Time-Optimal Feedback System with Identifier to Control Induction Heating Process

Yuliya Pleshivtseva
Samara State Technical University
Samara, Russia
yulia_pl@mail.ru

Ilya Levin
Samara State Technical University
Samara, Russia
levin.is@samgtu.ru

Bernard Nacke
Leibniz Universität Hannover
Hannover, Germany
nacke@etp.uni-hannover.de

Martin Schulze
Leibniz Universität Hannover
Hannover, Germany
schulze@etp.uni-hannover.de

Alexander Nikanorov
Leibniz Universität Hannover
Hannover, Germany
nikanorov@etp.uni-hannover.de

***Abstract* — The goal of the paper is to show a possible solution of time-optimal control problem applied to the induction heating process when the information about process parameters is not precisely known. In order to solve this problem a special method to construct time-optimal closed-loop control system was suggested. The identifier of unknown parameters is integrated in the implemented optimal control system. The proposed method is approved by numerical FLUX&Matlab simulation and experimental results.**

Keywords— induction heating, time-optimal control, interval uncertainties, feedback control systems.

I. INTRODUCTION

One of the central and most complex problems in modern control theory is to synthesize control algorithms and control systems under almost always existing conditions of uncertainty of industrial process characteristics primarily due to the inaccurate knowledge of its parameters and the action of uncontrolled external disturbances. In application to induction heating systems, the information about such parameters of the processes as initial temperature and heat loss, is usually not fixed, and only the intervals of their possible values variation are known. From engineering point of view the other important factor is necessity to obtain as simple control algorithm as possible to be implemented in practice. In order to achieve this goal the synthesis of time-optimal control system with identifier of uncertain parameters in the loop is required. The paper considers the developed procedure to solve this problem.

II. THE PROCEDURE OF STRUCTURAL-PARAMETRIC SYNTHESIS OF TIME-OPTIMAL FEEDBACK CONTROL SYSTEM

The process of static induction heating of cylindrical billet with interval uncertainty of initial temperature and heat loss values is considered. The temperature distribution $T(r,l,t)$ along axial $r\in[0,R]$ and radial $l\in[0,L]$ directions within the heated cylindrical billet considered as an axially symmetrical temperature field (fig. 1). For electromagnetic and temperature field analysis the non-linear two-dimensional numerical model developed in FLUX software has been used [1]. The parameters of induction heating system are shown in table I. The value of inductor voltage U is selected as a control input constrained by condition $0 \le U \le U_{max}$.

An optimization problem could be formulated in the following form. It is required to obtain a desired temperature T^* with maximum heating accuracy ε_0 using two-stage time optimal control U^* (fig. 2) in minimal process time t_{end} under

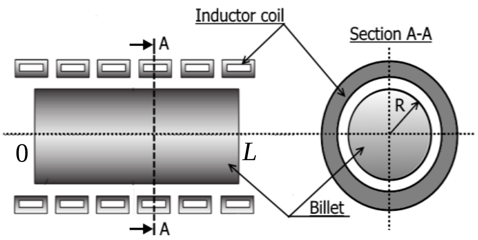

Fig. 1. Geometry of induction heating system

condition of interval uncertainty of the initial temperature T_0 and heat loss α values: $T_0\in[T_{0min}, T_{0max}]$, $\alpha \in[\alpha_{min}, \alpha_{max}]$. A final temperature distribution is considered along radial coordinate in the central cross-section of the billet (fig. 1, cross-section A-A).

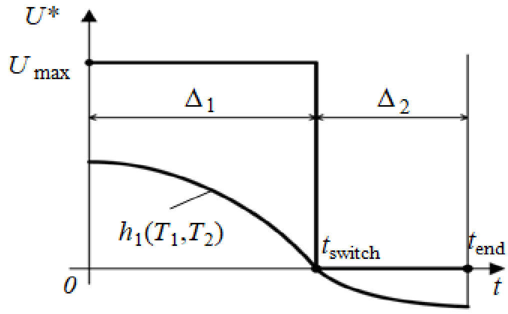

Fig. 2. Time-optimal control with two intervals of durations Δ_1 and Δ_2

The goal is to design an optimal control algorithm with feedback that provides a solution to the given problem.

First step is to synthesize deterministic optimal control system with the fixed values of initial temperature T_{0av} and heat loss α_{av}.

The solution of this problem is an optimal control algorithm that can be written in the following form:

$$U^*(T_1(t),T_2(t)) = \mathrm{U}_{max}/2 \times (1 + \mathrm{sign}\, h_1(T_1(t),T_2(t))). \quad (1)$$

Here $h_1(T_1(t),T_2(t))$ is switching function depended on the current values of measured temperatures at two selected points within the cross-section A-A of the billet:

$$h_1(T_1,T_2) = \rho_1(T^* - \varepsilon_0 - T_1(t)) + \rho_2(T^* - \varepsilon_0 - T_2(t)). \quad (2)$$

The points of measurement are located on the edge $T_1(t) = T(R,t)$ and at the center of the billet $T_2(t) = T(0,t)$; ρ_1, ρ_2 are feedback coefficients that could be obtained along with the maximum heating accuracy ε_0 after a solution of time-optimal control problem for open loop system is found [2]. Switching from one control stage to another happens when the sign of a switching function changes (fig. 2).

On the next step the identification of the uncertain process parameters T_0 and α can be done using special function that represents the dependence of unknown parameters on the results of measurements. In the considered case this function is formulated as the dependence $F(T_1(t_{fix}),T_2(t_{fix}))$ on the temperatures measured in the center $T_1(t_{fix})$ and on the surface $T_2(t_{fix})$ at the time t_{fix} which can be chosen arbitrarily within the heating time interval Δ_1. The procedure of approximation of this function described in [3].

Final step is integration of identifier $F(T_1(t_{fix}),T_2(t_{fix}))$ with the previously obtained algorithm (1) in order to provide a correction of the feedback coefficients ρ_1, ρ_2 in (2). Obtained control algorithm with identifier could be implemented as a program for industrial controller or as a module for control system software. The measurement in selected points could be done with temperature sensors.

III. Results

In order to test time optimal feedback control system with identifier in the loop computer simulation is used. Simulation procedure is divided into following steps. First, the solution of optimal program control problem is found using Matlab in order to obtain optimal parameters of control algorithm (Δ_1, Δ_2 and ε_0). Then the temperature distribution is imported from FLUX to Matlab software. After that it is possible to calculate feedback and identifier's correction coefficients and run simulation in Simulink. The results of computer simulation of time optimal feedback control system of induction heating of cylindrical billet with identifier in the loop are shown on fig. 3, 4. The results demonstrate a good coincidence with the optimal program control solution ($\Delta_1 = 1825$ sec., $\Delta_2 = 162$ sec., $\varepsilon_0 = 1.8$°C) when the difference between average and actual value of heat loss α equals to 10 %.

TABLE I. PARAMETERS OF THE INDUCTION HEATING SYSTEM

Parameter	Name	Aluminum billet	Steel billet
		Value	Value
Length of inductor , mm	L_i	1376	80
Number of turns	N	69	5
Distance between inductor and billet, mm	G	50	5
Size of turn, mm	TWxTH	12x16	6x12
Distance between turns, mm	Dt	4	5
Radius of the billet, mm	R	250	50
Length of the billet, mm	L	1000	95
Frequency of current, Hz	f	50	125000
Inductor voltage, V	U_{max}	470	237
Initial temperature, °C	T_0	20	20
Required temperature, °C	T^*	460	500

In order to obtain qualitative characteristics of the optimal control process, the verification of obtained optimal feedback control system without identifier is done by testing the developed algorithm on the existing laboratory installation of the Institute of Electrotechnology of Leibniz University. The parameters of the process are used only for the experimental case study but not for industrial application.

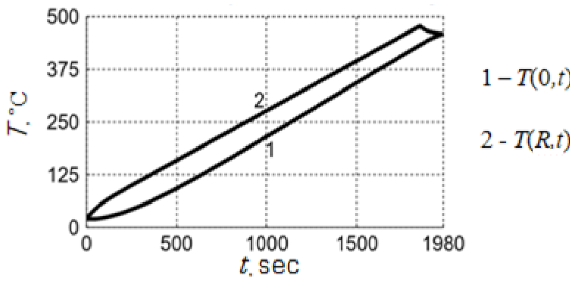

Fig. 3. Time-Temperature history (results of simulation)

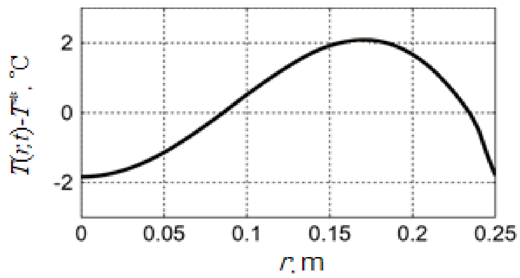

Fig. 4. Final radial temperature distribution in the center cross-section

Parameters and system geometry for a steel billet are shown in table I. In order to calculate feedback coefficients the results of previously obtained optimal control solution were used: $\Delta_1 = 95$ sec., $\Delta_2 = 80$ sec., $\varepsilon_0 = 2$°C. On fig. 5 the results of this experiment are in good agreement with the obtained solution: the moment of control switching coincides with optimal program control and the final temperatures reach the required value the with deviation not more than 4°C.

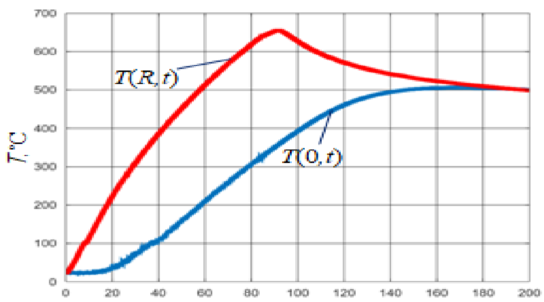

Fig. 5. Time-Temperature history (experimental results)

Acknowledgments

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