Refined Model of Induction Heater Taken into Acount Static Characteristics of Inverter

Vasiliy Frizen, Ivan Smolyanov, Salavat Fatkullin, Fedor Tarasov
Department of Electric Engineering and Electrotechnology Systems
Ural Federal University
Ekaterinburg, Russia
vfrizen@yandex.ru, i.a.smolyanov@gmail.com, solon2004@yandex.ru, f.e.tarasov@urfu.ru

***Abstract* — The paper is concerned with feasibility of the through heating calculation by using thermal circuits at the one-dimensional approximation. A part of paper is dedicated to justification of such approach applicability. The calculation is considered for a particular case of titanium cylindrical plants' treatment. Application of the proposed approach allows for considerable reduction of calculation time during the design process.**

Keywords— Equivalent circuit, induction heating, thermal circuit,

I. Introduction

When solving problems of cylindrical workpieces' induction heating for the purpose of plastic deformation under real industrial conditions, one often faces a case when it is required to heat the workpieces of different lengths and diameters with different thermal and electrical properties in one and the same inductor. The present problem solving includes the ability to predict behavior of thermal and electromagnetic processes in such plants for correct adjustment of control system. The correct adjustment means selection of optimal parameters of temperature regulator for different operation modes providing the required heat quality (temperature distribution uniformity over a heated workpiece section) as well as maximum energy efficiency (high heat rate and minimum electric energy consumption) for each specific workpiece.

This paper is a sequel to the series of papers [1, 2] concerning titanium workpieces' treatment. The problems of the plant design optimization, the possibility of elimination of nonuniform heating over the workpieces' length and radius as well as numerical models' verification by means of experiment were considered in previous papers. The finite elements method was used in the previous papers as a basic method for calculation of titanium workpieces' induction heating. This method requires considerable computational resources and computation time. The new approach to solving the coupled task concerning computation of electromagnetic and thermal field for induction heating of cylindrical workpieces is presented in this paper.

II. Description of the Heater

The heater consists of two copper water-cooled external and internal windings of inductor, which are connected in series. Every winding contains 54 turns. The external winding has a number of taps for efficient control of the workpieces' heating zone (bypassing the magnetic field). The paper considers a connection with all turns of the external winding. A lining is placed between the workpiece and the inductor. The geometry of the induction heating system is shown in Fig. 1. The installation is supplied by frequency inverter with maximum full power of 300 kVA and rated frequency from 100 till 300 Hz and connected to compensation capacity. The inductor, the workpiece, the compensated battery and the supply source create the oscillation circuit. The full cycle of work of the induction heaters system is described in work [3].

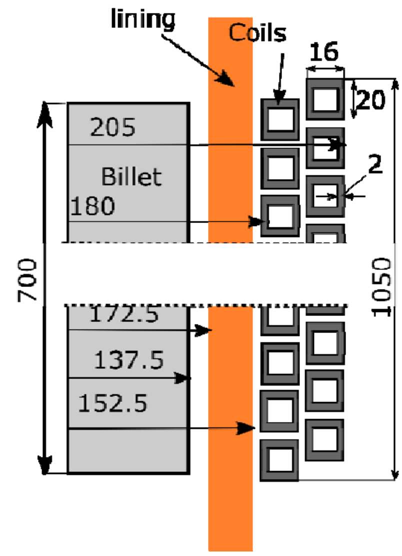

Fig. 1. Geometry of the induction heater

III. Description of the Proposed Approach

When solving electromagnetic field equation one can restrict to determination of integral parameters for the whole workpiece volume by means of equivalent circuit of inductive load due to small temperature difference during heating at the field penetration depth. In this case the source term of differential equation of heat balance (distribution of volumetric heat release in the load) can be calculated later on the basis of obtained solution of the differential equation of electromagnetic field in a one-dimensional statement. The frequency converter involves a certain difficulty during modeling. In this case the output parameters of the frequency converter depend on both the load circuit impedance, which changes during heating, and power control signal arriving at the input from the temperature regulator. Moreover, voltage at the converter output is non-sinusoidal and its harmonic composition depends largely on the operation mode (the set power level). The direct integration of converter model (with determination of instantaneous electrical values during solving) results in considerable increase in the required computational power in case the problem solving by the numerical methods due to a big difference between the time constants in the thermal and electrical problems. Therefore, for a converter model integration the array of stable operation modes across the entire range of the load impedance variation and across the whole range of power variation was preliminary calculated in order to obtain the numerical model of converter by means of the calculated data interpolation. In this case the converter output current restriction was considered. The control circuit operates in the same time scale as the thermal model and therefore it can be described by means of the ordinary differential equations.

The equations system, the solution of which describes the system state, is as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_r r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda_z\frac{\partial T}{\partial z}\right)=-q-c\rho\frac{\partial T}{\partial \tau}; \quad (1)$$

$$\frac{\partial}{\partial r}\left(\frac{1}{r\mu_z}\frac{\partial(rA)}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\mu_r}\frac{\partial A}{\partial z}\right)-i\omega gA=-j_0 \quad (2)$$

$$j=-i\omega gA; \quad (3)$$

$$q=g^{-1}j^2; \quad (4)$$

$$j_0=\frac{U}{Z_u\cdot S}; \quad (5)$$

$$U=f(Z_k,P_r);\ \omega=f(Z_k,P_r); \quad (6)$$

$$P_r=K_p\cdot\Delta T+K_i\cdot\int_0^{\tau}\Delta T dt. \quad (7)$$

With consideration of the assumptions made, the system equation (1) can be presented in a one-dimensional statement and it can be solved by one of the numerical methods (in this case it is convenient to use the finite difference method or equivalent heat balance diagrams' method) (7)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_r r\frac{\partial T}{\partial r}\right)=-q-c\rho\frac{\partial T}{\partial \tau}. \quad (7)$$

Equations (2) – (5) can be replaced by a ready-made solution of the current density distribution in a cylinder with radius of m2:

$$J_m(m,T)=\frac{\sqrt{-2\cdot i}}{\Delta(T)}\cdot H_{me}\cdot\frac{I_1(m)}{I_0(m_2(T))}, \quad (8)$$

IV. Results

The heating process modeling and the regulators parameters optimization was performed both for the bar stock and cylindrical titanium workpieces of different size in inductors of two different diameters. Geometrical dimensions of one of inductors are presented in Table 1.

Table 1 – Geometrical dimensions of induction heater

Workpiece diameter, mm	165..196
Internal diameter of inductor, mm	285
Internal diameter of lining (concrete), mm	216
External diameter of lining (concrete), mm	248
Inductor length, mm	1050

The computation results of the Ti6Al4V alloy bar stock workpiece heating are presented below. The workpiece length is 380 mm, the workpiece diameter is 166 mm and the heating temperature is 850 °C. The obtained heating curves are presented in Fig. 2, the power and frequency curves are presented in Fig. 3

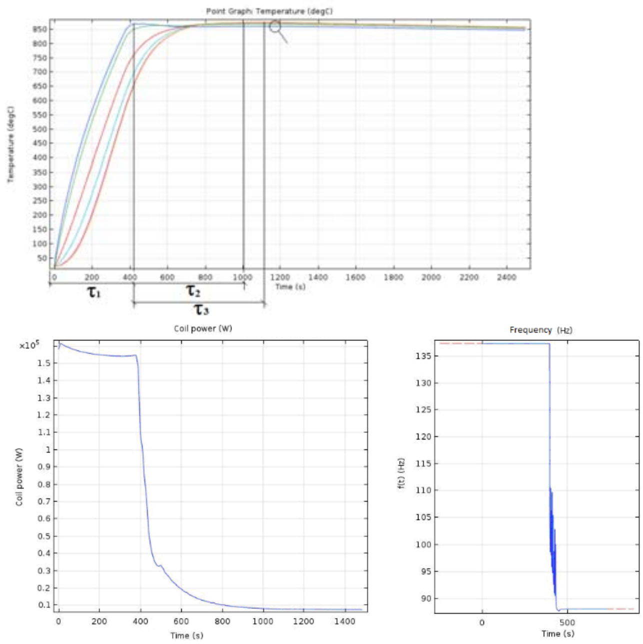

Fig. 3. Time dependence of the inductor power and current frequency

The variation of power consumed by inductor under the regulator control is seen from the obtained diagrams (maximum consumed power is 160.5 kW, maximum consumed power is 6.5 kW). The required heating quality was obtained for the regulator parameters calculated with the help of the model: the workpiece temperature at the end of heating was 850^{-2}_{+8} °C.

V. Conclusion

The obtained model of induction heating plant permits to make fast calculations of temperature fields in the cylindrical workpiece to sufficient detail with accuracy reasonable for temperature regulation. The model considers the peculiarities of the inductor electrical parameters variation during heating as well as operation peculiarities of the frequency converter being a part of induction equipment. For the induction unit model implementation one can use any mathematical software package capable for obtaining numerical solutions of differential equations systems.

Acknowledgment *(Heading 5)*

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