Modeling of Thermal Operating Modes of a Linear Electrical Machine in a Strong Coupled Task

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***Abstract* — In this paper, the possibility of reducing the nonlinearities of the model for calculating the thermal characteristics of a linear asynchronous machine is considered. The magnetic field is adopted as slowly varying in time (harmonic field). The temperature field is calculated in the time domain taking into account the change in the thermal and electromagnetic properties of the material at each time step. In the course of the work, it has been possible to neglect a number of nonlinearities, which makes it possible to save computing resources. The influence of methods for specifying natural convection in explicit and implicit form is analyzed. A method of correct heat transfer at high speeds is proposed.**

***Keywords* — linear induction motor; strong coupled task; temperature field; thermal problem; nonlinearity of characteristics.**

I. INTRODUCTION

The principle of operation of linear induction motors (LIM) is based on the ability of a three-phase system of currents to create a traveling magnetic field. If in a conventional asynchronous engine a stator of a cylindrical shape is cut along its axis and unfolded into a plane, we get a stator of a linear motor, called an inductor. As a result of the interaction of the magnetic field of the inductor with the secondary element, the latter comes into motion.

The use of linear electric motors is most promising in industrial and passenger transport. Also, LIM are widely used in the drives of various actuators and devices, for example, in impact machines or metal-cutting equipment.

This article deals with the thermal characteristics of a conveyor linear induction motor, represented as a 60-groove linear induction motor. The installation shown in Fig. 1 has a magnetic circuit of a secondary element (SE), which is required to close the magnetic flux, and also a ring winding, which allows, if necessary, to change the winding connection and the number of grooves per pole and phase.

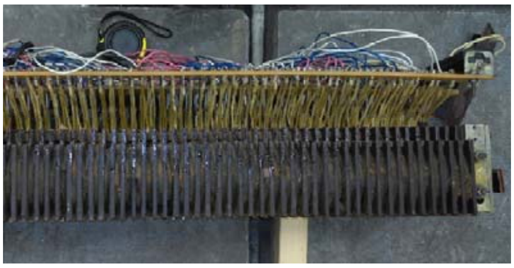

Fig. 1. Appearance of the simulated LIM

II. FORMULATION OF THE PROBLEM

The thermal calculation of the linear asynchronous motor was performed using the finite element method (FEM) in the COMSOL Multiphysics package. Another way of investigating LIM (the method of detailed substitution schemes) is considered in articles [1,2]. Using the Bolton coefficient [3], the influence of the third coordinate (the limited width of the secondary element) was taken into account.

The calculation is carried out for 100 seconds in 1 second increments. The initial temperature is assumed to be 20 °C. The calculated value of the sliding is equal zero (ideal idling).

The task of this paper is to compare the temperatures of the LIM elements in the modeling of various conditions:

1) weak coupled task (without temperature dependences);

2) strong coupled task (with taking into account the effect of temperature on the characteristics of the engine);

3) strong coupled task with allowance for the dependence of the relative magnetic permeability on temperature.

Also, the temperatures were compared for explicit and implicit convection tasks.

The basic geometric parameters of the model are shown in Table 1.

TABLE 1. GEOMETRICAL DIMENSIONS OF LIM

Description	Value, mm
Tooth width	5
Groove width	7,92
Groove height	39
SE magnetic core height	47
Thickness of air gap	5
Thickness of high-conductivity SE	2
SE width	122
Inductor width	120
Inductor length	820
Number of grooves	60
Number of slots per pole and phase	2

III. MATHEMATICAL MODEL

A continuous mathematical model of the process consists of two nonlinear partial differential equations describing the change in the magnetic and temperature fields in the system over time.

The magnetic field generated in the system by the inductor can be expressed in terms of the magnetic vector potential ***A*** as follows:

$$\mathrm{curl}\left(\frac{1}{\mu}\,\mathrm{curl}\,\boldsymbol{A}\right)+\gamma\frac{\partial \boldsymbol{A}}{\partial t}=\boldsymbol{J}_{\mathrm{ext}}, \tag{1}$$

where γ is electrical conductivity, μ is magnetic permeability and J_{ext} is the field current density (which takes a nonzero value only inside the inductor).

A sufficiently remote artificial boundary is described by the Dirichlet condition ***A*** = 0.

Unfortunately, the solution (1) in 3D is still practically unworkable. The main reason is a significant difference between the field current frequencies and the heating time constant. To solve the problem, we can simplify the model if we assume that the field values are harmonic. Then the magnetic field can be described by another equation:

$$\mathrm{curl}\,\mathrm{curl}\,\underline{\boldsymbol{A}}+\mathrm{j}\cdot\omega\gamma\mu\underline{\boldsymbol{A}}=\mu\underline{\boldsymbol{J}}_{\mathrm{ext}}, \tag{2}$$

where ω denotes the angular frequency [7].

A harmonic magnetic field is generated in a wheel induced currents. The current density induced in the SE is determined by the expression

$$\underline{\boldsymbol{J}}_{\mathrm{ind}}=-\mathrm{j}\omega\gamma\underline{\boldsymbol{A}}. \tag{3}$$

The magnitude of the average volume losses due to these currents can be calculated as follows:

$$w_{\mathrm{J}}=\frac{1}{2}\frac{|\underline{\boldsymbol{J}}_{\mathrm{ind}}|^2}{\gamma}. \tag{4}$$

Another type of heat loss is hysteresis loss. However, their magnitude is much smaller, in connection with which they can be neglected in this problem.

The temperature distribution in the time-dependent SE-inductor system is described by the heat-transfer equation:

$$\mathrm{div}\,(\lambda\,\mathrm{grad}\,T)=\rho c_{\mathrm{p}}\frac{\partial T}{\partial t}-w, \tag{5}$$

where λ is thermal conductivity, ρ is specific gravity, c_p is specific heat at constant pressure.

During the heating process, the loss value is calculated by formula (4), and during cooling it is assumed to be zero.

The boundary condition along the outer surface S of the SE can be written as follows:

$$-\lambda\frac{\partial T}{\partial n}=\alpha\,(T_{\mathrm{S}}-T_{\mathrm{ext}})+\sigma C\left(T_{\mathrm{S}}^4-T_{\mathrm{r}}^4\right), \tag{6}$$

where α is convective heat transfer coefficient, T_S is surface temperature, T_{ext} – ambient temperature, n is direction of the outer normal to the surface S of the system at a given point, σ is the Stefan-Boltzmann constant ($\sigma = 5{,}67\cdot 10^{-8}\,\frac{W}{m^2K^4}$), C is coefficient of emissivity and T_r is temperature of the surface on which the heat radiates from the system.

IV. ANALYSIS OF THE RECEIVED RESULTS

Using the Bolton coefficient to take into account the three-dimensionality of the installation is considered when creating quasi-three-dimensional models of LAD [3-6]. Such an assumption ensures a sufficiently high accuracy of the results of calculations.

In the calculations, we assume that the magnetic circuit of the secondary element, through which the magnetic field closes, is made of hot-rolled 1211 sheet steel, and the inductor is made of thin-sheet cold-rolled isotropic steel 2013. The secondary element itself is made of copper.

Fig. 2 shows the temperature dependence of the copper secondary element versus time. The temperature jump at the initial moment is due to the value of the step 1 s, which considerably exceeds the value of the period of the electromagnetic field. Nevertheless, for the calculated time the temperature in all cases has time to reach the steady-state value.

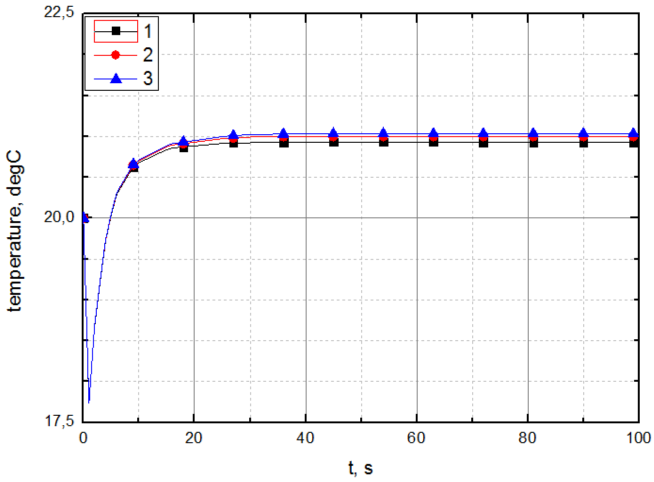

Fig. 2. Dependences of the temperature of the secondary element on time:

1 – weak coupled task; 2 – strong coupled task; 3 – strong coupled task taking into account the dependence μ(B,T)

From the data presented in Figure 2, it can be concluded that taking into account the nonlinearities of the characteristics has a negligible effect on the calculation results: the difference between the steady-state values does not exceed 0.2 °C.

In Fig. 3 shows the temperature dependence of the time for various convection tasks. As in the first case, the calculation is performed in the ideal idle mode. An explicit convection task in COMSOL Multiphysics is performed by adding the Laminar Flow unit and setting the temperature dependence of this block. In the case of an implicitly specified convection, a Heat Flux block was added to the heat calculation (in the calculations, the heat transfer coefficient is assumed to be 20).

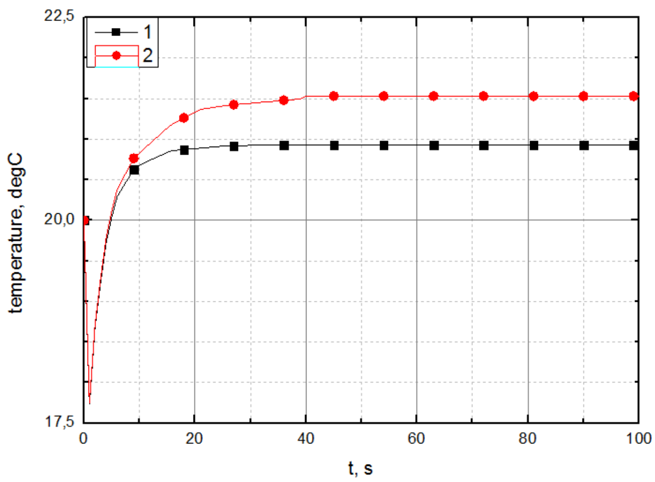

Fig. 3. Dependences of the temperature of the secondary element on time:

1 – implicit convection (Heat Flux); 2 – explicit assignment of convection (Laminar Flow)

It can be concluded from Figure 3 that the calculated value of the heat transfer coefficient in the case of an implicit convection is greater than in the case of an explicit specification, and therefore the difference between the steady-state values of the temperature is approximately 0,5°C.

V. CONCLUSION

In general, we can conclude that taking into account the nonlinearities of the LIM characteristics does not greatly affect the final results of thermal calculations, since the installation temperature varies within 10 degrees (in the case of ideal idling). It should also be noted that when calculating the nonlinearities, the calculation time increases noticeably: without taking into account the temperature feedback, the calculation time is 20 minutes, and when temperature dependences are introduced, it increases to 30 minutes. This allows us to conclude that the calculation of a loosely coupled problem is applicable without a significant increase in inaccuracies.

In the case of the choice of the method for specifying convection, it is necessary to say that the implicit method is preferable, based on the calculation time: 20 minutes with an implicit reference versus 26 minutes for the explicit. The use of implicitly specified convection will save the computational resources and time, but it is first necessary to perform a heat calculation with an explicitly specified conjecture for determining the value of the heat transfer coefficient.

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