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CALCULATION OF VOLTAGE TRANSFORMER PARAMETERS FOR MATHEMATICAL MODEL OF INDUCTION CHANNEL FURNACE

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Purpose. Nowadays, the upward continuous casting method is widely used copper wires and electric cables production. The electrothermal model of an induction channel furnace intended to solve the technological process modernizing issues, accounting specific production conditions, choosing the necessary electrical and energy characteristics of electrical equipment, as well as optimal operating modes. The working principle of the electrical unit of an induction furnace is similar to a single-phase power transformer operating in a short-circuited mode. Determining the parameters of this transformer is an important task requiring a specific calculation technique. Methodology. Fundamentals of electric circuit theory were applied. For further calculations, the equivalent circuit of transformer with secondary parameters transferred to the primary side was used. Results. Active resistance value of the primary winding at an operating temperature of 115 degrees Celsius is 0.005683 Ohms; inductive reactance of the primary winding is 0.008747 Ohms; active resistance of the secondary winding transferred to the primary winding at a temperature of 1080 degrees Celsius is 0.036 Ohms. Originality. The actual dimensions of the inductor for the induction channel furnace were used for the calculation. The inductor is the primary winding of the transformer, and the molten metal that fills the channel performs the role of the secondary winding. Since the secondary winding of the studied transformer, in fact, is a single short-circuited turn, then its inductance and inductive reactance can be neglected without losing accuracy. Practical value. Detailed calculation procedure for determining the single-phase furnace transformer parameters was proposed. Conclusions. This article explores the methodology for calculating the electrical parameters of the equivalent circuit of a specialized voltage transformer. These characteristics used for modeling the electrothermal processes in an induction channel furnace. Coming work for this research should focused on mathematical model enhancement and modeling of electrothermal processes in an induction channel furnace. References 12, figures 5.

Key words: upward continuous casting, induction channel furnace, voltage transformer, equivalent circuit.

PROBLEM STATEMENT. Nowadays, the upward continuous casting method [1-3] is widely used for power cable copper strand production. Besides manufacturing copper wires and electric cables, this method is widely used in various copper industries for making different shape copper products like copper bars or copper strips.

A special feature of the upward continuous casting is the production of wire rod of the required diameter exclusively by the casting operation and, therefore, the possibility of producing wire rod from oxygen-free copper. This technology makes it possible to obtain copper rod with high metal quality. These quality indicators for metals include, in particular: the homogeneity of the metal composition, the chemical purity of the metal, etc. There are two main types of induction furnace: coreless and channel [4]. The upward continuous casting technology is based on the induction melting of copper using an induction channel furnace, powered with an alternating current (AC) electrical energy. By this time, hundreds of induction channel furnaces have been installed in continuous casting plants over the world. Production capacity of upward continuous casting production line may exceed several tens of thousands of tons.

In order to solve the technological process modernizing issues, accounting specific production conditions, choosing the necessary electrical and energy characteristics of electrical equipment and its rational operating modes, an electrothermal model of an induction channel furnace was developed in [5]. The model is designed to simulate electromagnetic and thermal processes that last a long time (up to 36 hours). The model also accounts the consistent implementation of the main technological operations, such as heating and melting of the copper billet, loading and melting of copper cathodes, continuous casting of copper through a mold, etc.

At least two interrelated physical processes take place in an induction furnace: electromagnetic and thermal. Modeling such multiphysical processes is a rather difficult task. To solve it today, there are two main approaches. The first of these is the equivalent circuit approach. The second approach requires the electromagnetic field calculation and is implemented using the finite element method.

In [5], the authors chose the first approach based on the theory of equivalent circuits. This method of modeling coupled electrical and thermal processes is much easier to implement compared to field models and requires less computing power of computers [6].

The working principle of the electrical unit of an induction furnace is similar to a single-phase power transformer operating in a short-circuited mode. At the same time, the electrical parameters of a channel electric furnace and a conventional transformer are noticeably different, due to the difference in their designs.

Structurally, the furnace consists of a lined bath, which contains the entire volume of the melted metal and an induction unit with a melting channel [1, 3]. The bath is connected to the melting channel, as well as filled with the melt. The melt in the channel and the adjacent section of the bath forms a closed conductive ring. The system containing inductor and magnetic core is called a furnace transformer.

The lining that provides thermal insulation of the molten metal is a refractory array with a cylindrical slot into which the inductor is inserted. The coils of the inductor winding are wound on two rods of a closed magnetic core.

The induction unit combines a furnace transformer with a channel where the copper billet is located at first, and after it is melted, the channel is filled with molten copper.

The inductor is the primary winding of the transformer, and the molten metal that fills the channel and is located in the lower part of the bath performs the role of the secondary winding. The electric current flowing in the secondary circuit causes heating (due to the Joule heat energy released in it) and melting of the copper billet. In this case, almost all the energy is released in the channel having a small cross section.

When the electromagnetic approach is used, a single-phase linear transformer models an inductor with molten copper. A sinusoidal source of single-phase voltage of industrial frequency 50 Hz is connected to the primary winding of this single-phase transformer. A non-linear active load resistance is connected to the secondary winding, which depends on the temperature of the heated billet, as well as on the penetration depth of the magnetic field into its volume. The internal parameters of the primary winding, denoted as R_1, L_1 include the parameters of the connected line.

As mentioned above, the model [5] is based on the method of multiphysical simulation of electromagnetic and thermal transient processes having different time duration in an induction channel furnace for producing copper rod. In particular, the characteristic time for electromagnetic processes is 0.02 s, for thermal processes the characteristic time is 1 hour. It should be noted that the thermal process that actually takes place in copper production lasts tens of hours.

The method is based on interconnected nonlinear electrical and thermal equivalent circuits of a channel furnace, taking into account such acting factors as the dependence of the electrical conductivity and heat capacity of the copper billet on temperature. Also, these equivalent circuits take into account the presence of a phase transition in the copper billet when it is heated to a temperature exceeding the melting temperature, an increase in the mass of the melt of periodic loading of copper cathodes into the melt zone, and a decrease in the mass of the melt due to continuous casting of copper rod [5].

The main element of this model is a single-phase voltage transformer, which defines the relationship between an inductor, a magnetic core and a copper cathode to be melted. Determining the parameters of such a transformer is a rather non-trivial task and requires a specific calculation technique.

Given above, the aim of this article is to continue studies started in [7-9] that contribute the theory of transformers and to develop a methodology for calculating the parameters of the equivalent circuit of a single-phase furnace transformer for an induction channel furnace.

MATERIAL AND RESULTS. A photo of a channel furnace with a capacity of 10,000 tons per year is shown in Fig. 1. [7].

Fig. 1. General view of an induction channel furnace

The equivalent electrical circuit for the induction channel furnace is shown in Fig. 2.

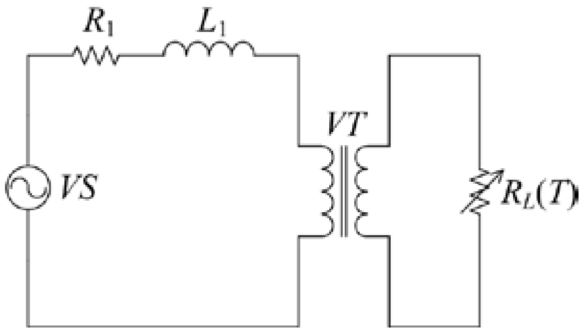

Fig. 2. Simplified equivalent circuit for an induction melting furnace

In Fig. 2: VS is an AC voltage source; VT is a single-phase voltage transformer; RL(T) is a nonlinear active load resistance depending on the billet temperature.

In this work a conventional T-shaped circuit shown in Fig. 3 was used as the voltage transformer equivalent circuit. For further calculations, the equivalent circuit of transformer with secondary parameters referred to the primary side was used.

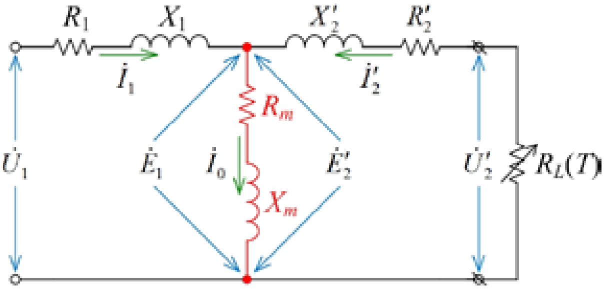

Fig. 3. Equivalent circuit of a single-phase furnace transformer for simulation of electromagnetic processes in an induction channel furnace

Fig. 3 depicts a transformer equivalent circuit referred to the primary side, i.e. all elements of the secondary side are transferred to the primary side.

In Fig. 3: R_1 is the primary winding resistance; X_1 is the leakage reactance of primary winding; $\dot{U}_1$ is voltage applied to the primary winding; R'_2 is the secondary resistance R_2 referred to the primary side; X'_2 is the secondary reactance X_2 referred to the primary side; $\dot{E}'_2$ is the secondary induced electromagnetic force $\dot{E}_2$ referred to the primary side; $\dot{U}'_2$ is a secondary terminal voltage $\dot{U}_2$ referred to the primary side.

As noted above, according to the working principle, the electrical unit of an induction furnace is alike a single-phase power transformer operating in a short-circuited mode. Therefore, the magnetizing circuit branch having parameters R_m, X_m (depicted in red color in Fig. 3) can be excluded from the equivalent circuit.

The active load denoted as $R_L(T)$ corresponds to the resistance of copper cathode, which melts during the furnace operation and therefore strongly depends on temperature. This resistance value is calculated at each instant of time by numerically integrating the equations describing the equivalent circuit shown in Fig. 3. Since the secondary winding of the studied transformer, in fact, is a single short-circuited turn, then its inductance and inductive reactance can be neglected without losing accuracy ($L_2 \approx 0$, $X_2' \approx 0$).

Therefore, it is necessary determine only three parameters of the equivalent circuit, specifically: parameters of the primary circuit branch R_1, X_1 and active resistance of the secondary circuit branch R_2'. The calculation was carried out according to the following procedure [9–11].

The primary winding conductor has a rectangular cross section, hollow inside (refer to Fig. 4). The cavity inside the conductor is designed to cool the winding with liquid coolant. Therefore, in Fig. 4 and further in the text of the article the cavity is called a "tube".

The cross section of the magnetic core with the primary winding (inductor) mounted on it is shown below in Fig. 5. Cylindrical double-layer winding is used in the inductor.

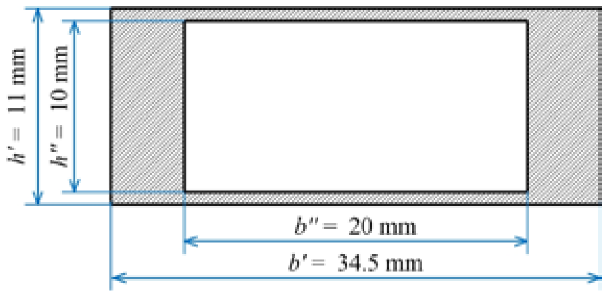

Fig. 4. Cross section dimensions of the primary winding conductor for the furnace transformer

In Fig. 5: 1 is the insulating gasket; 2 is the copper plate; 3 is the steel sheet; 4 is the composite insulation; 5 is the insulating coating; 6 is copper bar with an embedded rectangular tube; 7 is rectangular copper tube.

Using the geometric dimensions of the inductor (refer to Fig. 5) and cross-sectional dimensions of the primary winding conductor (refer to Fig. 4) one can propose the following method for calculating the equivalent circuit parameters of the furnace single-phase transformer.

The computation of parameter values begins with the calculation of the cross-sectional area of the copper bus bar of the primary winding conductor.

The cross-sectional area of a copper bar with an embedded rectangular tube is defined as follows:

$$S' = h' \cdot b' = 379.5 \text{ mm}^2.$$

The cross-sectional area of an embedded rectangular tube is defined as:

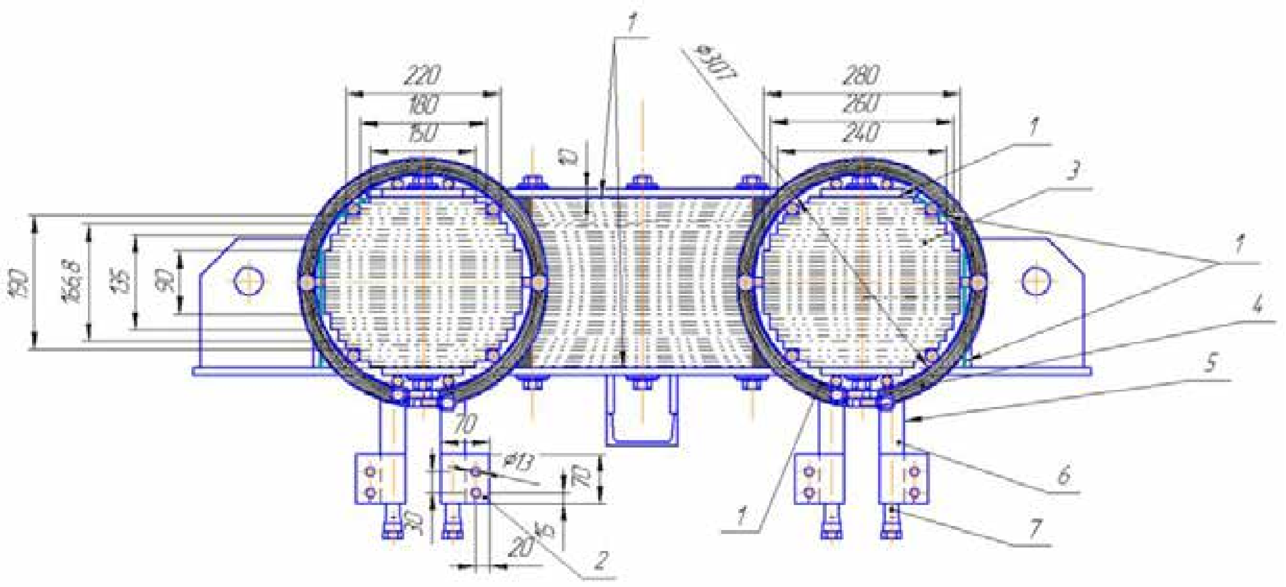

Fig. 5. Cross section dimensions of the inductor for the induction channel furnace

$$S'' = h'' \cdot b'' = 200.0 \text{ mm}^2.$$

The cross-sectional area of a copper bus is defined as:

$$S = S' - S'' = 379.5 - 200.0 = 179.5 \text{ mm}^2. \quad (1)$$

According to Fig. 5, the height of the magnetic core, and hence the height of the primary winding L = 765 mm, the diameter of the magnetic core D = 307 mm.

With this in mind, one can calculate the number of turns in one winding layer:

$$n = \frac{L}{b' + 2} = \frac{765}{34.5 + 2} \approx 21.$$

The total number of turns in the primary winding phase is:

$$w_1 = 2 \cdot n = 42 .$$

The conductor length of the lower layer of the winding is defined as follows:

$$l_1 = \pi \cdot (D + h') \cdot n \cdot 10^{-3} \approx 21 \text{ m}.$$

In its turn, the conductor length of the upper layer of the winding is defined from following expression:

$$l_2 = \pi \cdot (D + 3 \cdot h' + 4) \cdot n \cdot 10^{-3} \approx 23 \text{ m}.$$

The total length of the primary winding conductor is:

$$l_{w(1)} = l_1 + l_2 \approx 44 \text{ m}.$$

Next, one needs to determine the active resistance value of the primary winding at a temperature of 20 degrees Celsius.

The resistivity of technical copper at 20 °C is:

$$\rho_{Cu(1)} = 1.68 \times 10^{-8} \ \Omega\cdot\text{m}.$$

Then, the active resistance of the primary winding at 20 °C is:

$$R_{1(20°C)} = \rho_{Cu(1)} \cdot \frac{l_{w(1)}}{S} = 4.118 \times 10^{-3} \, \Omega,$$

where: S is the cross-sectional area of a copper bus given by (1).

Next, one needs to calculate the active resistance value of the primary winding at an operating temperature of 115 °C:

$$R_1 = R_{1(115°C)} = m_{t(1)} \cdot R_{1(20°C)} = 5.683 \times 10^{-3} \, \Omega, \quad (2)$$

where: $m_{t(1)} = 1 + 0.004 \cdot (115 - 20) = 1.38$ is the winding resistance correction factor for conversion to the temperature of 115 °C.

The next parameter to be calculated is the inductive resistance of the primary winding.

The distance between the central axis of the magnetic core and the middle of the interlayer space of the winding is defined as follows:

$$r_{middle} = \frac{D}{2} + h' + \frac{\Delta}{2} = 165.5 \text{ mm},$$

where: $\Delta = 2$ mm is the distance between the layers (cylinders) of the primary winding.

The diameter of the middle of the interlayer space of the winding is defined as: $D_{middle} = 2 \cdot r_{middle} = 331$ mm.

Geometric parameter for determining the conversion coefficient of an ideal stray field to a real one (which is called the Rogowski correction factor [12]) is defined as follows:

$$\sigma = \frac{\Delta + h' + h'}{\pi \cdot L} = 9.986 \times 10^{-3}.$$

Rogowski correction factor is:

$$k_R = 1 - \sigma = 0.99.$$

Then, the inductive reactance of the primary winding is:

$$\begin{aligned} X_1 &= 2 \cdot \pi \cdot \mu_0 \cdot f \cdot w_1^2 \cdot \\ &\cdot \frac{\pi \cdot D_{middle} \cdot k_R}{L} \cdot \left(\Delta + \frac{h' + h'}{3} \right) = \\ &= 8.747 \times 10^{-3} \, \Omega, \end{aligned} \quad (3)$$

where: $\mu_0 = 4 \cdot \pi \times 10^{-7}$ H/m is the magnetic permeability in a classical vacuum; f = 50 Hz is the industrial frequency.

Finally, primary winding inductance value is:

$$L_1 = \frac{X_1}{2 \cdot \pi \cdot f} = 2.784 \times 10^{-5} \text{ H}.$$

Further, the parameters of the secondary winding are actually determined based on the geometric overall dimensions of the copper billet (i.e., cathode) to be melted. The following values were used in the work: L_{bil} = 768 mm is billet height; R_{bil} =323 mm is the outer radius of the billet; a_{bil} = 53 mm is billet width; d_{bil} = 140 mm is billet thickness.

The number of turns in the secondary winding phase is: w_2 = 1.

The length of the secondary winding turn is defined as follows:

$$l_{w(2)} = 2 \cdot \pi \cdot \left(R_{bil} - \frac{a_{bil}}{2} \right) \cdot 10^{-3} = 1.863 \text{ m}.$$

Further, one needs to determine the active resistance value of the secondary winding (single turn) at a temperature of 20 °C.

The resistivity of copper billet at 20 °C is:

$$\rho_{Cu(2)} = 1.55 \times 10^{-8}\ \Omega \cdot \text{m}.$$

Then, the active resistance of the secondary winding (single turn) at 20 °C is:

$$R_{2(20°C)} = \rho_{Cu(2)} \cdot \frac{l_{w(2)}}{S_{bil}} =$$

$$= \rho_{Cu(2)} \cdot \frac{l_{w(2)}}{a_{bil} \cdot d_{bil}} = 3.892 \times 10^{-6}\ \Omega,$$

where: $S_{bil} = a_{bil} \cdot d_{bil}$ is the cross-sectional area of a copper billet.

Finally, one needs to determine the active resistance of the secondary winding transferred to the primary winding for a temperature of 1080 °C (melting point of copper).

The active resistance of the secondary winding at 1080 °C is:

$$R_2 = R_{2(1080°C)} = m_{t(2)} \cdot R_{2(20°C)} = 2.039 \times 10^{-5}\ \ \Omega,$$

where: $m_{t(2)} = 1 + 0.004 \cdot (1080 - 20) = 5.24$ is the winding resistance correction factor for conversion to the temperature of 1080 °C.

Eventually, the active resistance of the secondary winding transferred to the primary winding at a temperature of 1080 °C is:

$$R_2' = k_{tr}^2 \cdot R_2 = 0.036\ \Omega, \qquad (4)$$

where: $k_{tr} = \frac{w_1}{w_2} = \frac{42}{1} = 42$ is the transformation ratio.

CONCLUSIONS. This article explores the methodology for calculating the electrical parameters of the equivalent circuit of a specialized voltage transformer.

In [5], the method of multiphysical modeling of long-term (tens of hours) electromagnetic and thermal transients of different duration in an induction channel furnace for producing copper rod was applied and substantiated. The method is based on interconnected non-linear electrical and thermal equivalent circuits of a channel furnace.

It is shown that an equivalent resistive-capacitive circuit with nonlinear and switched capacitances can model the processes of heat and mass transfer. In addition, the inductor, which, with the help of a varying magnetic field, entails heating and melting copper, is well modeled by a single-phase linear furnace transformer operating in a short-circuited mode.

The procedure and results of calculating the parameters of the equivalent circuit of the furnace single-phase transformer are given (2), (3), (4). These characteristics are used for modeling the electrothermal processes in an induction channel furnace.

Coming work for this research should focused on mathematical model enhancement and modeling of electrothermal processes in an induction channel furnace.

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РОЗРАХУНОК ПАРАМЕТРІВ ТРАНСФОРМАТОРА НАПРУГИ ДЛЯ МАТЕМАТИЧНОЇ МОДЕЛІ ІНДУКЦІЙНОЇ КАНАЛЬНОЇ ПЕЧІ

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На даний час метод безперервного висхідного лиття широко використовується для виробництва мідних проводів і електричних кабелів. Електротермічна модель індукційної канальної печі призначена для вирішення питань модернізації технологічного процесу, врахування конкретних умов виробництва, вибору необхідних електричних та енергетичних характеристик електрообладнання, а також оптимальних режимів роботи. Принцип роботи електричного блоку індукційної печі близький до однофазного силового трансформатора, що працює в режимі короткого замикання. Визначення параметрів цього трансформатора є важливою задачею, що вимагає спеціальної методики розрахунку. Було застосовано основи теорії електричних кіл. Для подальших розрахунків використовувалася еквівалентна схема трансформатора з вторинними параметрами, приведеними до первинної сторони. Значення активного опору первинної обмотки при робочій температурі 115 градусів за Цельсієм становить 0,005683 Ом; індуктивний опір первинної обмотки становить 0,008747 Ом; активний опір вторинної обмотки, приведений до первинної обмотки при температурі 1080 градусів за Цельсієм, становить 0,036 Ом. Для розрахунку використано фактичні розміри індуктора для індукційної канальної печі. Індуктор є первинною обмоткою трансформатора, а роль вторинної котушки виконує розплавлений метал, який заповнює канал. Оскільки вторинна обмотка досліджуваного трансформатора, по суті, є одним короткозамкненим витком, то її індуктивністю та індуктивним опором можна знехтувати без втрати точності. Запропоновано детальну методику розрахунку визначення параметрів однофазного пічного трансформатора. У статті досліджено методику розрахунку електричних параметрів схеми заміщення спеціалізованого трансформатора напруги. Ці характеристики використовуються для моделювання електротермічних процесів в індукційній канальній печі. Майбутні роботи за тематикою цього дослідження повинні бути зосереджена на вдосконаленні математичної моделі та моделюванні електротермічних процесів в індукційній канальній печі.

Ключові слова: безперервне висхідне лиття, індукційна канальна піч, трансформатор напруги, еквівалентна схема.

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