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CALCULATION OF THE EQUIVALENT ELECTRICAL PARAMETERS OF THE INDUCTOR OF INDUCTION CHANNEL FURNACE WITH DEFECTS IN ITS LINING

Aim. The aim of the paper is to determine a quantitative relationship between measured impedance of the inductor and the electrical characteristics of the separated melt circuit parts for the determination of the place of a liquid metal leakage and for the improvement in such way the diagnostic system of lining state of induction channel furnaces. Technique. The study was performed on the basis of the concepts of theoretical electrical engineering, mathematical physics, and mathematical modeling. Results. Using two equivalent electrical circuits of the inductor the analytical expressions and graphical dependencies, which determine a quantitative relationship between the parameters of the separated parts of a liquid-metal circuit and the impedance of the whole inductor measured in practice, for the presence of different lining defects, were found. The method for calculating the increments of equivalent electrical parameters of the inductor as a function of increments of the parameters of the secondary liquid-metal circuit was proposed. Scientific novelty. It is proved that for small changes (less than 10 %) of the parameters of the liquid-metal circuit, it is expedient to use a linear relationship between its increments and to create the sensitivity matrix, which clearly shows the presence of a strong or weak interrelation between the disturbed values of the parameters of the secondary circuit and the inductor. Practical significance. The use of this technique allows to develop the database for various types of lining defects for a given furnace and on its basis to predict the places of a melt leakage and the state of furnace lining owing to periodical measurements of the inductor parameters. References 10, figures 3.

Key words: **equivalent electric parameters, mathematical modeling, induction channel furnace, defects of lining, diagnostics of the lining state.**

Цель. Целью статьи является установление количественной связи между измеряемым импедансом индуктора и электрическими характеристиками отдельных участков контура расплава для установления места протекания жидкого металла и усовершенствования таким образом системы диагностики состояния футеровки индукционных канальных печей. Методика. Для проведения исследований использовались положения теоретической электротехники, математической физики, математического моделирования. Результаты. С использованием двух электрических схем замещения индуктора получены аналитические выражения и графические зависимости, устанавливающие количественную связь между параметрами отдельных участков жидкометаллического контура и измеряемым на практике импедансом всего индуктора при наличии различных дефектов в его футеровке. Предложена методика расчета приращений эквивалентных электрических параметров индуктора в зависимости от приращений параметров вторичного жидкометаллического контура. Научная новизна. Доказано, что при малых изменениях (менее 10%) параметров жидкометаллического контура целесообразно использовать линейную связь между их приращениями с построением матрицы чувствительности, которая наглядно показывает наличие сильной или слабой связи между возмущенными значениями параметров вторичного контура и индуктора. Практическое значение. Использование данной методики позволяет разработать базу данных для различных типов дефектов футеровки для индукционной канальной печи и на ее основе, путем периодического измерения параметров индуктора, прогнозировать места протеканий расплава и состояние футеровки. Библ. 10, рис. 3.

Ключевые слова: **эквивалентные электрические параметры, математическое моделирование, индукционная канальная печь, дефекты футеровки, диагностика состояния футеровки.**

Introduction. Today consumers of metallurgical products make high demands on the quality of copper rolled wire (homogeneity, chemical purity, etc.). The copper rolled wire manufactured in induction channel furnaces generally satisfies the highest requirements [1]. On the strength of this circumstance, it is induction installations of this type that are used in the cable industry in the manufacture of copper rolled wire for the production of power cable cores [2].

The peculiarity of the induction furnaces, in particular channel type is the lining destruction under various factors: 1) the high temperature of the molten metal; 2) intensive hydrodynamic molten metal flow destroying the internal walls of the lining, forming caverns and leading to a decrease in thickness of the walls during prolonged operation, and 3) the presence of an electromagnetic field that causes vibrational phenomena in the liquid metal and in the outer metal casing.

Modern researches are aimed at increasing the efficiency and operating life of induction furnaces. In particular, they are aimed at analyzing the distribution of temperature fields inside the refractory lining under different operating conditions [4, 5], determination of mixing features of the metal melt [6], improving the diagnostic systems and continuous monitoring of the furnace lining state in industrial use [8, 9] and improvement of structural elements of furnaces and inductors [3, 7].

In particular, the improvement of the systems for diagnosing the state of furnace lining is an important scientific problem, since it allows to more accurately predict the residual life of the equipment, adjust its operating modes to extend the service life and prepare in advance for the necessary replacement of the lining, as it is related with complete stoppage of the furnace and draining the metal melt.

In order to diagnose the state of the lining of a channel induction furnace, the following three methods can potentially be used in practice:

1) Periodic measurement of the complex equivalent resistance (pure resistance and image impedance) of the inductor, the value of which depends on the state of the lining (the presence of pits and caverns, thickening of the channel and narrowing of the channel filled with liquid metal, etc.) [10].

2) Regular measurement of the temperature distribution over the surface of the furnace outer casing by means of pyrometer, for example, or an infrared imager. This distribution allows to identify the «hot spots» on this surface, which are due to the appearance of caverns or pits filled with liquid metal in the lining. [5, 9].

3) Evaluation of the dielectric properties of the lining by measuring the capacitance between the outer furnace casing and the liquid metal, which are separated by a dielectric lining, as well as measuring the dielectric loss tangent of this capacity, generally at a different frequency of the external supplementary source. An analysis of the dependences obtained in this way allows to conclude that there are defects in the furnace lining [1].

At present, the systems for diagnosing the state of induction channel furnaces, offered by their manufacturers, generally based on a measuring the complex impedance (impedance) of the inductor melt channel and measuring the temperature rise of water as it passes through the cooling system pipes [10].

The disadvantages of such systems are the impossibility of determining the location and dimensions of the areas of liquid metal flowing into the defects of the lining. However, this is important, because the melt channel has a branched shape (it consists of three branches and forms two contours as shown in Fig. 2,*a*), and the melt leakage can be directed both to the outer walls of the body and to the inner ones in the direction of the magnetic circuit with inductance coils.

Improvement of this diagnostic method can be the ability to determine the problem area of the melt channel according to the inductance impedance measured in practice. If we determine a quantitative relationship between the impedance of the inductor and the electrical characteristics of the separated parts of the melt contour, then they in turn can be related to the geometric characteristics of these parts (an increase or decrease in the local section – the occurrence of leakage or overgrowing of the channel). Obtaining such important information will allow us to more accurately predict the residual life of the induction channel furnace.

Therefore, the **aim of the paper** is to determine a quantitative relationship between the measured impedance of the inductor and the electrical characteristics of the separated parts of the melt contour for finding the leakage location of the liquid metal and thus improving the diagnostics system of the lining state of induction channel furnaces.

As a typical example of an induction channel furnace, we considered the UPCAST US20X-10 furnace in the line for the continuous casting of oxygen-free copper rod [10] with a power of 500 kW installed at PJSC «Yuzhkabel Works» (Kharkiv).

The general view of the investigated furnace is shown in Fig. 1.

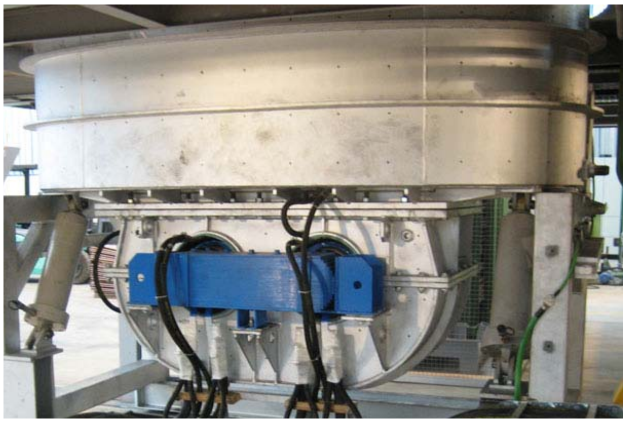


Fig. 1. Induction channel furnace for the production of copper rolled wire

Structurally, the furnace consists of a lined tank, which contains the whole mass of the metal being melted, and the inductor located under the tank [1, 5, 10]. The tank is connected with the melting channel filled with melt too. The copper template is lined with a refractory mixture with a working temperature of 1800 °C. After the template melting and sintering of the lining, a melting channel, which together with the adjacent part of the tank forms a closed conductive ring, is formed.

The principle of induction furnace operation is similar to the principle of the action of a single-phase power transformer in the short-circuit mode [1, 2]. However, the electric parameters of the furnace and the transformer are significantly different due to the difference in its design.

The inductor, whose turns are wound up on two rods of a closed magnetic circuit, is the primary winding of the transformer, and the secondary winding is the molten metal. The current flowing in the secondary circuit causes heating of the melt. At that almost all energy is released in the channel having a small cross section (90-95 % of the electric energy supplying the furnace is released in the channel).

The metal is heated owing to heat exchange and mass transfer between the channel and the tank. The movement of the metal is mainly determined by the action of the electrodynamic forces that arise in the channel and to a lesser degree by convection due to the overheating of the metal in the channel in comparison with tank [7, 8].

Electrical equivalent circuits of the induction channel furnace and calculation of their equivalent parameters. As a starting point, the paper considers two equivalent electric circuits (simplified equivalent electric circuits and refined one) of the inductor as a transformer with a short-circuited secondary winding as well as we use the assumption based on the physical nature that when defects arise in the lining, the electrical parameters of the secondary liquid metal circuit of the induction furnace are changed.

The investigated induction furnace is schematically shown in Fig. 2,*a*. There are both main elements and the current contours in the molten metal indicated with dashed line in the figure.

In the secondary circuit formed by the melt, we can distinguish three branches (2-1-3, 2-3, 2-4-3), which, due to various geometric characteristics, can be conveniently divided into five sections (2-1, 1-3, 2-3, 2-4, 4-3), indicated by Roman numerals (I, II, III, IV, V) in Fig. 2,*a*.

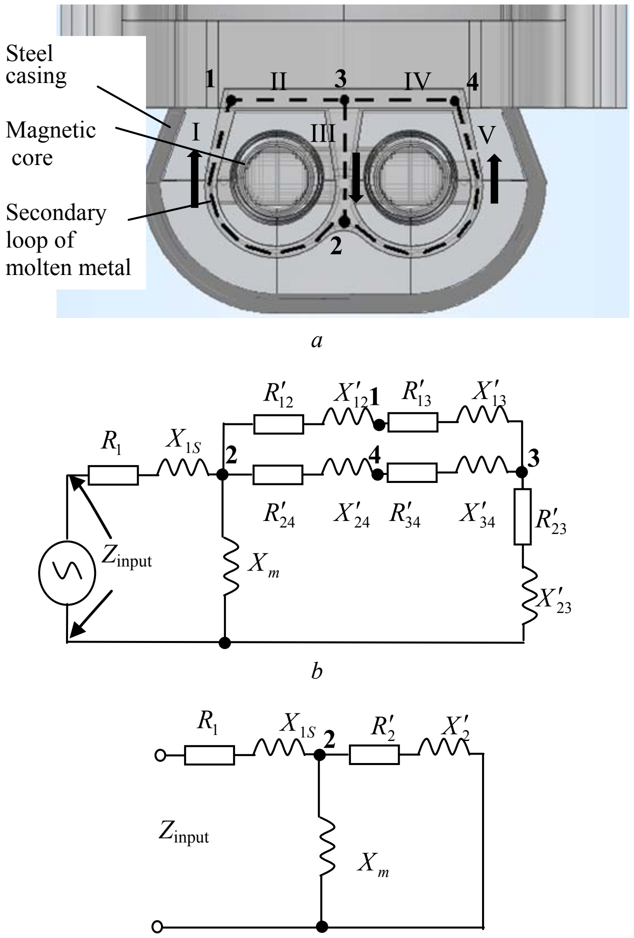


Fig. 2. *a* – configuration of induction channel furnace and *b* – its equivalent circuits with subdivision of the secondary circuit into separate branches; *c* – simplified equivalent circuit of the furnace when branches are replaced by a single turn with equivalent parameters

Fig. 2,*b* shows the electrical equivalent circuit of the furnace as an electrical transformer whose secondary winding has two short-circuited turns with a common branch III located between nodes 2 and 3 (see Fig. 2,*a*) through which the currents of both circuits flow.

The circuit under consideration includes the parameters of the inductor – the pure resistance and leakage inductance R_1, X_{1s}, the parameter of the magnetization circuit – X_m (which is caused by the magnetic flux in the magnetic core of inductor) and the parameters of the secondary liquid-metal circuit reduced to the winding of the inductor as the primary winding of the transformer. In this case, each parts of branch of the secondary circuit in Fig. 2,*a* corresponds its own branch in the electrical equivalent circuit in Fig. 2,*b*.

A simplified equivalent circuit for the furnace is shown in Fig. 2,*c*. In this equivalent circuit the secondary circuit is presented in the form of a single turn with equivalent parameters R_2', X_2' reduced to the winding of the inductor. The complex impedance of the simplified equivalent circuit in Fig. 2,*c*, which is measured in practice at the inductor terminals, is determined by the following equation:

$$Z_{input} = Z_1 + \frac{jX_m(R_2' + jX_2')}{R_2' + j(X_m + X_2')} .$$

Hence the functional dependencies of the inductor resistances (pure resistance R_{input} and image impedance X_{input}) on the parameters of the secondary liquid-metal circuit R_2' and X_2' have the following form:

$$R_{input} = f_R(R_2', X_2') = \mathrm{Re}(Z_{input}) = \\ = R_1 + \frac{X_m R_2'(X_2' + X_m) - X_m X_2' R_2'}{(R_2')^2 + (X_m + X_2')^2}; \quad (1)$$

$$X_{input} = f_X(R_2', X_2') = \mathrm{Im}(Z_{input}) = \\ = X_{1S} + \frac{X_m (R_2')^2 + X_m X_2'(X_2' + X_m)}{(R_2')^2 + (X_m + X_2')^2}. \quad (2)$$

The dependences calculated on the basis of expressions (1) and (2) are shown in Fig. 3.

Note that here, for greater generality, all values are given in relative units and the graphs are valid regardless of the specific numerical values of the parameters of the equivalent circuit.

As an example, let us consider the following values of the parameters of the equivalent circuit, calculated on the basis of the geometric and electrical characteristics of the inductor coils, magnetic circuit and melt loop, as well as those indicated in the technical documentation for the furnace under study [10] and measured experimentally at PJSC «Yuzhkabel Works» [9]:

$$R_1 = 0.12\ \text{m}\Omega,\ \ X_{1s} = 24\ \text{m}\Omega,\ \ X_m = 0.2\ \Omega, \quad (3)$$

$$R_2'\big|_0 = 1.2\ \text{m}\Omega,\ \ X_2'\big|_0 = 24\ \text{m}\Omega,$$

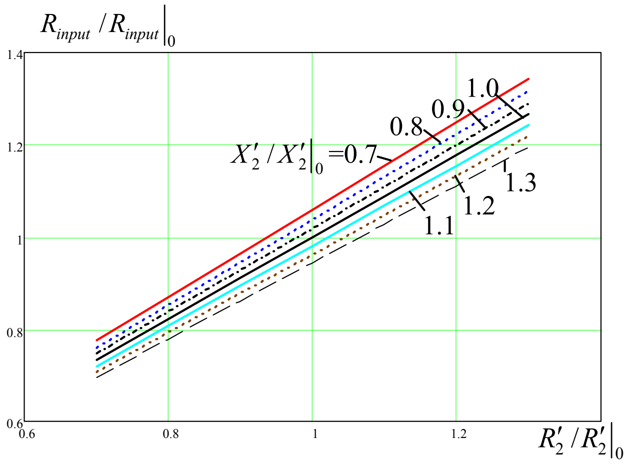
$$R_{input}\big|_0 = 1.08\ \text{m}\Omega,\ \ X_{input}\big|_0 = 0.05\ \Omega. \quad (4)$$

Here, the basic values correspond to a furnace with a new lining without defects, as shown by the dot in Fig. 3 with values $R_2'/R_2'\big|_0 = 1$ and $X_2'/X_2'\big|_0 = 1$.

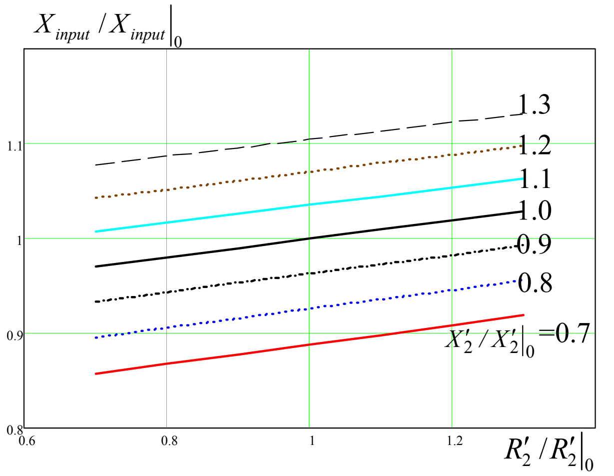
From the results obtained, we can conclude the following:

1) If in the furnace with initially defect-free lining parameters – $R_2'/R_2'\big|_0 = 1$ and $X_2'/X_2'\big|_0 = 1$ only the value R_2' will be increase (due to the occurrence of any defect in the lining), that this leads to an increase in the measured values both R_{input} and X_{input}.

Increasing only the value X_2' will lead, that value X_{input} will increase, but value R_{input} will decrease.



a



b

Fig. 3. Dependences of the relative value of the complex impedance of the inductor on relative values of pure resistance of secondary circuit and at various values of inductive impedance of the circuit: *a* – pure resistance; *b* –image impedance

2) In the general case, with simultaneous changes in both R_2' and X_2', the quantitative changes in the pure resistance and image impedance of the inductor can be determined from the graphs in Fig. 3.

3) Using the data in Fig. 3 or directly functional dependences (1) and (2) for relatively small changes in the values of R_2' and X_2' one can determine a linear relationship between their increments in the neighborhood of a point with a defect-free lining in the form of the following vector-matrix equation:

$$\begin{bmatrix} \dfrac{\Delta R_{input}}{R_{input}|_0} \\ \dfrac{\Delta X_{input}}{X_{input}|_0} \end{bmatrix} = \begin{bmatrix} 0.9 & -0.075 \\ 0.1 & 0.35 \end{bmatrix} \begin{bmatrix} \dfrac{\Delta R_2'}{R_2'|_0} \\ \dfrac{\Delta X_2'}{X_2'|_0} \end{bmatrix}. \quad (5)$$

Here, the resulting matrix, which can be called the sensitivity matrix $\boldsymbol{A} = \begin{bmatrix} 0.9 & -0.075 \\ 0.1 & 0.35 \end{bmatrix}$, characterizes the sensitivity of the change in the equivalent inductor resistances with respect to the change in the resistances of the secondary circuit in accordance with the simplified equivalent circuit in Fig. 2,*c*.

Note, that elements of matrix $\boldsymbol{A}$ are dimensionless and show the degree of influence of separated parameters of the secondary circuit (melt) on the input resistances of the inductor. Although, in this example the matrix $\boldsymbol{A}$ was calculated for the particular inductor, but within the framework of the proposed approach, it can be easily recalculated for an another one.

The relatively large values of the diagonal elements of the matrix $\boldsymbol{A}$ (0.9 and 0.35) indicate a strong connection between the pure resistances of the inductor and the secondary circuit and the less strong connection between their image impedance, and the small values the other matrix elements indicate relatively weak cross-connections. Moreover, the negative value of the coefficient, that equals to –0.075, attests a decrease in the value R_{input} with growth of R_2'.

4) For practice, it would be interesting to determine a feedback between the values increments. For this purpose, calculating the inverse sensitivity matrix $\boldsymbol{A}^{-1}$ from equation (5) we get:

$$\begin{bmatrix} \dfrac{\Delta R_2'}{R_2'|_0} \\ \dfrac{\Delta X_2'}{X_2'|_0} \end{bmatrix} = \boldsymbol{A}^{-1} \begin{bmatrix} \dfrac{\Delta R_{input}}{R_{input}|_0} \\ \dfrac{\Delta X_{input}}{X_{input}|_0} \end{bmatrix} = \begin{bmatrix} 1.09 & 0.23 \\ -0.31 & 2.8 \end{bmatrix} \begin{bmatrix} \dfrac{\Delta R_{input}}{R_{input}|_0} \\ \dfrac{\Delta X_{input}}{X_{input}|_0} \end{bmatrix}. \quad (6)$$

This expression makes it possible to calculate and analyze the deviations of the parameters of the secondary liquid-metal circuit based on the measured deviations of the inductor parameters and then to estimate the probability of the appearance of any defect in the lining.

The obtained results are applied to the simplified equivalent circuit in Fig. 2,*c*. However, in practice, when analyzing the effect of lining defects on the parameters of the secondary circuit, it is expedient to use the refined equivalent circuit in Fig. 2,*b*. It allows to evaluate the effect of the defect directly on the parameters of each part of branch separately.

For the subsequent conversion to a simplified equivalent circuit and use of the results in Fig. 3, the following expressions can be used to determination the relationship between the parameters of the two equivalent circuits under consideration:

$$R_2' = \mathrm{Re}((Z_{12}' + Z_{13}') \| (Z_{24}' + Z_{34}') + Z_{23}'), \quad (7)$$

$$X_2' = \mathrm{Im}((Z_{12}' + Z_{13}') \| (Z_{24}' + Z_{34}') + Z_{23}'). \quad (8)$$

Here the parallel connection operator of two arbitrary complex impedances Z_1 and Z_2 is defined as:

$$Z_1 \| Z_2 = Z_1 Z_2 / (Z_1 + Z_2).$$

With the help of expressions (7) and (8) and analyzing the processes and functional dependencies between all parameters of the refined equivalent circuit in Fig. 2,*b*, one can pass to the simplified circuit in Fig. 2,*c* and then use the graphical dependencies in Fig. 3 or directly expressions (1) and (2), and in the case of small increments, expressions (5) and (6).

In practice, the inverse problem is usually solved: from the measured input impedance of the inductor the resistances Z'_{12}, Z'_{13}, Z'_{24}, Z'_{34}, and Z'_{23} are determined. For this, it is proposed to create a certain database of resistance values for various liner defects. For its filling, the values of Z'_{12}, Z'_{13}, Z'_{24}, Z'_{34}, and Z'_{23} are defined by a search of possible variants, where the upper and lower limits are determined from the electrical and geometrical characteristics of the parts of the melt channel, and the degree of sampling (step of changing in values) – from practical industrial necessity.

For each combination of resistances of channel parts, the values of R'_2 and X'_2 are determined. And as a consequence, by measuring them in practice, it is possible to set a suitable combination of channel resistance areas from the database.

The technique for calculating the influence of the parameters of the liquid-metal circuit on the values of the input impedances of the inductor. Let us consider the following example showing how the previously obtained results can be used to estimate the relationship between the parameters of a particular induction furnace.

We shall use the furnace with a defect-free lining with data according to (3) and base values according to (4), which correspond to the simplified equivalent circuit in Fig. 2,*c*. In the case of a defect-free lining, the secondary circuit parameters will be equal:

$$R_2' = R_2'\big|_0 = 1{,}2\ \text{m}\Omega, \quad X_2' = X_2'\big|_0 = 24\ \text{m}\Omega. \qquad (9)$$

Turning to the refined equivalent circuit in Fig. 2,*b*, we consider that for the case of a defect-free lining the electrical parameters of the parts of branches (based on their configuration) are equal:

$$Z_{12}' = Z_{24}' = 0.8\text{+j}16\ \text{m}\Omega, \quad Z_{13}' = Z_{34}' = 0.8\text{+j}16\ \text{m}\Omega,$$
$$Z_{23}' = 0.4\text{+j}8\ \text{m}\Omega. \qquad (10)$$

As an example, let us consider such «defect» when the lining thickness h in the branch V (in Fig. 2,*a*) becomes thinner by 10 %. Because of this fact, the complex impedance of the branch Z_{24}' will decrease by approximately 10 % of the value in expression (10) and amount to $Z_{24}' = 0.72 + \text{j}14.4\ \text{m}\Omega$.

In order to move to the simplified circuit from refined equivalent circuit, it is necessary to substitute new value Z_{24}' and all other values according to (10) in expressions (7) and (8). Then, performing transformations, we obtain new perturbed values of the parameters of the secondary circuit for the circuit in Fig. 2,*c*: $R_2' = 1.18\ \text{m}\Omega$, $X_2' = 23.6\ \text{m}\Omega$.

Comparing with the values for the defect-free lining (9), we can see how change in the value Z_{24}' by 10 % varies R_2' and X_2'. The new relative values R_2' and X_2' for the basis quantities according to (9) will be equal to

$$R_2' / R_2'\big|_0 = 1.18/1.2\text{=}0.98, \quad X_2' / X_2'\big|_0 = 23.6/24\text{=}0.98.$$

Further, using expression (5) for the case of small perturbations of the parameters values, let us finally determine how the inductor parameters change:

$$\begin{bmatrix} \dfrac{\Delta R_{input}}{R_{input}\big|_0} \\ \dfrac{\Delta X_{input}}{X_{input}\big|_0} \end{bmatrix} = \begin{bmatrix} 0.9 & -0.075 \\ 0.1 & 0.35 \end{bmatrix} \begin{bmatrix} 0.02 \\ 0.02 \end{bmatrix} = \begin{bmatrix} 0.017 \\ 0.009 \end{bmatrix}.$$

Thus, this example shows that decrease in the parameters of one branch in the circuit in Fig. 2,*b* by 2 % leads to decrease in the parameters of the entire secondary circuit in Fig. 2,*c* and this result in decrease in the input parameters of the inductor by 1.7 % for the pure resistance and by 0.9 % for the image impedance.

The sequence of operations for calculating the change in the values of the inductor parameters when the values of the equivalent circuit parameters are changed can be represented as a calculation technique consisting of the sequential execution of the following steps.

Step 1. For the investigated furnace, two equivalent circuits are selected – refined one and simplified one as in Fig. 2,*b* and *c*, respectively. Then, for simplified circuit, the graphics dependences are plotted according to Fig. 3,*a*, and for the case of small increments, the dependence (5) is constructed with determination of the sensitivity matrix $\boldsymbol{A}$.

Step 2. To assess the effect of any lining defects we determine the influence degree of this defect on the particular branch parameters of the refined equivalent circuit in Fig. 2,*b*. It can be done, for example, using the basic expressions for calculating the transformer parameters or using the program packages to solve the corresponding field task.

Step 3. Using the expressions (7) and (8) the transition to the perturbed values of the parameters of the simplified circuit in Fig. 2,*c* is made, and then, according to the graphics dependences as in Fig. 3 for the investigated furnace or using the expression (5) in the case of small increments, the new values of the inductor parameters are determined.

Step 4. Based on the results of such calculations, a database is created for the different types of lining defects for a given furnace. The use of this database makes it possible to predict the state of furnace lining by periodic measurements of the inductor parameters.

Conclusions.

1. The paper considers one of the methods for diagnosing the state of the lining of an induction channel furnace. The method is based on comparison of the measured values of the complex impedances of the furnace inductor with a defect-free lining and lining with defects. In this case, only defects leading to a change in the electrical parameters of the secondary liquid-metal circuit are taken into account.
2. Using two electric equivalent circuits of the inductor, the analytic expressions and graphics dependencies determining a quantitative relationship between the parameters of the liquid-metal circuit and the inductor parameters measured in practice are obtained. In the case of small changes in these parameters (less than 10 %), a linear relationship between their increments is

used with the determination of a sensitivity matrix $\boldsymbol{A}$, which clearly demonstrates the presence of strong or weak coupling between the perturbed values of the secondary circuit parameters and the inductor ones.

3. The technique for calculating the increments of equivalent inductor parameters as a function of increments of the parameters of the secondary liquid-metal circuit is proposed. The use of this technique allows to develop the database for various types of lining defects for a given furnace and on its basis predict the state of its lining by means of periodic measurements of the inductor parameters.

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