Evaluation of energy requirements of electric induction air heater for renewable energy sources

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Abstract

The materials of the work present the results of the analysis of the refined mathematical model of electromagnetic processes in the electric induction air heater based on the method of secondary sources, according to which the inductor is considered as the primary source, and the load, flanges and casing are replaced by secondary sources (eddy volumetric conduction currents and surface currents on the walls of the elements). The introduction of surface currents into consideration provides a jump in the tangential component of the magnetic induction vector at the boundary of magnetic materials. The inductor is considered as a solenoid. The load, flanges and casing are accepted as a combined integrated system load. The system of Fredholm integral equations is obtained on the basis of the laws of electrical engineering with taking into account all the interactions of the considered primary and secondary sources, the solution of which is carried out by the method of complete averaging of the kernel.
Methodological provisions have been developed in the form of a computer program for determining power and estimating energy requirements to meet the production needs of an electric induction air heater with any traditional or non-traditional power source.
By using the obtained computer program, the parameters of the induction air heater were ascertained and the manufacturing testing were carried out. The results of the testing good correlate with the calculated values.

Keywords

Electric induction air heater, Fredholm integral equations, complete averaging of the kernel

1. Introduction

Within the period 2015…2020, there was an increase in the cost of heat and electrical energy obtained from the non-renewable sources, as opposed to a decrease in the cost of heat and electrical energy obtained from solar radiation, wind, biofuels, utilization of industrial gases, waste and geothermal heat.

Today, direct electric heating is already competitive in the Ukrainian market, and the direct use of renewable energy installations eliminates the need for a set of works to modernize the electrical grids, aimed at increasing their passing ability. According to statistical researches, the distribution of energy consumption, for example, in the home is: 70 – 75% goes to rooms heating, 15% – to thermal processes, 5 – 10% of energy is consumed by household appliances, and up to 5% of energy is spent on lighting.

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The situation at this stage of the country's economic development requires attention to the wider use of systems that provide: the possibility of fragmentation of equipment by capacity, the simplicity of the supplying the primary energy to the place of consumption, flexibility in the technological regimes control, the reducing of the production areas and staff. Electrothermal systems greatly correspond to the mentioned requirements. The main their disadvantage is considered to be the double conversion of energy. But taking into account the low average annual efficiency of fuel boiler houses, losses during transportation, storage and losses in the heating networks, limited ability to regulate heat supply - the efficiency of fuel supplied from the boilers houses is not higher than or equal to the efficiency of the primary energy resources in the power supplying.

Analysis of the literature sources on the design of these electric heaters allowed to develop their classification (Figure 1).

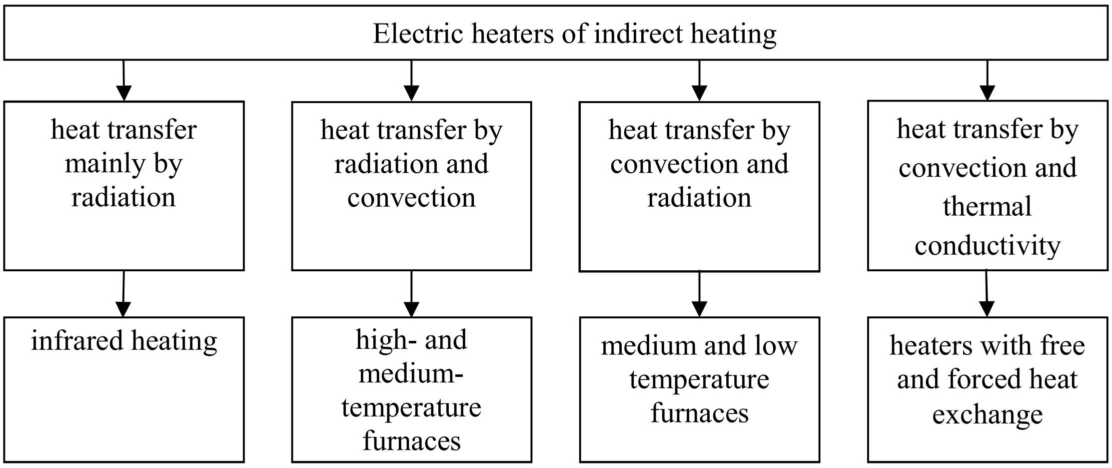

Figure 1: Electric heaters of indirect heating

Electro-induction air heaters are indirect heating devices.

The induction method of electric heating is widely used in various sectors of economic activity of countries [1 – 3]. A large number of researches are devoted to the theory and methods of electrodynamic calculations of induction installations, the results of which are most thoroughly described in [4 – 14]. The analysis of these works shows that there is a lack of attention paid to taking into account the magnetic properties of the load for weak quasi-stationary electromagnetic fields. With the aim to solve this problem the guidelines in the form of a computer program are given.

2. Materials and Methods

The aim of the work is to analyze the refined mathematical model of electromagnetic processes in electric induction air heaters based on the method of secondary sources, according to which the inductor is considered as the primary source, and loads, flanges and casing are replaced by secondary sources (eddy bulk conduction currents and surface currents on the walls of the elements), forming a closed electromagnetic circuit.

The effect of heat generation during the induction heating is determined by the volumetric density of the current and the amount of heat emitted in the material.

The electrinduction heater constructively consists of a steel pipe with the developed internal surface of heat exchange (load) over which the winding (inductor) is mounted. The load and the inductor are placed in a steel casing, and the casing is connected to the load by flanges which together forms a closed ferromagnetic circuit.

The distribution of conduction currents in all elements of the system as well as surface currents at the boundaries of magnetic elements is calculated in the mathematical model. The calculation was performed for supplying the system with a single-phase voltage of 220 V of the industrial frequency. This allows the use of quasi-stationary calculation methods. The magnetic fields generated in the system do not reach saturation, so at these field amplitudes, the nonlinearity of the magnetic permeability is not manifested and is not taken into account in the problem statement.

The calculation is based on the method of secondary sources [4], according to which the inductor is considered as the primary source, and the load, flanges and casing are replaced by secondary sources, namely eddy bulk conduction currents and surface currents on the walls of the elements. The introduction of surface currents into consideration provides a jump of the tangential component of the magnetic induction vector at the boundary of magnetic materials. The interaction of the primary and secondary sources according to this method is considered in vacuum. The inductor is considered as a solenoid. Load, flanges and casing are considered as a combined integrated load.

When solving the problem, the ring current tubes are considered: Q in the ring of consideration, including surface current strips; P in the integrated load elements (area A); T in the inductor (region B) and N on the surface of the integrated load. The cross-sectional areas of these tubes, respectively, dS_Q, dS_P, dS_T, and the width of the surface current strip dl_n. Taking into account all the interactions of the considered primary and secondary sources on the basis of the laws of electrical engineering, a system of Fredholm integral equations is obtained:

$$\begin{cases} 2\pi R_Q \rho_Q \dot{J}_Q + j\omega\left(\int\limits_{S_A} M_{QP}\dot{J}_P dS_P + \int\limits_{L_A} M_{QN}\dot{I}_n dl_n\right) = -j\omega \int\limits_{S_B} M_{QT}\dot{J}_T dS_T\,, Q \in A, B \\ 2\pi \frac{R_Q}{l_Q}\dot{Z}_{0Q}\left(\int\limits_{S_A} N_{QP}\dot{J}_P dS_P + \int\limits_{L_A} N_{QN}\dot{I}_n dl_n\right) - j\omega\left(\int\limits_{S_A} M_{QP}\dot{J}_P dS_P + \int\limits_{L_A} M_{QN}\dot{I}_n dl_n\right) = 0, Q \in N, \end{cases} \tag{1}$$

where R_Q – the radius of the ring Q; ρ_0– the electrical resistivity of the material of the ring Q; $\dot{J}_p$,$\dot{J}_T$– complex values of current density of rings P of integrated load and T of inductor; S_A, S_B, – the cross-sectional areas of the integrated load and the inductor, respectively; M_{QP}, M_{QN}, M_{QT} – mutual inductances of the ring Q with the corresponding rings; L_A – the contour of the integrated load surface; $\dot{I}_n$– the complex value of the surface current of the n-th strip; l_n – the width of the n-th surface current strip; N_{QP} – coefficient of magnetomotive force.

The solution of the system of integral equations (1) is carried out by the method of complete averaging of the kernel, due to which the system of integral equations is reduced to a system of algebraic equations. The technical characteristics of modern computers have allowed as workpieces of the load, flanges, casing to consider the rings of rectangular cross-section with a small cross-sectional area, namely to make a large degree of detail of the calculation.

3. Results and Discussions

Calculation program m-files have been created in the MatLab environment for the numerically solve the system of equations and investigate the parameters of the device. Among them are subroutines-functions for calculating the self-inductances and mutual inductances of current rings and magnetomotive force coefficients N_{QP}. The calculation of self- and mutual inductances is performed by numerical-analytical method on the basis of materials [15], coefficients of magnetomotive force according to the method [5]. The computational speed is facilitated by the presence of elliptical functions built into the MatLab system, which eliminates the need for multiple numerical double integration to calculate these values. MatLab's built-in matrix inversion operation was used to solve the system of equations after filling in the coefficient matrix and the constants matrix.

The block diagram of the computer program is shown in Figure 2.

In block 1, electrical and magnetic constants, resistivity of the material of the inductor wire (copper), resistivity and magnetic permeability of the material of the load, casing and flanges (steel), parameters of the electrical network, frequency 50 Hz, voltage 220 V are inputted.

In block 2, the geometric dimensions of the load, casing, flanges, insulation thickness between the load and the inductor, the cross-sectional area of the inductor wire, the number of turns and the filling factor of the inductor winding are inputted.

In block 3, the parameters of detail calculations, the number of workpieces of each part by radius and height are inputted.

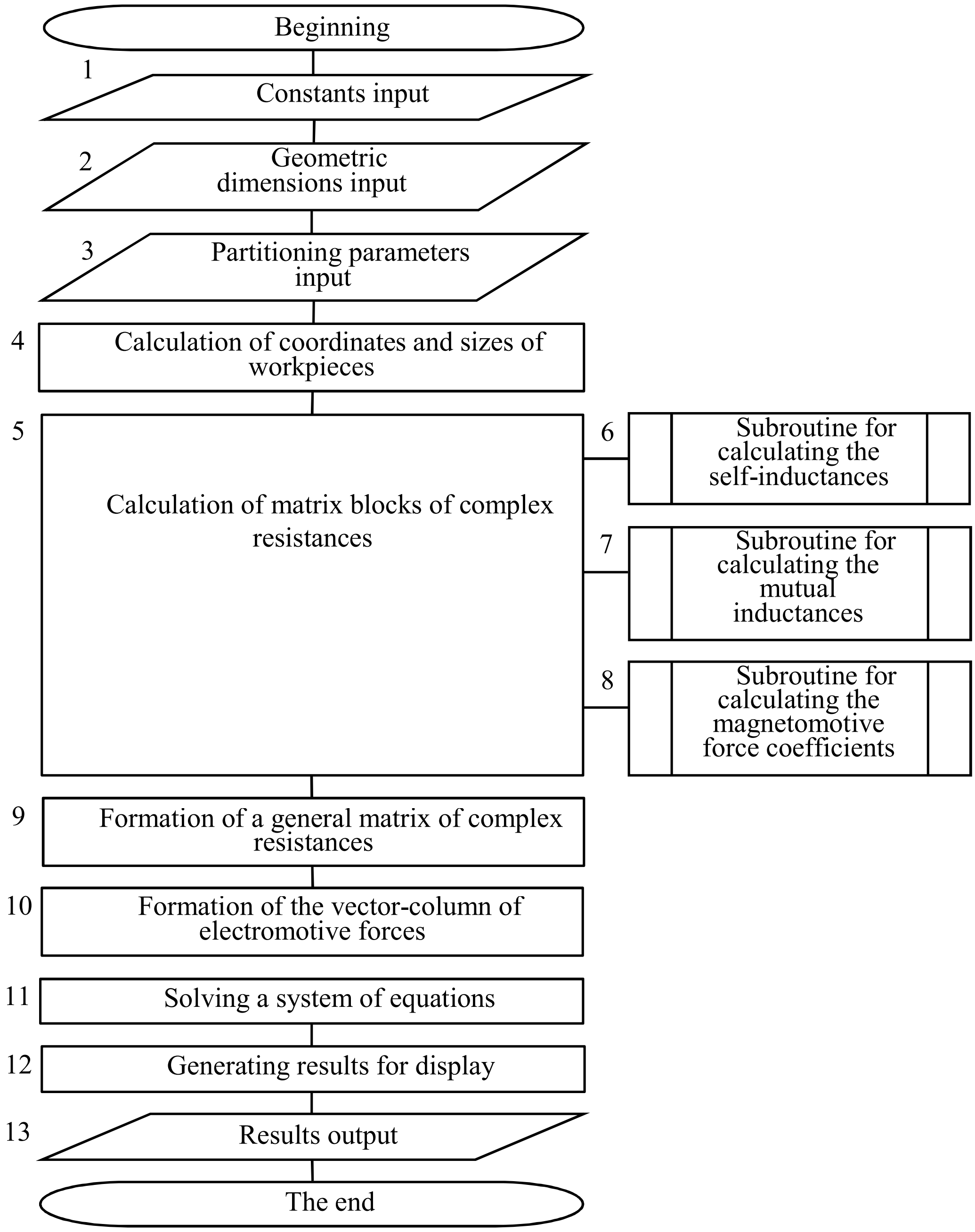

Figure 2: block diagram of the computer program

In block 4, the coordinates of the elements of the partition of all parts of the system, radial and height, as well as the coordinates of the surface currents are calculated. At the same time, the cross-sectional areas of the rings (workpieces) and the width of the strips (surface current elements) are calculated.

In block 5, the blocks that make up the matrix of complex resistances, which is a coefficients matrix of systems of linear algebraic equations, are calculated. The blocks of the matrix of complex resistances, which make up the general coefficients matrix of system, are the matrices of self- and mutual resistances between workpieces of the following elements: inductor, integrated load, surface currents. Accordingly, the number of such blocks-matrices is equal to 9. When calculating these blocks-matrices, subroutines-functions are used to calculate the self-inductances, mutual inductances and coefficients of magnetomotive force (blocks 6, 7, 8, respectively).

In block 9 of the blocks-matrices, calculated in block 5 of the block diagram, a general matrix of coefficients of the system of equations is formed. In block 10, the constant matrix of the system of equations is formed. In this problem, it is a vector-column of electromotive forces in each workpiece. For the inductor this value is equal to the mains voltage, for all other circuits it is zero.

In block 11, the system of algebraic equations is solved. The solution is calculated as the multiplication of the matrix inverse to the coefficient matrix, and constant matrix. The solution of the system of equations is the set of complex values of all currents: the input current of the inductor, the eddy currents of the workpieces of the integrated load and surface currents. This set of currents is the primary output parameters of the system, based on which the calculation of other output parameters, such as modulus of input current and power factor is performed.

In block 12, the results are formed for analysis and displaying. Integrated load currents are distributed by individual parts and radial layers. The integrated parameters of the system, such as input current and power factor, are calculated.

In block 13, two-dimensional and three-dimensional graphs of current density distribution and other results are formed.

According to the results of calculations, an induction air heater was manufactured and tested. The sequence of determining the parameters of the heater:

1. the required power and heat transfer surface are accepted;
2. the unit surface power is determined;
3. the number of ampere turns of the inductor is determined;
4. the inductor current is determined;
5. the number of turns of the inductor is determined.

According to this method, an example of determining the parameters of the electric induction air heater is performed. Setting a power consumption of 2 kW, for a load of 0.9 m height with an inner diameter of 75 mm, it was determined that the asked power is provided by a single-layer winding of 716 turns.

The manufacturing testing of a single-phase electric induction air heater was carried out in a production room with a volume of 66 m^3. The initial temperature in the room at the level of the workplace (1.2 m) was 12 ºC. It was necessary to establish for what time the normative minimum values of temperature 15 ºC will be reached.

Figure 3 shows the curve of temperature change in the production room during the testing. The task was achieved within 3 hours. It should be noted that the ratio of energy consumption time from the grid to the pause time (heat transfer due to accumulation) was 1: 4, ie consumption time was 45 minutes, and the amount of energy - 1.5 kWh. The comparison with the estimated value of the amount of energy for heat supply, taking into account losses through the fence gives an error of 5%. The average value of the power factor during the production testing was 0.93.

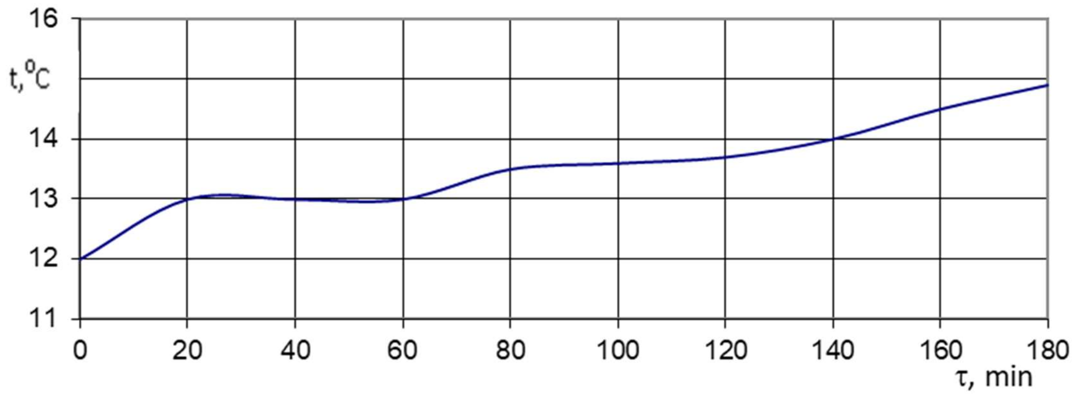

Figure 3: The changing of the temperature in the working room during testing.

4. Conclusions

The analysis of the refined mathematical model of electromagnetic processes in the electroinductive air heater based on the method of secondary sources, according to which the inductor is considered as a solenoid, and the flanges and casing are accepted as a combined integrated system load. Based on the laws of electrical engineering, a system of Fredholm integral equations is obtained, which was solved by the method of complete averaging of the kernel.

The obtained methodical provisions in the form of a computer program for numerical solution of the system of equations and research of device parameters in the MatLab environment. Among them are subroutines-functions for calculating the self- and mutual inductances of current rings and magnetostrictive coefficients.

According to the results of calculations an induction air heater with a capacity of 2 kW was manufactured and tested, which provided the production task, while the average value of the power factor was 0.93.

5. References

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