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The induction heated rotating steel cylinder as a control plant.

PROBLEM STATEMENT

Nowadays the research on the application of rotating steel cylinders heated by a high-frequency induction heating has arisen as an important field in electro technological area. Such cylinders can be used mainly in paper making, textile and chemical industry, ensuring higher efficiency and more environment-friendly operation then usually applied cylinders heated by steam or oil.

Modern high-quality technological processes performed in above mentioned branches of industry require the heating system of the cylinders to fulfill the following conditions:

- Required temperature distribution along the cylinder (uniform or given non-uniform),
- Repeatability of temperature level at the surface,
- Minimization of the influence of disturbances acting at the cylinder surface,

To follow as precisely as possible the required temperature distribution at the cylinder surface, in the presence of various inevitable thermal disturbances, usually caused by heated charge (e.g. paper ribbon), it is necessary to apply the closed loop temperature control system. The scheme of this system is presented in fig. 1.

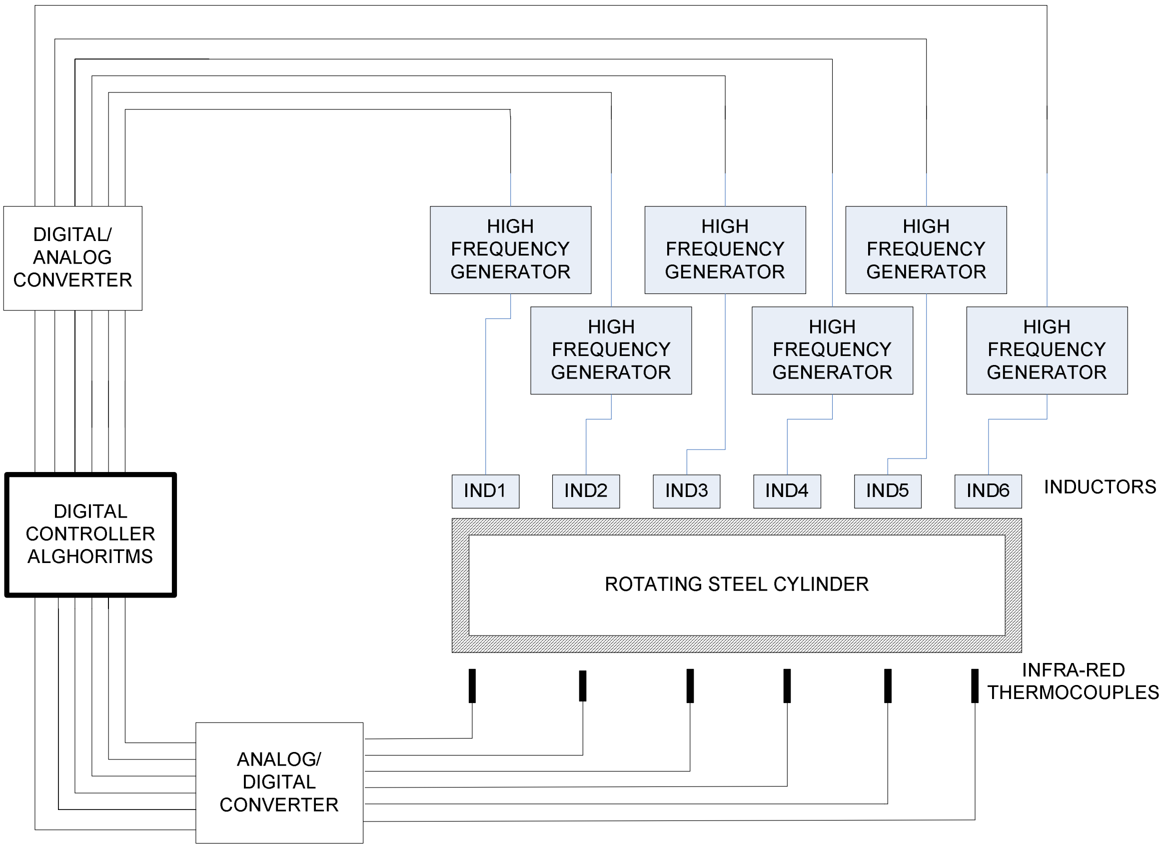

Fig. 1. Scheme of temperature control of the rotating steel cylinder surface. INDx – inductors (x=1:6 – no. of inductor)

It is well understood that any control system of the given quality requirements needs the appropriate dynamic model of controlled plant. Such a model should not be too complicated if structure and parameters of the controller is to be determined basing on it, but on the other hand it has to cover the most important properties of the real plant. In the case of the regarded rotating steel cylinder several factors should be take into consideration:

- Many inputs and outputs of control system – multidimensional control system,
- Noticeable thermal interactions between heating zones,
- Distributed material parameters of the system.

In order to avoid time-consuming experiments the simplified two-dimensional numerical model of the analyzed heating system has been elaborated, basing on heat transfer equations. This model, implemented in the commercial MATLAB-SIMULINK software environment, imitates six induction heating zones, generating the active power under the surface of the cylinder. Such a model was then used to determine the multi-input multi-output transfer function model which can serve as basis for controller design procedure.

NUMERICAL MODEL OF INDUCTION HEATED ROTATING STEEL CYLINDER.

In considered numerical model, discrete both in space and time, eddy currents induced in reality in the cylinder mantle under inductors are replaced by nodes with active power placed near the penetration depth.

During thermal analysis the following assumptions were assumed:

- The model can be regarded as two dimensional, because the heat conduction along the cylinder axis and through the thickness of the heated cylinder mantle are important. In the paper [1] the negligible (below 1C) temperature fluctuation along diameter of the rotating cylinder (for rotational speed more than 50 rad/s) has been proved.
- Value of total active power put in power nodes was derived from prior electromagnetic calculations of the inductor-cylinder system with 20kHz voltage excitations. This value was verified by calorimetric method on the real laboratory model [1].
- Thermal properties and the heat exchange coefficient between the cylinder surface and the ambience are constant (at least in the narrow range of working temperatures).
- Analyzed regions are isotropic.
- Ambient temperature is constant.

Heat exchange in considered conditions can be described by the Fourier-Kirchhoff formula as follows:

$$\frac{\partial \vartheta}{\partial t} = \frac{p_v}{c_w \gamma_w} + \frac{-\lambda}{c_w \gamma_w}\left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2}\right) \tag{1}$$

where: λ - conductivity of cylinder mantle, ϑ - temperature, p_v - volumetric active power density, c_w - specific heat of analyzed region, γ_w - density

is applied and heat exchange boundary condition is applied:

$$\alpha(\vartheta_\infty - \vartheta)\Big]_{surfaace} = -\lambda A\left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2}\right)\Big]_{surfaace} \tag{2}$$

where: A – surface area.

Equation (1) together with boundary conditions can be solved numerically using FDM.

Meshing of cylinder's mantle with marked boundary conditions is shown in fig. 2.

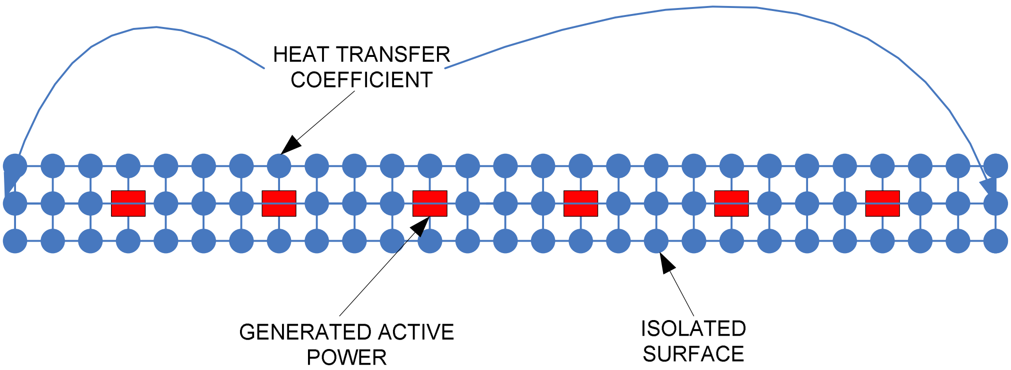

Fig. 2. Meshing of cylinder's mantle. Red (square) nodes represents active power induced under the surface of the inductor.

For calculations the following material parameters and coefficients have been chosen (table 1):

Table 1. Coefficients used

Conduction λ [W/(m·K)]	*Heat transfer coefficient* α [W/(m^2·K)]	*Specific heat x density* $c_w \gamma_w$ [J/(kg·m^3)]	*Total active power per node [W]*
40	50	$3.6 \cdot 10^6$	1000

Such a model enables to observe the temperature at various places of the cylinder as well as the temperature distribution along its axes. Exemplary results of heating up curves are shown in the fig. 3 and corresponding temperature distribution in steady-state condition is given in fig. 4.

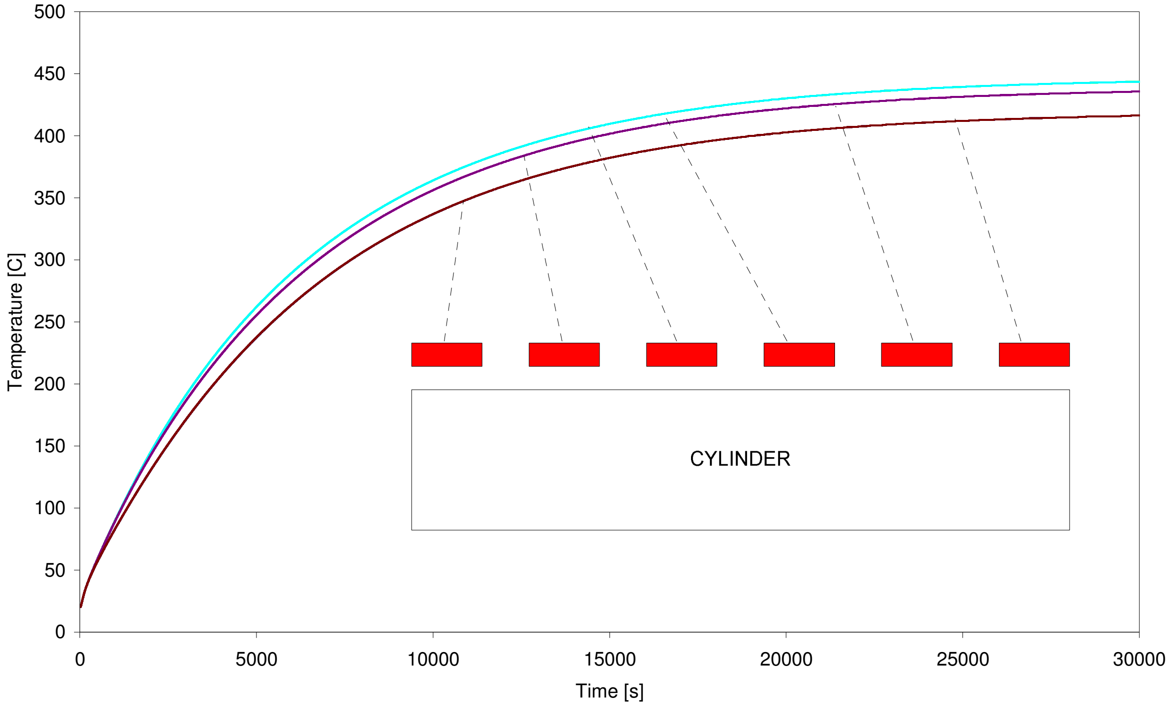

Fig. 3. Heating up curves of the cylinder surface. Each heating zone is supplied with the nominal active power (1kW).

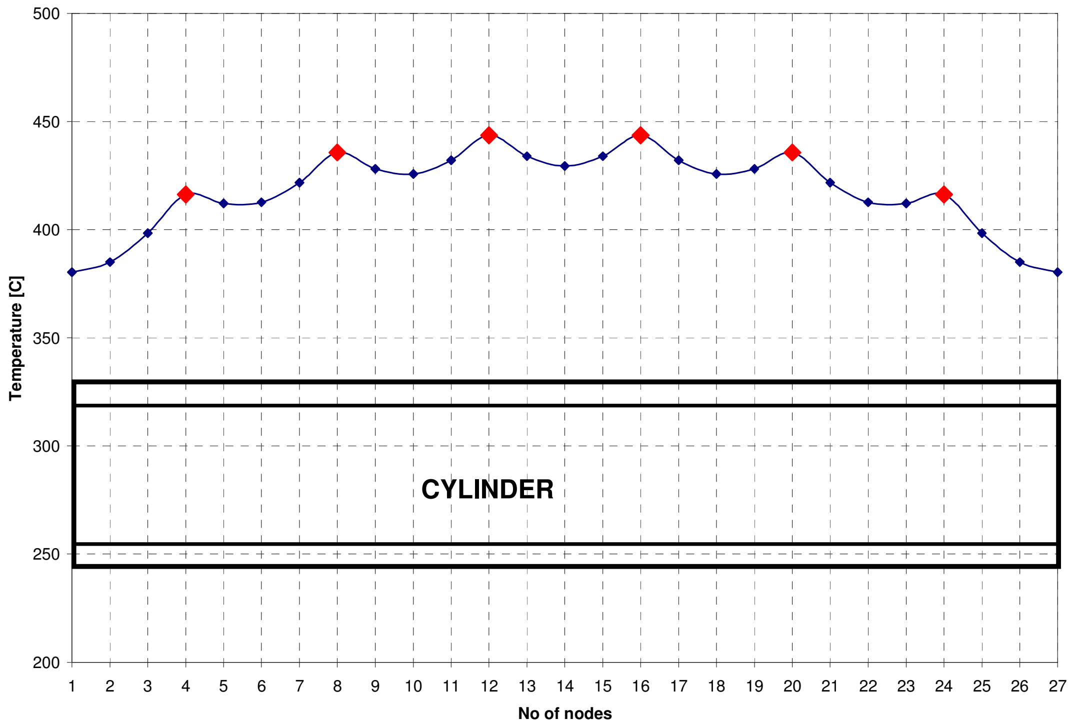

Fig. 4. Temperature distribution on the cylinder surface along its axis of rotation. Red squares correspond to the power nodes.

MULTI-INPUT MULTI-OUTPUT TRANSFER FUNCTION MODEL

Designing of a temperature control system of the heated cylinder requires a model covering the most important dynamic properties of the plant. One of the possible approach is to represent an input-output behaviour of the plant in the form of transfer functions. The structure of such a model can be derived from the analysis of the mutual influence of heating zones. Generally speaking, as the cylinder is made of a good thermal conductor, the locally generated heating power is actually transferred through the entire volume of the cylinder. Thus each inductor can potentially influence the temperature of every zone, which can be represented by coupling transfer functions, leading to the block diagram shown in Fig. 5

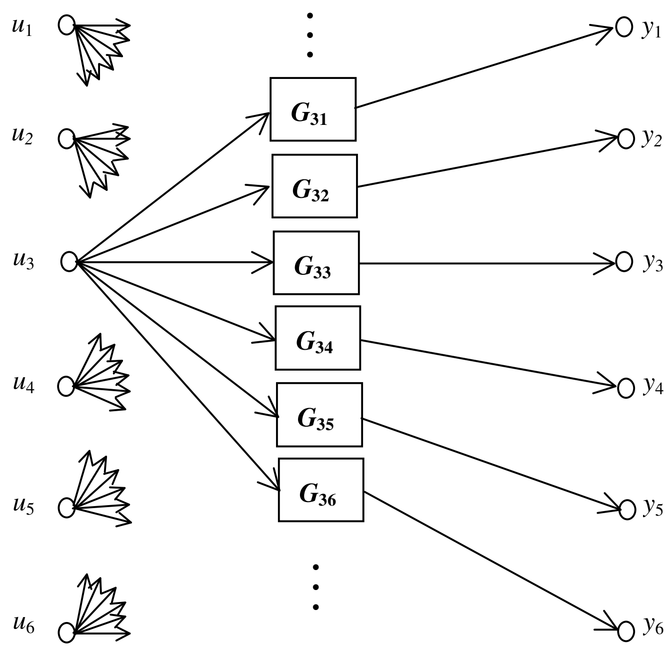

Fig. 5. Structure of the transfer function model of the induction heated cylinder (for the sake of readability a full structure is shown only for zone 3, while similar structures exist for other zones).

Resulting transfer function model of the induction heated cylinder can be represented by the following matrix equation:

$$Y(s) = G(s) \cdot U(s) \tag{3}$$

where input and output vectors U(s), Y(s), as well as the transfer function matrix G(s) have the form:

$$\mathbf{U}(s)=\begin{bmatrix} u_1(s) \\ \cdot \\ \cdot \\ \cdot \\ u_6(s) \end{bmatrix};\qquad \mathbf{Y}(s)=\begin{bmatrix} y_1(s) \\ \cdot \\ \cdot \\ \cdot \\ y_6(s) \end{bmatrix};\qquad \mathbf{G}(s)=\begin{bmatrix} G_{11}(s) & G_{12}(s) & \cdot & \cdot & \cdot & \\ G_{21}(s) & G_{22}(s) & & & & \\ \cdot & & \cdot & & & \\ \cdot & & & \cdot & & \\ \cdot & & & & \cdot & \\ & & & & & G_{66}(s) \end{bmatrix} \tag{4}$$

It has been widely approved that dynamics of the heating phenomena, especially in electroheat appliances, can be effectively modelled by a relatively simple transfer function comprising a first order inertia and a time delay [3]. Therefore it can be assumed that each block Gij(s), representing the thermal interaction between i-th zone and j-th inductor, has the form as follows:

$$G_{ij}(s)=\frac{K_{ij}}{1+N_{ij}s}e^{-sL_{ij}} \tag{5}$$

where K, N, L, are gain, time constant and time delay respectively.

In order to determine the parameters K, N, L for each block of the model several identification experiments have to be performed. Since each inductor being excited separately activates six blocks out of the full structure of the model, six step-input experiments is necessary to obtain all parameters of the system. Step-input response analysed numerically in terms of its derivative and the inflection point [4] allows the determination of the required parameters also in noisy environment.

The identification results obtained by a simulation based on the numerical model of the induction heated steel cylinder described in previous section are presented in Fig. 6.

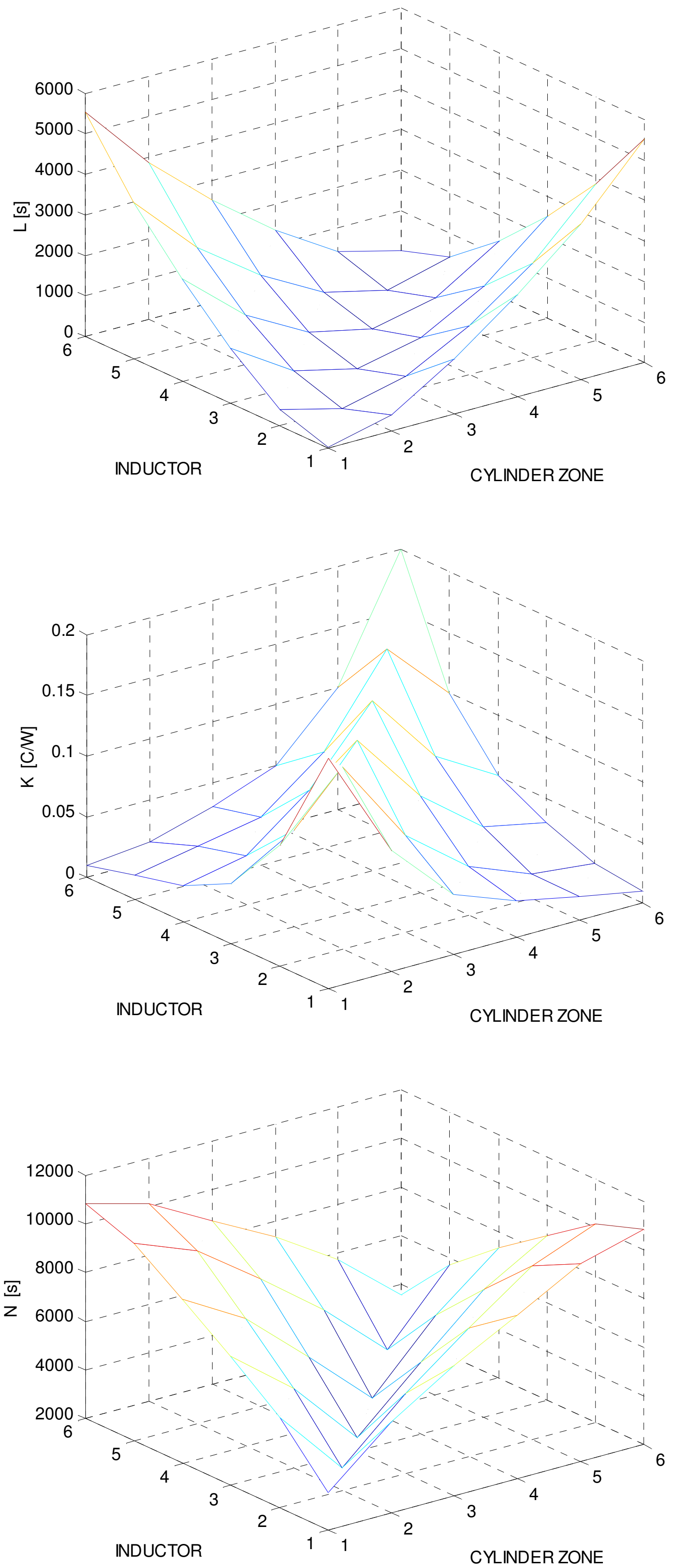

Fig. 6. Parameters of multi-input multi-output transfer function model of the induction heated cylinder.

As it could be anticipated, each inductor influences most significantly the zone of the cylinder placed directly under it (the highest gain along with the lowest both the time constant and time delay for transfer functions Gij where i=j). The farther the zone is located from the inductor the weaker influence is observed, but additionally performed simulations indicates that this coupling can not be neglected if the behaviour of the heated system is to be modelled properly in various working conditions. Chosen examples of a temperature signal of zone 3 resulting from both the numerical model and transfer function model for different configurations of working inductors are shown in Fig. 7.

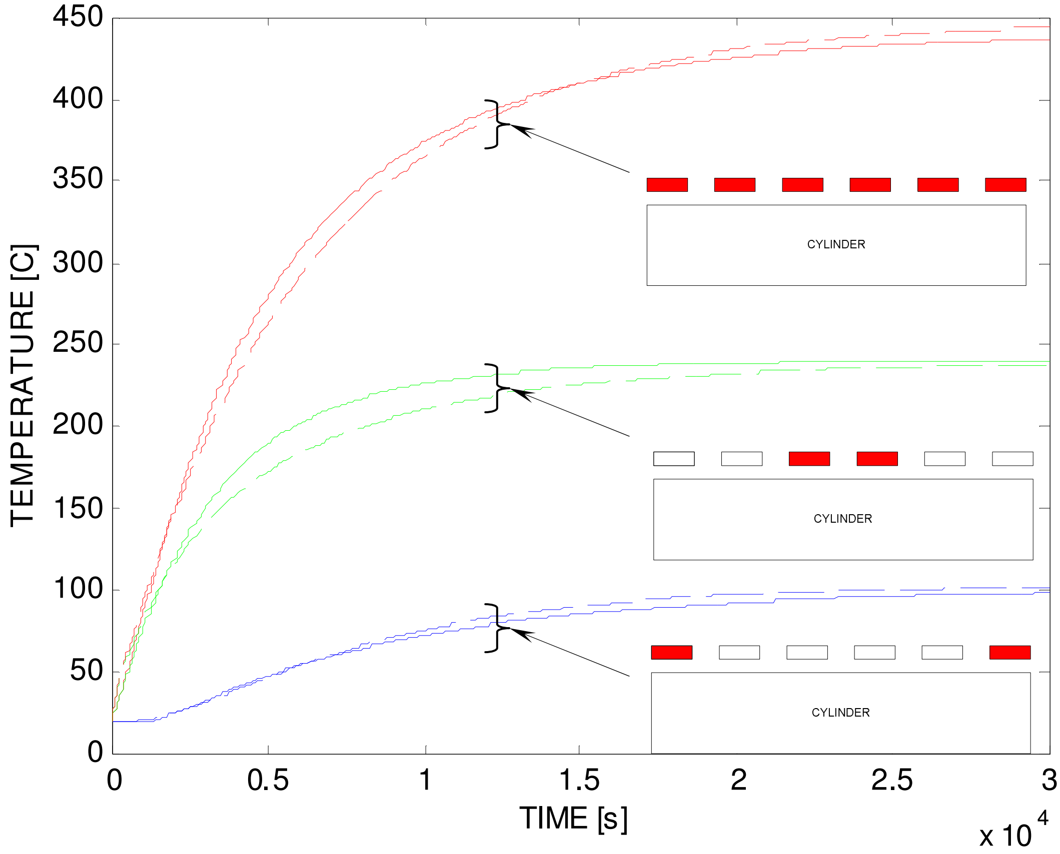

Fig. 7 Step-input response of zone 3 for three different configurations of working inductors. Comparison of the numerical (solid lines) and transfer function model (dashed lines).

The obtained set of parameters reveals also an expected symmetry (visible in Fig. 6) which suggests the possibility of reduction of the identification procedure. In practice however each inductor may have slightly different characteristics (due to not exactly the same shapes of electromagnetic circuits) so that this reduction should be undertaken with care.

CONLUSIONS

In the paper chosen methods of modeling of an induction heated rotating steel cylinder have been analyzed. Such cylinders are becoming more and more popular for various electrotechnologies in several branches of industry, but the sufficiently precise temperature control still remains an important challenge in this area. Regarded heating system can be modeled by a numerical solution of well-known thermal laws, whereas parametric models of the plant, usually in the form of transfer functions, are typically a basis for a control system design procedure. Multi-input multi-output transfer function model, with relatively simple particular blocks, has been built and the sufficient equivalence of the two types of models has been shown. Proposed approach enables to perform a preliminary identification of the heating system for temperature control purposes avoiding time-consuming experiments.

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