt} &= M_{eq} - M_{r\,eq} \end{aligned}\right\} \quad (1)$$

Where i_{aeq} = m·i – equivalent current, A; $R_{aeq} = R_{\Sigma a}/m$ – equivalent resistance of the armature circuit, Ohm; $L_{aeq} = L_{\Sigma a}/m$ - equivalent inductance of the armature circuit, Ohm; $J_{eq} = J \cdot m$ – equivalent armatures inertia moment, kg·m^2; M_{eq} = M m – equivalent torque moment, H·м; $M_{eq} = M_r$ m – equivalent modulus of resistance, H·м; m – number of drivers that are replaced by one equivalent.

The equation of the resistance module of TF electric drivers has following form:

$$\left. M_R = \left(F_{jk} + F_f\right)\frac{r}{i} + K_{red} \cdot M_{Rjk} + \frac{a \cdot n}{60} \right\}, \quad (2)$$

where F_{jk} – the tensile force in the strip; F_f – friction force, H; r – rollers radius, m; i – gear reduction rate; K_{red} – reduction coefficient takes into account the impact of interacting masses previous to TF; a – dissipation factor characterizes the self-oscillation attenuation process in the system, H·m·s; n – rollers rotational speed; M_{Rjk} – moment of interacting masses static resistance; for TF2 - the moment of deformation wave propagating from the TF1, for TF3 - from the deformation wave propagating from TF1 and TF2, for TF4 - from the deformation wave propagating from TF1, TF2 and TF3.

Resistance module of electric drivers TF No3 and No4, as well as TA are described by equations similar to (2) with taking into account the influence of the interaction of the respective masses from the neighboring units.

For the simulation of CAU electric drives the software package MATLAB 7.0. with extension Simulink was applied. When the numerical integration of the large number of dynamic sub-systems with constant time significantly different from each other the sampling simulation time and discrete-time signals processing were applied.

At the next stage the sequential iterative debugging of the first-level models was made then of subsystems and CAU electric drives system to ensure their adequacy. This was accomplished by comparing the results of multiple implementations obtained when oscillographic testing with the results of simulation experiments. In the process of debugging we have tried to achieve the convergence of simulation results with the results of oscilloscopic testing of elements, subsystems and CAU electric drives system operation in design modes with an accuracy of 10-15% which is sufficient for engineering applications. In the process of models iterative debugging the actual values of elasticity and plasticity of the treated metal and dissipation, active resistances and electric drivers parameters of the magnetic system were specified and defined. All the obtained changes were included in the models. During this the strip elasticity in the model is successively reduced in TF1 and TF2 and further increased in TF3 and TF4 in accordance with temperature conditions of heat treatment.

For the TF electric drive the assessment of the studied model adequacy was carried out on measurements of the actual system and on the results of the experiment on the model in accordance with Carl Pearson's chi-squared test [9]. According to calculations, when the significance level α=0.10, the number of measurements in the series m=7, the number of normal distribution constants s=2 and the number of

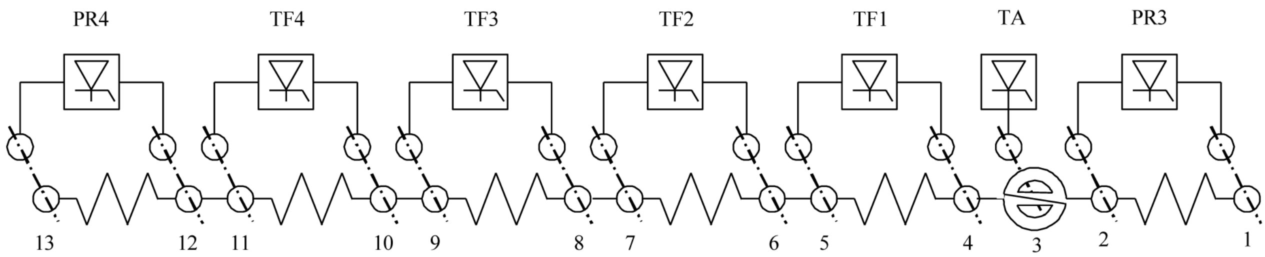


Figure 3. The design scheme of CAU electromechanical system

freedom degrees q=5, criterion $\chi 2=0.582>0.10$, which indicates that the model is adequate to the object. By the similar methods debugging of the system model of the existing CAU interconnected electric drive in design modes of the unit operation was performed. This model was the starting point for the modernization of CAU electric drivers [5, 6].

To evaluate the adequacy of CAU electric drive model the evaluation of sub-models subsystems was used. To assess the adequacy of the small samples Fisher criterion was used [9].

For n=6 measurements, m=2 series, the number of freedom degree q1=5 and q2=6 the experimental value of the criterion is less than the table kpe=1.2< kft=5.0. Consequently, the model obtained with 95% confidence coefficient describes the simulated process. Analysis of the oscillograms of simulation modeling results and statistical fitting criteria has shown that the model describes adequately with sufficient accuracy the dynamic processes occurring in TF electric drivers. Error of simulation does not exceed 10% (see. Fig. 2a and 2b which shows one implementation obtained when oscillographic testing and simulation modeling). When developing the model and carrying out the experiments only the low-frequency component was evaluated. The delay of propagation of elastic oscillations forces in different TF tambours identified during the oscillographic testing was confirmed.

Then structural and parametric optimization of electric drives of TF chambers was performed. It has been established that the TF chambers current regulator is insufficiently effective for controlling the strip tension under dynamic conditions [1, 10]. It is proved that the adjustment of regulators should be performed in speed function of the initial tension and rigidity of the strip. Moreover, by reducing the speed magnification factor of the regulator should reduce and the time response of the proportional plus reset controller should increase. The TF electric drive structure closed by negative feedback along the load current and the positive feedback on the speed derivative was synthesized. A distributed tension adjuster providing the compensation of losses to friction during the strip movement on the basis of electric drives of TF chambers closed by load currents with the PI controllers for floating tension control was proposed.

For damping of the elastic wave oscillations along the strip when changing its velocity an additional positive feedback according to speed derivative is introduced. It is proved that under condition $K_d = 2T_m \cdot K_{cs}$, where K_d - transmission coefficient of the differentiating element; T_m – mechanical time constant of the equivalent TF drive, K_{cs} – current sensor transmission coefficient, the combination of positive feedback according to the derivative speed and the negative feedback according to the current is equivalent to negative feedback according to the derivative tension forces with a first-order filter [10]. For the practical implementation the additional signal from the power-up sensor of given PR4 electric drive moment (leading mechanism of CAU) on the current controller inputs of TF electric drives has been introduced in the system. This signal is proportional to the specified dynamic moment, but it does not contain the clutters typical for speed signal sensor. The parameters of the regulators adjustment of TF chambers of electric drives have been determined. Application of distributed tension adjusters on the basis of TF electric drives has allowed us to implement smooth starting of the unit. The results of simulation experiments showed that the overshoot, i. e. dynamic stresses in the strip were decreased from 21% to 2%. After debugging the system on the model the electric drives were put into operation as part of CAU. The modernization raised the speed of metal heat treatment from 2.5 to 8 m/s with minimal dynamic loads in the strip [10].

Conclusion

In the process of modernization of the CAU electric drives a number of new results was obtained. The hierarchical three-level mathematical model of interconnected through the treated metal multi-motor electric drive taken into account changes in the elastic properties of the strip in the continuous heat treatment during its transition from elastic state to the elastic-plastic and again to the elastic state, as well as the propagation of elastic deformation of the waves along and against the strip movement direction was developed. The equivalenting technique of the connected by metal strip multi-motor electric drives of tower-type furnaces, as well as subsequent method of iterative debugging of models elements, subsystems and CAU electric drives systems and ensuring their adequacy were suggested.

The structure of the interconnected CAU electric drive containing the distribution tension adjusters on the basis of the group electric drives of the tower-type furnaces closed by positive feedback according to derivative of the given speed (dynamic moment) and negative feedback according to the load current was synthesized.

The regulators settings parameters of electric drives of the tower-type furnaces as the speed function, the initial tension and rigidity of metal providing reducing of the dynamic forces in the strip when changing its speed were established.

The results obtained can be used for the modernization of CAU metallurgical enterprises of the CIS countries, as well as be distributed to electromechanical systems of a continuous hot aluminizing and galvalumizing which also carried out a continuous heat treatment of metal by a similar technology.

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