Influence of Magnetic Steel Induction Heating Power Density on Inductor Resistance Range

Soslan V. Dzliev[1], Aleksei A. Khorshev[2],
Alena A. Zhukova, Ilya A. Tsvetkov
Department of Electrical Technology and Converter Engineering
Saint-Petersburg Electrotechnical University "LETI"
St. Petersburg, Russia
[1]dzlsv@mail.ru, [2]aahorshev@yandex.ru

Konstantin E. Pishchalev
"INTERM" LLC,
St. Petersburg,Russian Federation
Pischalev@mail.ru

***Abstract*— Range dependency of the inductor resistance vector in process of induction heating of a cylindrical piece of magnetic steel from 20 ℃ to 1000 is investigated. The research was carried out by simulation and experimentally using a specially prepared specimen of a cylinder made of magnetic steel.In the simulation, the coupled electromagnetic and thermal problems were solved. Experimental research was carried out by heating the specimen at a frequency of 66 kHz with a heating power of up to 40 kW. It was established that the vector of inductor resistance changes 3 ... 5 times with a high specific heating power, characteristic of high frequency currents hardening, and reaches 20 times with a specific power of 2 ... 10 W / cm^2, characteristic during heating for a hot fitting or softening. The results of the research will be useful in the development of induction synchronizer units with power supply.**

Keywords—induction; resistance; magnetic steel; hodographs; magnetic permability

I. INTRODUCTION

The "inductor-component" system (induction system) is a dynamic system with distributed parameters, in which interconnected electromagnetic and thermal processes take place, and in some cases also electromechanical, gas or hydrodynamic processes, thermal deformations and stresses occur. To accurately describe the processes in the induction system, numerical simulation methods are used and implemented, for example, in the simulation package UNIVERSAL 3D [1]. Numerical models allow you to optimally design an induction system to obtain the desired technological effect.

In the theory of induction heating, electrical replacement circuits with lumped parameters Fig. 1, a) and b). Scheme 1a allows for the physical interpretation of each element within it. It is convenient for assessing the influence of electromagnetic and thermal properties of materials on the properties of an induction system.

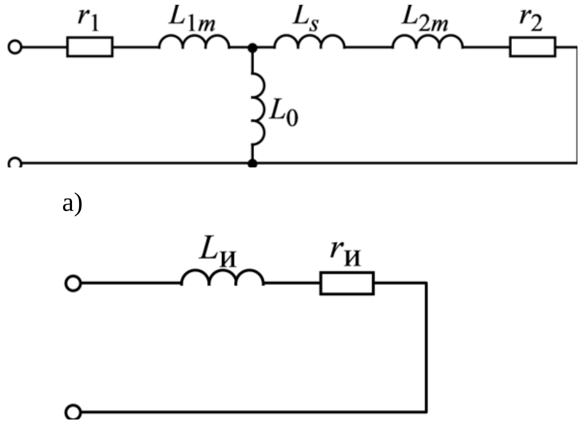

Fig. 1. Inductor replacement circuits

The parameters of this scheme depend on the geometrical dimensions of the induction system and the properties of the materials of the inductor and the load and have the following physical meaning: r_1 – is the resistance of the inductive wire; L_{1m} – is the inductance characterizing the leakage flux inside the inducing wire; L_s – is the leakage inductance associated with the leakage flux in the gap between the surfaces of the inductor and the part; L_{2m} – inductance associated with the magnetic flux passing through the cross section of the part; r_2 – is the active resistance of the part in which the effective power is allocated; L_0 – inductance, which characterizes the magnetic resistance of the reverse circuit of the flow outside the inductor and component.

However, to solve the problems of matching the power supply and the induction system, as well as the control problems of the power transmitted to the inductor, neither detailed modeling of the technological process nor a complex replacement circuit is required. A rather simplified replacement circuit for the inductor, shown in Figure 1b, describes the induction system as a power supply load and the parameters of which are easily recalculated from the circuit 1a. The parameters of the inductor L_i and r_i in the process of heating

978-1-7281-0339-6/19/$31.00 ©2019 IEEE

component made of magnetic steel change mainly due to changes in the electrical resistivity ρ and the magnetic permeability of steel μ from temperature [2].The electrical resistivity of steel directly affects the resistance of the current induced in the component and, in addition, μ and ρ affect the depth of penetration of high-frequency current into steel

$$\Delta = 503\sqrt{\frac{\rho}{\mu f}} \qquad (1)$$

i.e. change the cross section through which the current induced in the part flows. In the replacement circuit 1a, as μ and ρ change, the values of L_{2m} and r_2 change.

The change in resistance of the induction system during the heating of parts has a negative effect on the efficiency of the induction heaters, since it does not allow transferring the maximum power from the source to the load throughout the entire process. In the modes of stabilization of the power or current of the inductor it is necessary significantly, sometimes two or more times to reduce the level of stabilized parameters in comparison with the maximum capabilities of the source. This leads to the need to use a more powerful source, if it is necessary to stabilize the parameters at the right level, or it is necessary to allow power dips (current) at certain intervals of the heating process.

These negative effects can be minimized by optimally matching the inductor with the power source, i.e. selection of the optimal value of the transformation ratio of the matching transformer and the capacitance of the compensating capacitor. With a particularly large range of changes in the parameters of the inductor from the temperature, the heating process is divided into intervals and the transformation coefficient or capacitance of the compensating capacitor is switched so that at each time interval the matching of the inductor with the source is optimal.

A convenient and informative mathematical description of an inductor to determine the optimal parameters of its coordination with a power source is the hodograph of the impedance vector of a sequential inductor replacement circuit. It allows, without considering the heating process in time, to describe the range and possible combinations of the active and reactive parts of the inductor impedance.

II. HODOGRAPH OF INDUCTOR IMPEDANCE VECTOR

The experimentally obtained hodographs of the vector X_i (r_i) for various induction heaters are shown for example in Figure 2 [3], where curve 1 corresponds to heating the copper short-circuiting ring of the motor rotor by an annular inductor during brazing (Figure 3a), curve 2 - heating an I-beam by a circumferential inductor (Figure 3b), curve 3 — heating a pipe with a ring inductor (Figure 3c) and curve 4 — heating a pipe with a section inductor (Figure 3d).The hodographs are obtained by processing data that is recorded by the control system of the transistor generator TGI 60/66 [4].

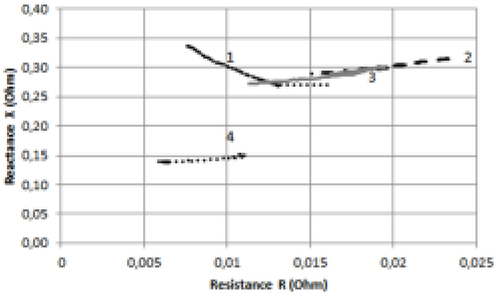

Fig. 2. Experimental hodographs of the inductor impedance vector

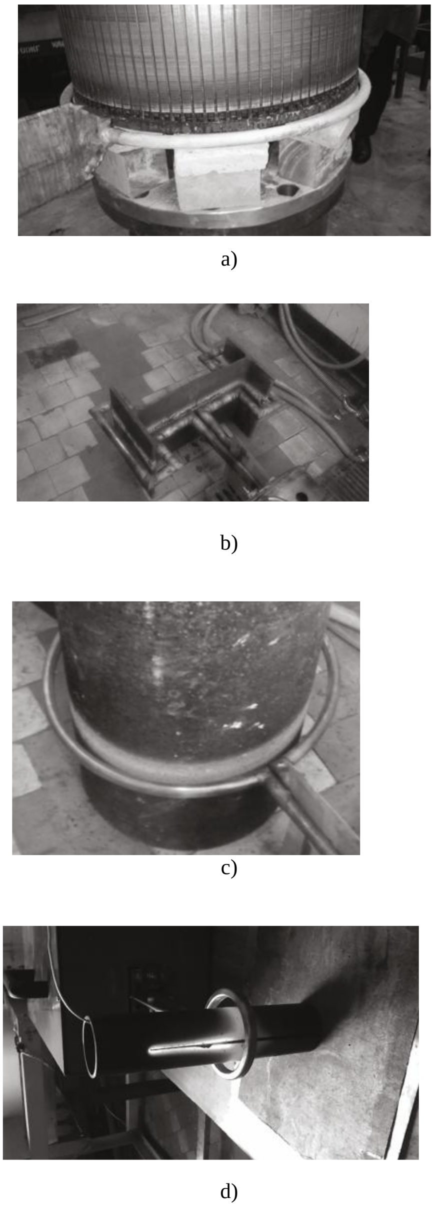

Fig. 3. Examples of induction systems

The feature of the hodograph 1 is the reduction of the inductance of the inductor during heating - due to the reduction of the gap between the inductor and the detail due to thermal expansion of the part. The remaining three hodographs have a characteristic for heating magnetic parts, characterized by an increase in both components of resistance as the temperature rises to the Curie point, followed by a sharp proportional decrease in both components after the component loses its magnetic properties. Considering that inductive resistance of the inductor consists not only of the inductive resistance of the part, which depends on the part temperature, but also from the leakage inductance, inducting wire and current wires, which do not depend on temperature (exception - hodograph 1), hodographs are located almost horizontally, i. e. inductive resistance of the inductor changes slightly in the process of heating (by 10%), while the active resistance of the inductor changes 3 ... 5 times.

The multiplicity of changes in the active resistance of an inductor with a magnetic part can be significantly greater with a low specific heating power, since the magnetic permeability of steel under the inductor increases with decreasing magnetic field strength (Figure 4), and, consequently, the range of variation of μ increases.

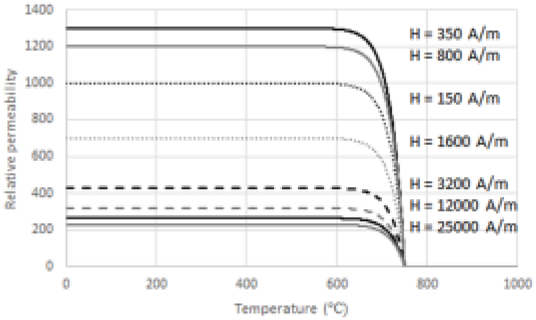

Fig. 4. The dependence of the magnetic permeability of steel on temperature at various values of the magnetic field strength

Figure 5 shows two hodographs of the multi-turn inductor when the steel magnetic detail is heated, calculated for different values of the inductor current. Each hodograph is built on three points corresponding to temperatures of 20, 600 and 800 under the assumption that the whole part is uniformly heated to these temperatures. The calculation did not take into account the parameters of the inductor current wires, i.e. only the inducting wire parameters were taken into account. It can be seen that at an inductor current of 0.25 kA, the active resistance of the inductor varies in the range (0.004 ... 0.084) Ohms, i.e. approximately 20 times, and with inductor current 16 kA in the range (0.004 ... 0.038) Ohms, i.e. 9.5 times. In all cases, the inductive resistance of the inductor varies slightly in the process of heating.

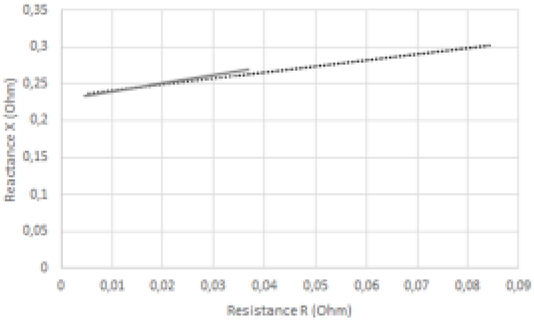

Fig. 5. Hodographs of resistance of a multi-turn inductor when heating a pipe made of magnetic steel at different currents of the inductor

Experimental evaluation of the range of changes in the parameters of the inductor in the heating process was carried out by heating a tube of magnetic steel 900 mm long with a diameter of 160 mm and a wall thickness of 5 mm with a multi-turn spiral inductor made from a copper tube, which consisted of 6 sections of 5 turns connected in parallel. The power source is a TGI 40/66 transistor generator with a bridge voltage inverter and frequency regulation [4]. The matching transformer has a K_{tr} = 10, and the load circuit is tuned to 66 kHz.

Figures 6 and 7 show how the basic parameters of the actual heating process change. A low power level of 10 ... 15 kW transmitted to a load from a generator with a rated power of 40 kW indicates that during the entire heating process, the inductor resistance was significantly different from the nominal load resistance of the TGI generator 40/66 R_{nom} = 5 Ohm. In the first stage of heating, when the temperature of the pipe is below the Curie point, the active resistance of the inductor is greater than the nominal load resistance of the generator 5 Ohm and the inverter operates at a resonant frequency of 66 kHz. After heating above the Curie point, the active resistance drops sharply and becomes less than 5 Ohms, and the generator switches to output current limiting mode at 100 A by increasing the output frequency from 66 to 77 kHz.

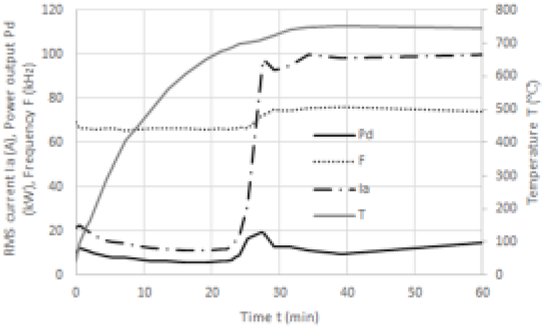

Fig. 6. Changing the main parameters of the process of induction heating of a magnetic tube

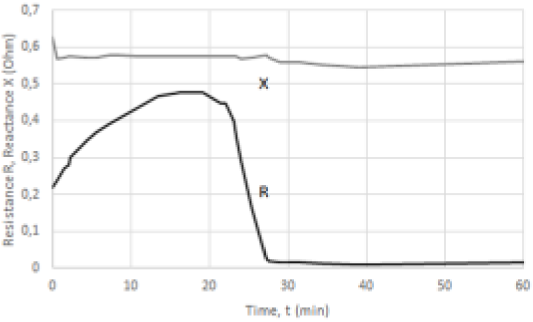

Fig. 7. The change in the active and inductive resistance of the inductor in the process of heating the magnetic tube

Figure 8 shows a hodograph of the vector of inductor parameters (R_i, L_i) in this process. The hodograph begins at the point R_i = 0.22 Ohm, X_i = 0.57 Ohm cold pipe), and ends at the point R_i = 0.01 Ohm, X_i = 0.56 Ohm (temperature above Curie). Before the Curie point, the resistance vector is maximum R_i = 0.48 Ohm, X_i = 0.58 Ohm. The active component of the inductor resistance changes during heating by 48 times, and the inductive component - only by 3.5%, i.e. practically unchanged.

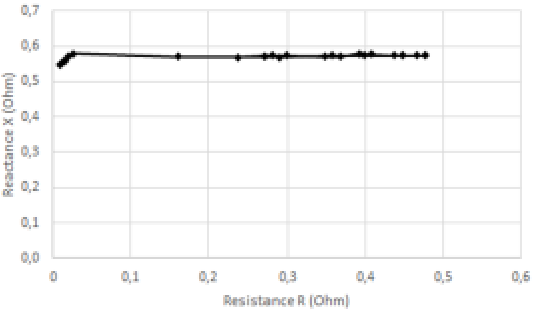

Fig. 8. Hodograph of the inductor resistance vector according to the experiment

III. FINDINGS

1. During induction heating of parts made of magnetic steel, the inductor resistance increases due to an increase in the resistivity of the steel being heated, and after heating above the Curie temperature, it decreases sharply.

2. The resistance of an inductor with a low specific heating power of magnetic steel can change by 20 ... 50 times, since the steel is not saturated.

3. Inductive resistance of the inductor varies slightly.

4. In order to maintain the required power level during the whole process at low values of the specific heating power of magnetic steel, a rapid switching of the transformation ratio of the matching transformer during the heating process is required.

5. A slight change in the inductance of the inductor, as a rule, does not cause problems in matching the inductor with the generator, since the frequency range of the generators exceeds the possible variation of the resonant frequency of the load circuit.

REFERENCES

[1] V.B.Demidovich,F.V. Chmilenko, Numerical simulation of induction heating devices,SPb: Publishing house SPbEU«LETI», 2010,p. 158
[2] A.E.Sluhotskiy, S.E. Riskin, Inductors for induction heating, Leningrad:Energia, 1974, p. 264
[3] S.V. Dzliev, Transistor Generators for Induction Heating,SPb: Publishing house ETU«LETI»», 2012, p.142
[4] Site "INTERM" LLCwww.interm.su