Waveform of Inductor Current at Low-Temperature Induction Heating

M. L. Strupinskiy, N. N. Khrenkov
Special Systems and Technologies,
LLC, Mytischi, Moscow Region   E-mail:
hrenkov@sst.ru

A. B. Kuvaldin, M. A. Fedin, M. A. Rashevskaya
National Research University
"Moscow Institute of High-Power Engineering"

Abstract—**A method of calculation of cylindrical inductor of induction-type immersion water heater operating at industrial frequency is described. The inductor is located between two walls to be heated, made of ferromagnetic steel. A model of this electromagnetic system connected in an electric circuit is developed in *ELCUT* software package and investigations of inductor current waveform depending on the water heater power are carried out.**

Keywords—induction heating; immersion water heater; magnetic field; numerical analysis.

I. INTRODUCTION

Various design versions of electrical water heaters are industrially used including those based on induction heating. The immersion heater is made in a form of sealed casing with an inductor inside (see Fig. 1). Its construction is axi-symmetric.
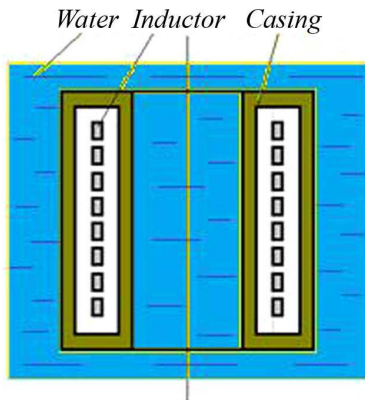

Fig. 1. Scheme of water heater of immersion type

Specific features of the inductor calculation are as follows:

1. Two-sided heating is realized.

2. Non-linear properties of ferromagnetic steel should be taken into account (dependence of related magnetic permeability on magnetic field strength).

3. Heat output in ferromagnetic casing caused by the hysteresis effect should be taken into consideration.

The following assumptions made in the calculation should be noted:
- Butt regions of the heater (end effects and presence of metal wall at the top and at the bottom) are not included in the calculation.
- Heating temperature is below 100°C and temperature dependence of the related magnetic permeability is not taken into account.

- Variations of specific electrical resistance of the inductor and casing material in the course of heating are not taken into account;
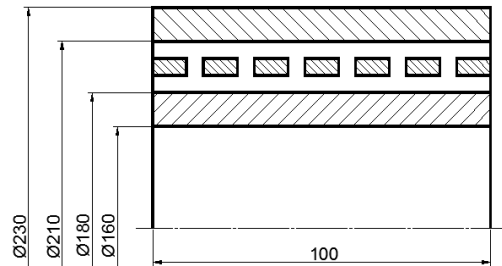

Fig. 2. Computational region

A fragment of computational region 100 mm long with related dimensions is shown in the Figure 2. The casing material is steel 10, the inductor material is copper, the inductor current frequency f = 50 Hz.

Calculation of such electromagnetic system is a nonlinear problem since the system includes two nonlinear ferromagnetic regions (casing walls), each of them requiring taking into account the dependence of the related magnetic permeability on the magnetic field strength. When such electromagnetic system is powered from harmonic voltage source, the resultant current waveform becomes nonsinusoidal.

The computational region in *ELCUT* environment is shown in Fig. 3. The following boundary conditions are used in the calculation: the set value of magnetic potential A = 0 (Dirichlet condition, for boundaries 1, 3), the set value of tangential component of the magnetic field intensity H_t=0 (Neumann condition, for boundary 2). Zero Dirichlet condition on the axis for axially symmetric problem (boundary 3) is set by default. In view of the problem's symmetry, we can leave only the right haf of the coil in the computational region (upper half of its cross-section is shown in the picture). So the electrical parameters of the circuit should be set at a half of their actual values for the calculation. The problem to solve in *ELCUT* is a problem of calculation of nonstationary magnetic field with an affiliated external electrical circuit. The values of electrophysical parameters of the materials used in the water heater construction are defined more exactly in the course of solving of coupled electrothermal problem.

The magnetic field pattern calculated in *ELCUT* is shown in Fig. 4 and timing diagrams of the inductor current for various power outputs of the induction heater calculated in *ELCUT* are presented in Fig. 5. Butt regions of the heating unit were not taken into account in this magnetic field calculation.
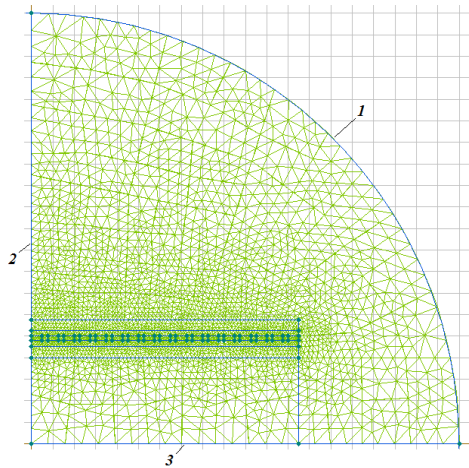
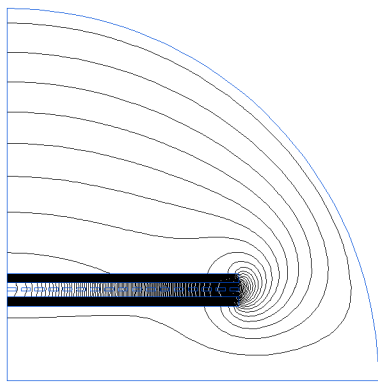Fig. 3. Computational region in *ELCUT* environment

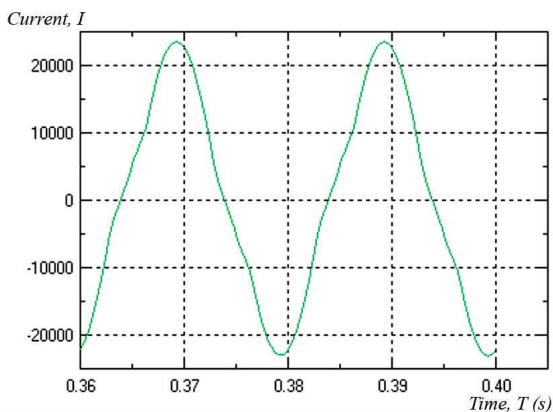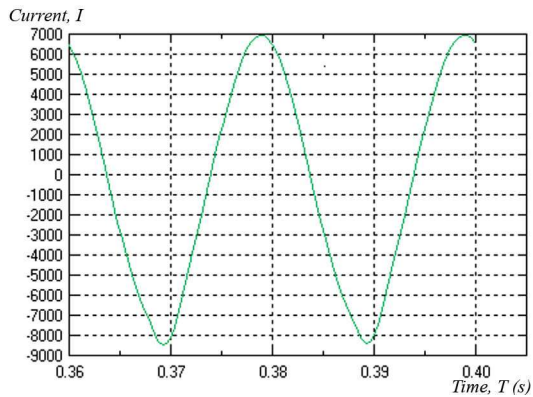Fig. 4. The magnetic field pattern calculated in ELCUT

Fig. 5. Variation in time of the inductor current for the heater power output: top – 5.3 kW; bottom – 34.2 kW

The Fourier series representation of the inductor current curve gives the following results for the heater power output 5.3 kW: contribution of third harmonic component – appr. 11.7 %, of the fifth component – appr. 6.4 % (Fig. 6). Further increase of supply voltage leads to significant growth of high-order harmonics contribution. At power output of 3 kW and less, there is no contribution of high-order harmonics to the resulted current curve.
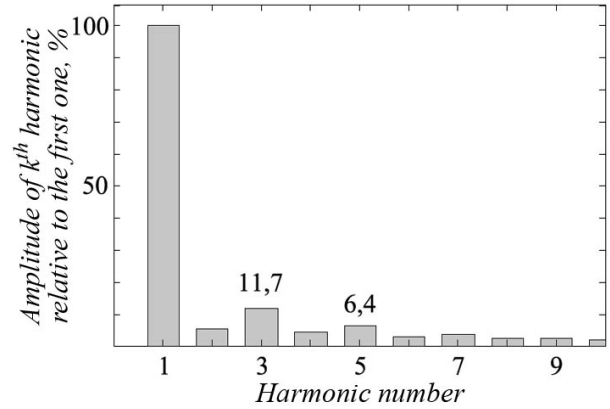

Fig. 6. Spectrum of inductor current curve¨

The presence of high-order harmonics in the load current curve leads to distortion of sinusoidal waveform of the voltage at secondary side of power transformer that results in increase of such electric energy quality indicators as voltage waveform distortion factor k_U and n^{th} harmonic coefficient $k_{U(n)}$. Values of these indicators, at high power output of induction water heater, can exceed their limits provided in GOST 13109-97 "Electric energy. Electromagnetic compatibility of technical equipment. Power quality limits in public electrical systems".

I-62