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Shevchenko D.V., Ovcharuk A.N., Bezugliy A.V., Nikolenko A.V.

Research of the ore reducing furnaces electrical modes for ferronicel production

The paper presents the results of a study of the electrical modes of ferronickel furnaces OTF-1 and OTF-2 at the Pobuzhsky ferronickel plant. It was found that the furnaces operate in arcless mode. An asymmetrical voltage mode is observed: electrode casing - under, which indicates an unbalanced mode of the furnace. As a result of measurements, a significant transfer of power was detected in the area of the electrical circuit of the 4th, 5th, 6th electrodes. An analysis of the electrical mode of a 48 MVA round ferronickel furnace in the city of Hua-Hua (China) showed that the use of a furnace transformer without a voltage booster and an autotransformer makes it possible to provide the necessary electrical mode of ferronickel furnaces.

An analysis of the electrical mode of a 90 MVA round ferronickel furnace in Guatemala showed the possibility of operating these furnaces in a combined mode, i.e. in the presence of an electric arc, which is controlled by the resistance of the electrodes and the power ratio in the electric arc and slag.

Key words: ferronickel, ore thermal furnace, electric mode, mathematical modeling six-electrode furnace

Introduction

The main quantity of ferroalloys is produced in three-electrode and six-electrode ore reduction furnaces. Round three-electrode furnaces, which are symmetrical not only in geometry, but also creates a symmetrical load on the network, have become widespread. Along with this, six-electrode furnaces with round and rectangular electrodes are also used in industry. If a lot of research has been carried out on round three-electrode furnaces, their optimal modes for various alloys have been determined, then on rectangular furnaces, there are few such researches and it is still not clear how the current is distributed in the working space of the furnace and what electrical mode is optimal. To study this issue, we developed an electrical model of a furnace, where the internal resistance of a section of the electrical circuit was determined by the internal resistance of ammeters. To solve this problem, the widespread computer program Electronic Workbench 5.12 was used.

Theoretical and Experimental Researches

As six-electrode furnace is a powerful consumer of a symmetrical three-phase network, then the circuit for connecting consumers of each phase is equivalent to an open triangle, and the source voltage of each phase is distributed among the half-phases [1]. To determine the role of the metal in the electrical circuit of the furnace and the distribution of current in the bath, the first model does not have grounding in half phases. Despite the symmetry in voltage between the half-phases of phases A and B, the current between them is about 7% of the phase current (Fig. 1). As a result, the current between half-phases increases. Thus, this model makes it possible to estimate the current distribution in the furnace with a sufficient degree of accuracy.

Based on theoretical assumptions, the electrical modes of two six-electrode furnaces OTF-1 and OTF-2 of the Pobuzhsky ferronickel plant were studied. During the research, it was found that the hearth of the furnace bath is grounded with the workshop structures. In the area of the measuring complex, the potential of the metal structures differs by 2-3 volts from the potential of the furnace hearth.

During the research process, a method for identifying the third harmonic, indicating the presence of an arc, was developed and tested. To do this, while starting one of the furnaces, an arc mode was artificially created, which confirmed the possibility of using this method for six-electrode furnaces. After the furnace was brought into operating mode, the third harmonic was absent, which indicated that the furnace was operating without an arc [2].

While analyzing the measuring complex of furnaces OTF-1 and OTF-2, it was found that in the source circuit of each phase there are two sections of the circuit of the so-called half-phases. The furnace control system ensures the symmetry of each half-phase in current, voltage and power. It is believed that the symmetry of these parameters ensures optimal operation of the furnaces.

The reaches which were made of electrode-under voltages on both furnaces do not confirm the symmetry of the input power into the furnace (Tables 1, 2). In the tables the voltage are indicated as next: on the secondary windings of transformers – U_{fA}, U_{fB}, U_{fC}; on half-phases – U_{ao}, U_{ox}, U_{Bo}, U_{oy}, U_{co}, U_{oz}, on electrodes – U_{e1}, U_{e2}, U_{e3}, U_{e4}, U_{e5}, U_{e6}.

A characteristic feature of the values given in the table is that the sum of the half-phase voltages (not arithmetic, but geometric) is equal to the phase voltage, which indicates the influence of the current of neighboring phases. Voltages of different magnitudes on the electrode casing in relation to the hearth indicate an unbalanced mode of the furnaces.

© D.V. Shevchenko, postgraduate student; A.N. Ovcharuk, Doctor of Technical Sciences, Professor; A.V. Bezugliy, senior lecturer; A.V. Nikolenko, head of department, candidate of technical sciences, associate, Ukrainian State University of Science and Technologies i

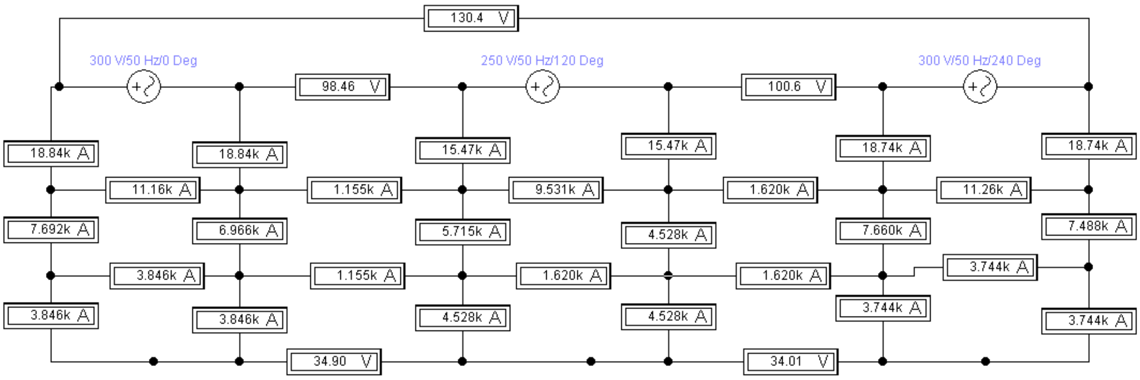


Fig. 1. Equivalent electrical circuit of a six-electrode furnace in the absence of zero at the hearth of the bath

With the advent of a metal equivalent, the voltage symmetry between sources is broken, but remains the same between half-phases (Fig. 2).

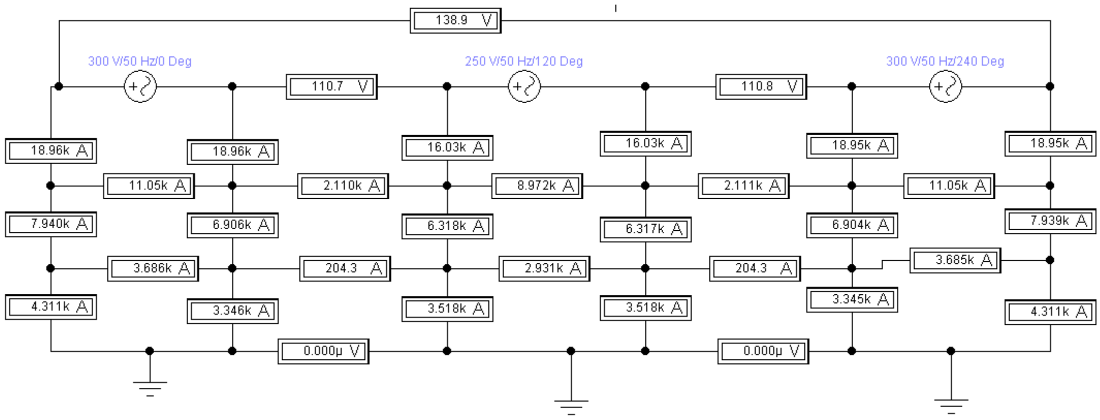


Fig. 2. Equivalent electrical circuit of a six-electrode furnace with a zero at the hearth of the bath

Table 1. Results of voltage measurements on the electrodes OTF-1

#	U_{fA}	U_{fB}	U_{fC}	U_{ao}	U_{ox}	U_{Bo}	U_{oy}	U_{co}	U_{oz}	U_{e1}	U_{e2}	U_{e3}	U_{e4}	U_{e5}	U_{e6}
1	388	390	373	253	202	257	255	271	271	249	194	248	252	264	268
2	348	375	367	262	218	252	260	272	274	260	216	257	255	268	261

Table 2. Results of voltage measurements on the electrodes OTF-2

#	U_{fA}	U_{fB}	U_{fC}	U_{ao}	U_{ox}	U_{Bo}	U_{oy}	U_{co}	U_{oz}	U_{e1}	U_{e2}	U_{e3}	U_{e4}	U_{e5}	U_{e6}
1	447	355	434	236	222	272	227	205	320	225	219	255	227	202	303
2	466	374	407	240	192	263	268	320	243	219	181	201	202	325	235

Of particular interest were measurements of the voltage between the electrode casings of one phase, which turned out to be much greater than the voltage of the secondary winding of the transformer.

As shown by measurements between 3rd and 4th, and especially between 5th and 6th electrodes, the voltage of the secondary winding of the transformer of phases B and C significantly exceeded, which indicates the transfer of power from adjacent phases using a magnetic field. A large voltage between the electrodes of adjacent phases indicates a significant current between the electrodes of adjacent phases. The unbalance of the voltages measured in the electrode-under section indicates an unbalanced power distribution (Fig. 3 – 6).

The calculations showed that the power losses for the first and second modes of OTF-1 were 751.8 kW and 861.6 kW, respectively, taking into account losses in the transformer - 1303.1 kW and 1412.9 kW [3].

OTF-2 is characterized by artificial current unbalance, power transfer between phases B and C, as well as losses on a short network that are greater than on OTF-1 - in total they were 1534.7 kW and 1484.3 for the first and second measurements, taking into account losses in the transformer - 2089.7 kW and 2039.3 kW.

The measured voltage between the electrodes and the hearth confirms the unbalance of power introduced across the half-phases.

Measurements showed the presence of a current between adjacent phases, which for a symmetrical mode is more than 10% of the electrode current, i.e. it is impossible to assume that in a six-electrode furnace the phase circuits are autonomous.

After processing the measurement results of the electrical mode, a mathematical model of a six-electrode ferronickel furnace was compiled, taking into account power transfer. The resistance of sections of the electrical circuit was represented by the internal resistance of the current meters. There is no nonlinear element in the furnace circuit - an electric arc. The model shows complete symmetry in phases. The transfer of energy by the magnetic field of adjacent phases is represented by additional sources of EMF for phases B and C. The electrode currents of phases B and C are higher than phase A. The current in the upper horizons of the furnace is 50% of the electrode current. The current between adjacent phases is 15% of the electrode current. Noteworthy is the large voltage unbalance in the half-phases between the electrode casing and the furnace hearth - and this means that there is an unbalance of the power introduced into the furnace in half-phases. The voltages between the electrode casings, measured on an operating furnace, are close in value to those obtained from the mathematical model.

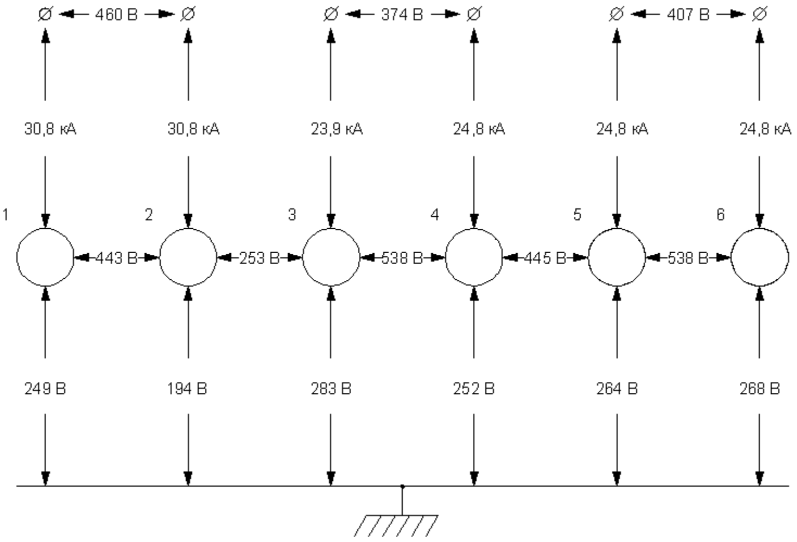


Fig. 3. Voltage measurement scheme OTF-1

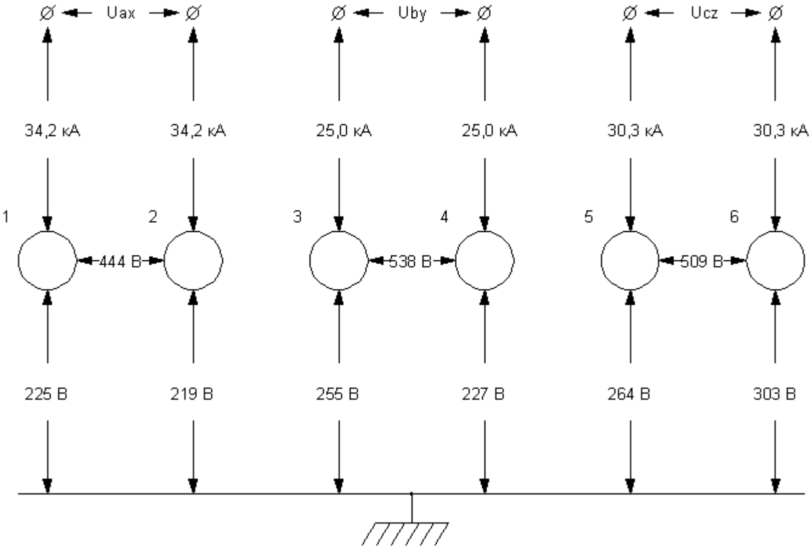


Fig. 4. Voltage measurement scheme OTF-2

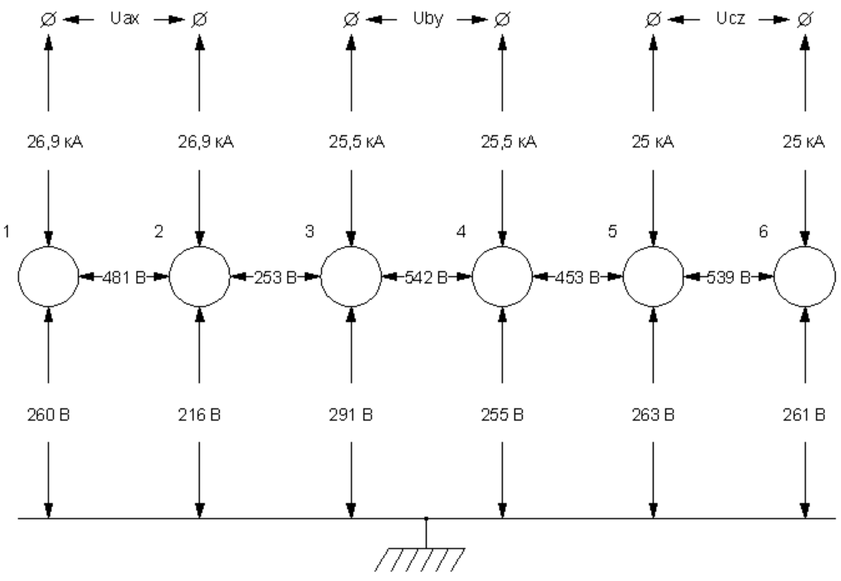


Fig. 5. Voltage measurement scheme OTF-1

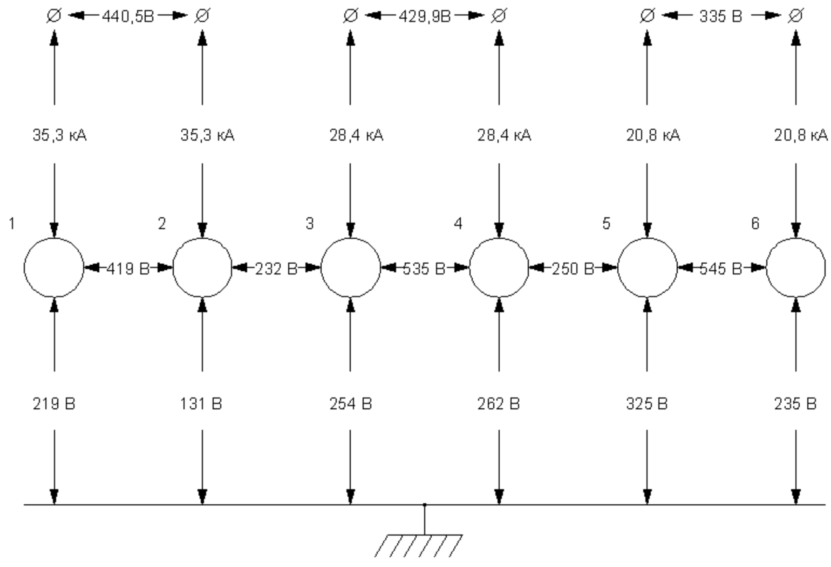


Fig. 6 Voltage measurement scheme OTF-2

Using a mathematical model, the electrical mode was analyzed by half-phases of a six-electrode ferronickel furnace (Fig. 7).

Based on the data obtained from the measurement results at OTF-1 and OTF-2 and the mathematical model, proposals were made that make it possible to increase the accuracy of measurements and ensure symmetrical operation of the furnaces.

Thus, based on numerous measurements of the electrical operating modes of six-electrode furnaces OTF-1 and OTF-2, it was established:

- furnaces operate in resistance mode and the main amount of energy is released in the upper horizons of the furnace;
- furnaces producing ferronickel from oxidized nickel ores are characterized by arcless operation;
- significant power transfer was noted in phases B and C. This indicates an asymmetric operating mode of the furnaces, which causes an increase in the voltage between electrodes 3-4 and 5-6, respectively;
- the potential of the OTF-2 measuring complex differs from the furnace feed potential by 2-3 V.

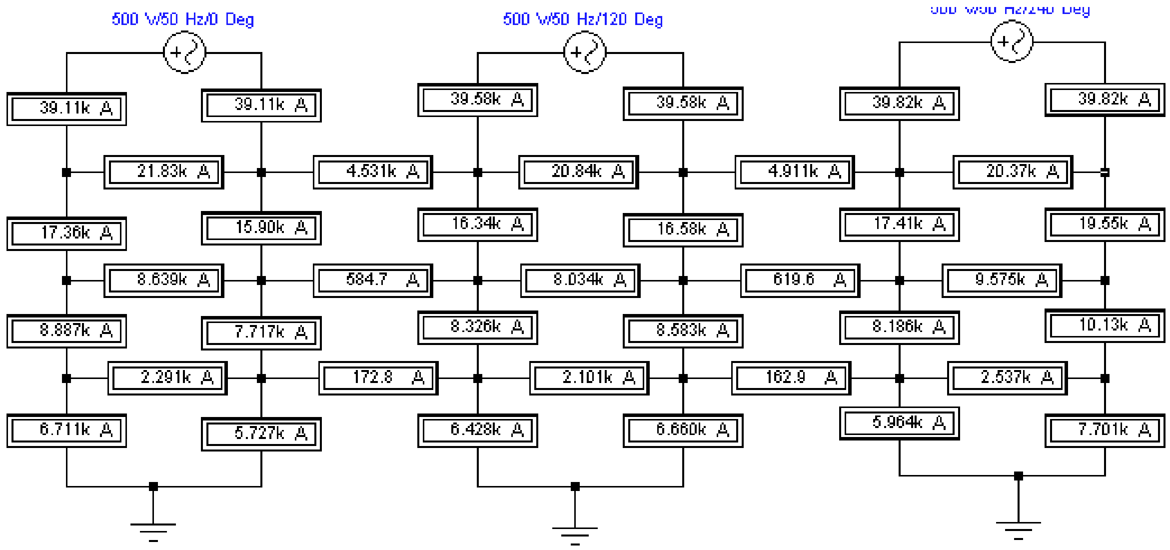


Fig. 7. Mathematical model of the electrical mode of a six-electrode OTF

Round three-electrode furnaces are powered by a three-phase alternating current network, which is provided by single-phase and three-phase furnace transformers. In the second case, the short network is asymmetrical and power transfer is observed. With single-phase transformers, a short network can be symmetrical. Under these conditions, it becomes possible to work at different stages in phases. This generates an equalizing current in the triangle circuit. Its magnitude is not controlled by anyone, and given the triangle switching on the electrodes, this current, passing between the cheeks of adjacent phases, can cause overheating of the electrode casing, disrupt the mode of its formation and subsequently break. Therefore, it is unacceptable to work at different stages on phases. In such furnaces, it is easy to control their electrical mode using the third harmonic, indicating the presence of an arc.

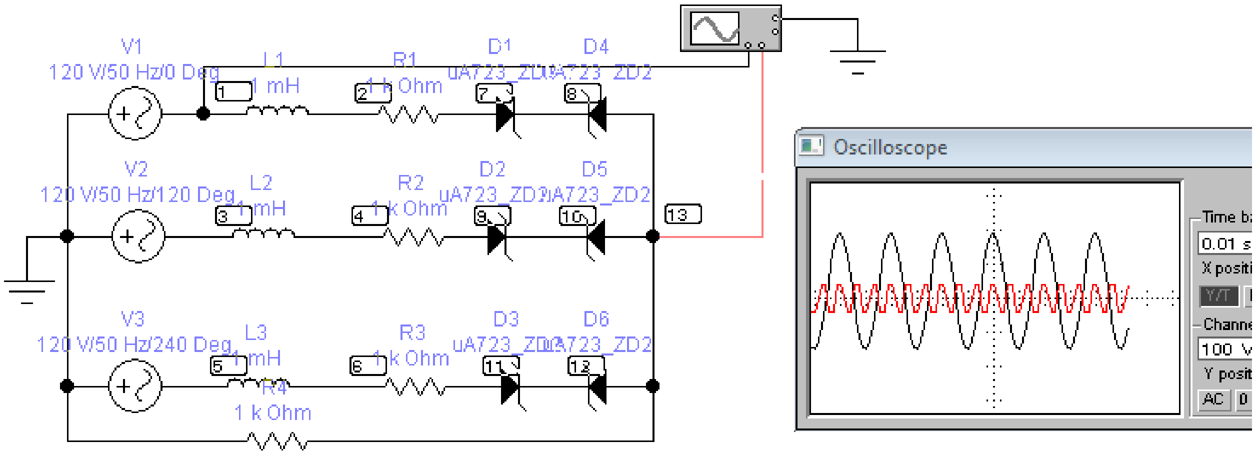


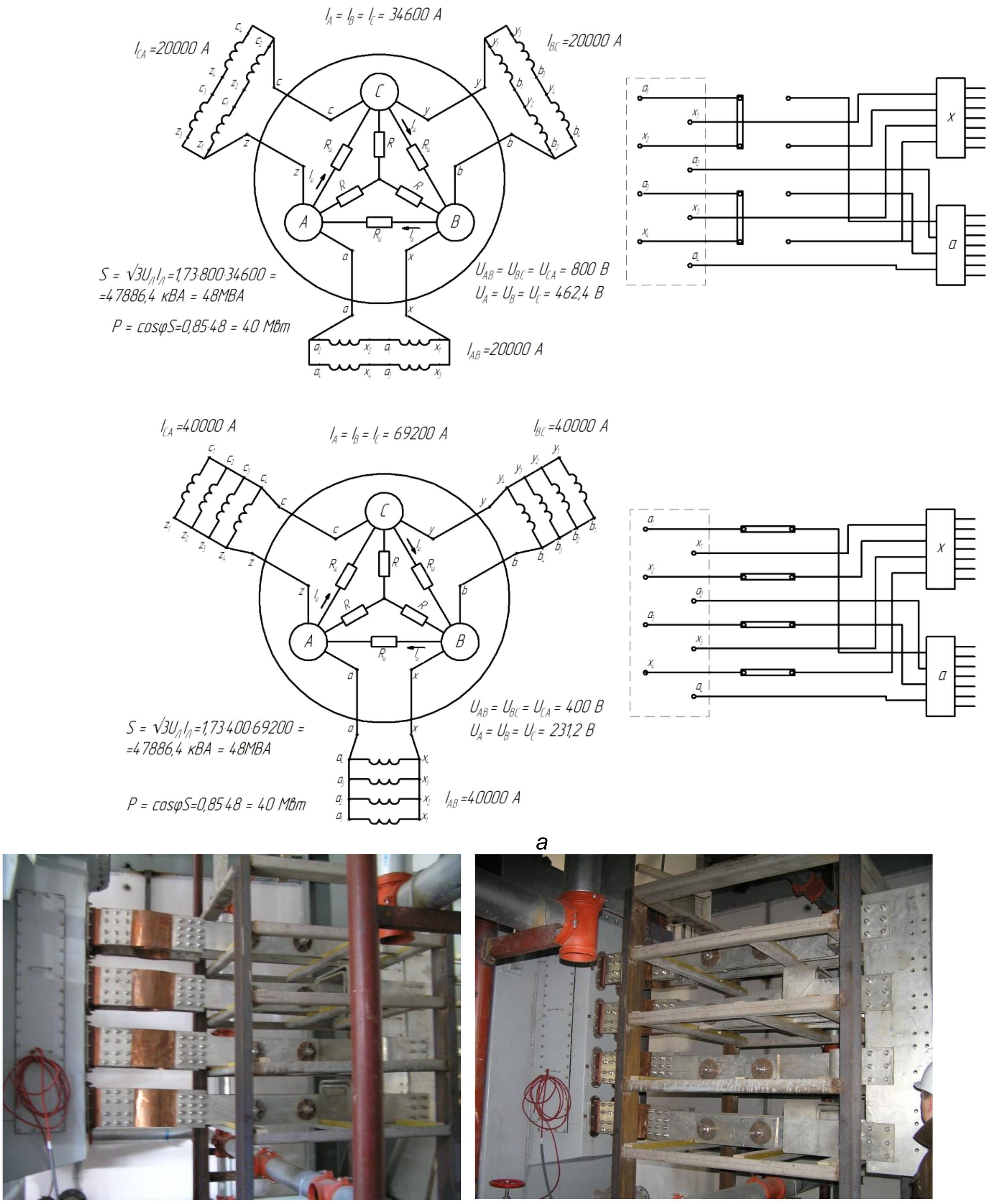
Fig. 8. Electrical diagram of a three-electrode furnace research

As already noted, three-electrode arc furnaces create a symmetrical load on the network. To compensate for reactive power, longitudinal or transverse compensation is used. With longitudinal compensation, the inductive reactance of a short network can be compensated to a large extent, while the X_L/R condition of continuous arc burning is violated, which limits the power input into the furnace. Therefore, a transverse compensation scheme is mainly used. Furnaces operating at low cos φ provide conditions for continuous arc burning. Traditionally, furnaces were equipped with furnace units, where, in addition to the furnace transformer, booster transformers and autotransformers were used. In one of the projects of a ferronickel plant in China, a furnace transformer without a booster transformer was proposed. The secondary winding of each phase consisted of 4 windings for a current of 10000 A. Switching of these windings is carried out using jumpers.

The technical characteristics of the ore-thermal round furnace with a capacity of 48 MVA are given in table 3.

Table3. Technical characteristics of the ore-thermal round furnace with a capacity of 48 MVA

Parameters	Unit	Meaning
Furnace power	MVA	48
Transformer rated power	MVA	16
Number of transformers	–	3
Primary voltage	kV	110
Limits of secondary line voltage when connecting secondary windings in series	V	800-340
Limits of secondary line voltage with parallel connection of secondary windings	V	400-170
Number of transformer stages	–	24



a

b

Fig. 9 – Short network switching: *a* – diagram; *b* – general view

As indicated in the characteristics, the furnace has 3 single-phase transformers of 16 MVA each.

The project envisaged the use of nickel-containing raw materials with various physical and chemical properties in the processing process. In this regard, the furnace transformer must have a wide range of voltage adjustment of the secondary winding with a high utilization rate of the installed power of the transformer.

We have thoroughly worked out the theoretical basis for solving this problem. The existing method of increasing the cross-section of the secondary winding at several subsequent stages compared to the first one does not provide a solution to the problem. In our case, it was necessary to solve this problem by changing the voltage of the secondary winding of the furnace by 50%. A split-phase circuit was proposed, consisting of 4 secondary windings designed for a current of 10 kA with their subsequent switching, which ensures a minimum number of switching elements and a minimum switching current. To solve this problem, a non-standard arrangement of the terminals of the secondary windings of the transformer was proposed, which was successfully implemented by the Chinese transformer manufacturer (Sinosteel company) based on a patent of Ukrainian specialists [4]. During switching process 4 secondary windings were connected in parallel, which provided a phase current of 40 kA and an electrode current of 69.2 kA. The circuit was assembled with 4 jumpers in 10 kA circuits with a linear voltage of 400 V. The second switching mode provides for pairwise series-parallel connection of secondary windings. Switching is carried out by two jumpers in a 10 kA current circuit (Fig. 9).

With this switching, the linear voltage of the secondary winding is 800 V at a rated phase current of 20 kA, and the electrode current of 34.6 kA. Feeding substation with deep input 110 kV (Fig. 10). The 110 kV current supply to the furnace units is carried out through modern measuring and switching devices.

With the help of hydraulics bypass and move the electrodes happens. During the period of operation of the furnace, switching devices and other components of the electrical circuit showed reliable operation and efficient operation of the furnace at optimal electrical parameters for conducting the process on nickel-containing raw materials with various physical and chemical properties.

The ore-thermal furnace (OTF) at the ProNico plant (Guatemala) is a round furnace designed for smelting cinder with a nominal power of 90 MW [5]. The three-transformer 45 MVA furnace is designed to melt 180 tons of cinder per hour at a furnace power of 90 MW, with a specific hearth power of approximately 400 kW/m^2 and a power utilization factor of 0,85 under load. A summary of the design parameters of the furnace section is given in Table 4.

Table 4. Parameters of round OTF

Parameter	**Unite**	**Operation with one tubular rotary furnace**	**Operation with two tubular rotary furnace**
Furnace power	MW	45	90
Melting of the cinder	t/h	90	180
Cinder temperature	℃	850-900	
Total electricity consumption (per 1 ton of cinder)	kW·h/t	520	480
Furance diameter (inside the casing)	m	18	
Furnace diameter (inside the lining)	m	16,9	
Furnace operating mode		Half-arc	Arc
Hearth area	m^2	225	
Specific power of the hearth	kW/m^2	200	400
Bath specific power	kW/m^2	200	130
Bath resistance for 1 electrode	mOhm	6	12
Electrode current strength	kA	45	45
Characteristics of electrodes	3 Soderberg electrodes – 2 m in diameter		
Transformer rated power	MBA	135	
Transformer rated current	kA	60	
Metal release temperature	℃	1525	
Temperature of the liquid phase of the metal	℃	1450	
Slag release temperature	℃	1600	
Temperature of the liquid phase of the slag	℃	1550	
Metal production rate	t/h	4,1	9,7
Metal release frequency	pcs/day	2,1	5
Slag production rate	t/h	64,6	158,3
Dust generation rate	t/h	0,9	
Exhaust gas volume	nm^3/h	14385	35970
Flue gas temperature	℃	750-850	

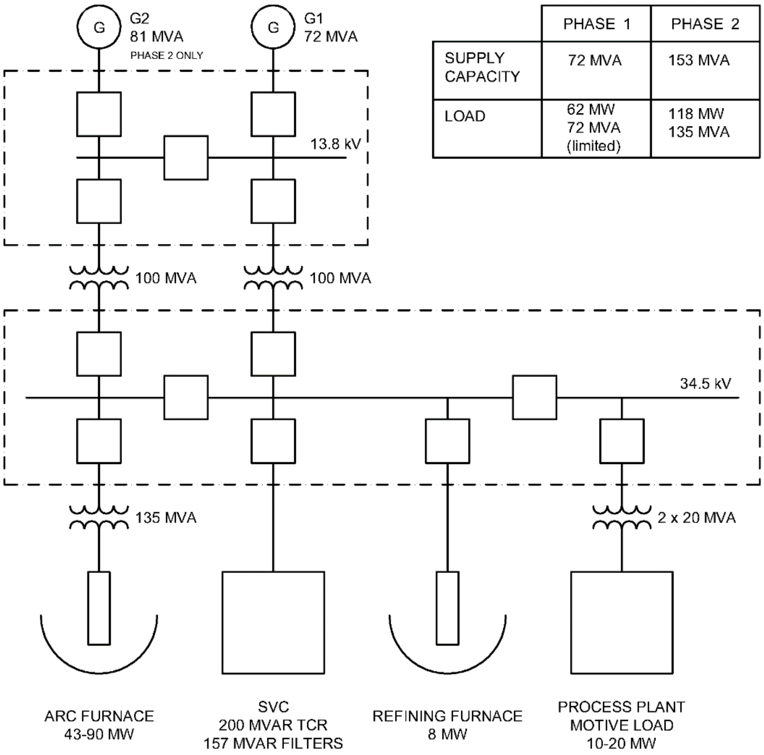
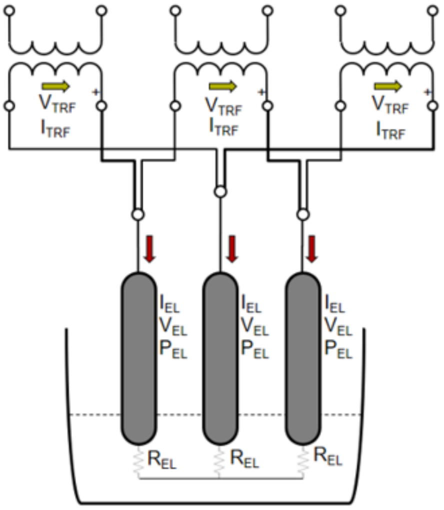


Fig. 10 – Furnace power supply diagram

Controlling the electrical mode of the furnace is in changing the following parameters [6]:

- current on the electrodes (I_{el}) – depends on the voltage on the electrodes. As the resistance increases, the current decreases and vice versa;
- voltage on the electrodes (U_{el}) – depends on the supply voltage on the high side (5.52 kV, 11 kV, 17.25 kV, 34.5 kV), the connection diagram of the furnace transformer windings (Y or Δ), and the position of the voltage step switch (1-35).

The current and voltage on the electrodes determine the power by phase and the total power of the furnace (Fig. 11).



$$V_{EL} = \frac{V_{TRF}}{\sqrt{3}}$$

$$I_{EL} = \frac{V_{EL}}{R_{EL}} = \frac{V_{TRF}}{\sqrt{3} \times R_{EL}}$$

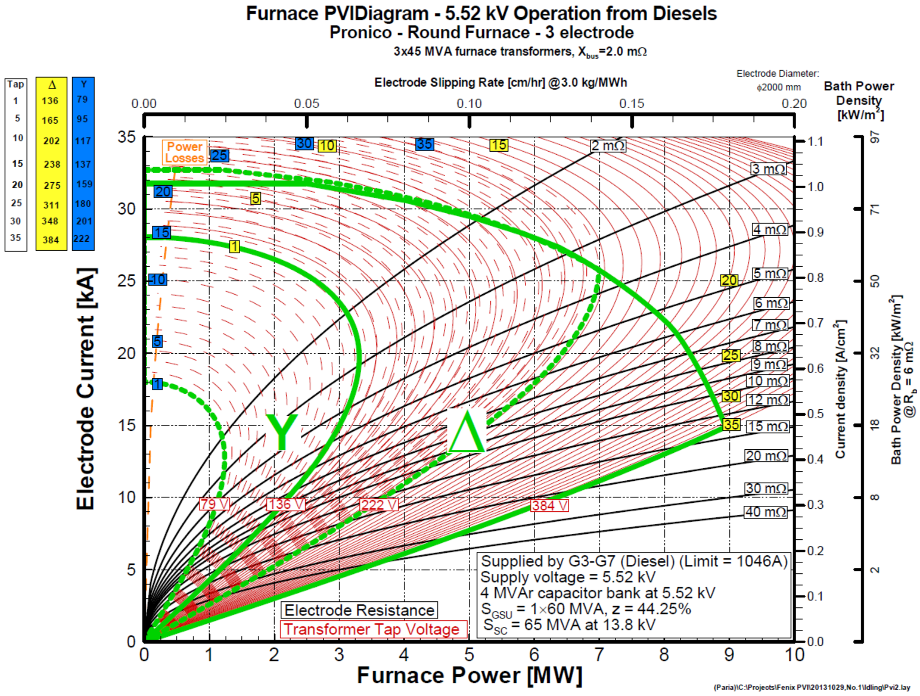
$$P_{EL} = V_{EL} \times I_{EL}$$

3 ELECTRODES ARE CONDUCTING

$$P_{FNC} = 3 \times P_{EL}$$

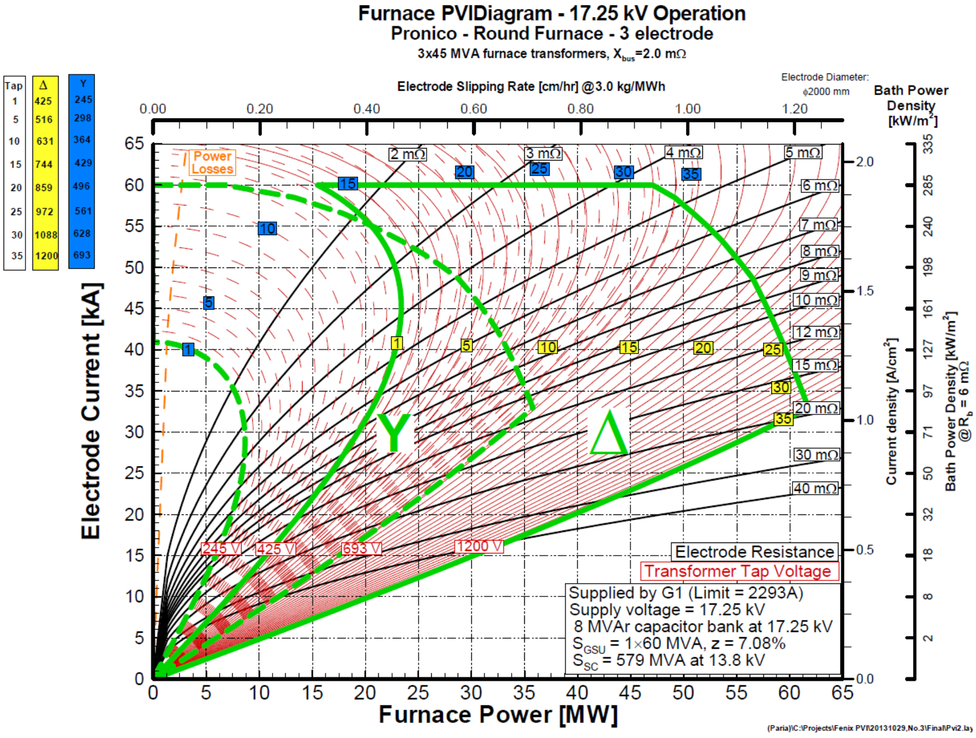
Fig. 11 – Schematic diagram of the connection of furnace transformers and electrodes

The choice of electrical mode under different conditions is shown at Fig. 12-15.



Supplied by G3-G7 (Diesel) (Limit = 1046A)
Supply voltage = 5.52 kV
4 MVAr capacitor bank at 5.52 kV
S_{GSU} = 1×60 MVA, z = 44.25%
S_{SC} = 65 MVA at 13.8 kV

Fig. 12 – 5.52 kV Operation on diesel generation



Supplied by G1 (Limit = 2293A)
Supply voltage = 17.25 kV
8 MVAr capacitor bank at 17.25 kV
S_{GSU} = 1×60 MVA, z = 7.08%
S_{SC} = 579 MVA at 13.8 kV

Fig. 13 – 17,25 kV Operation on one turbogenerator

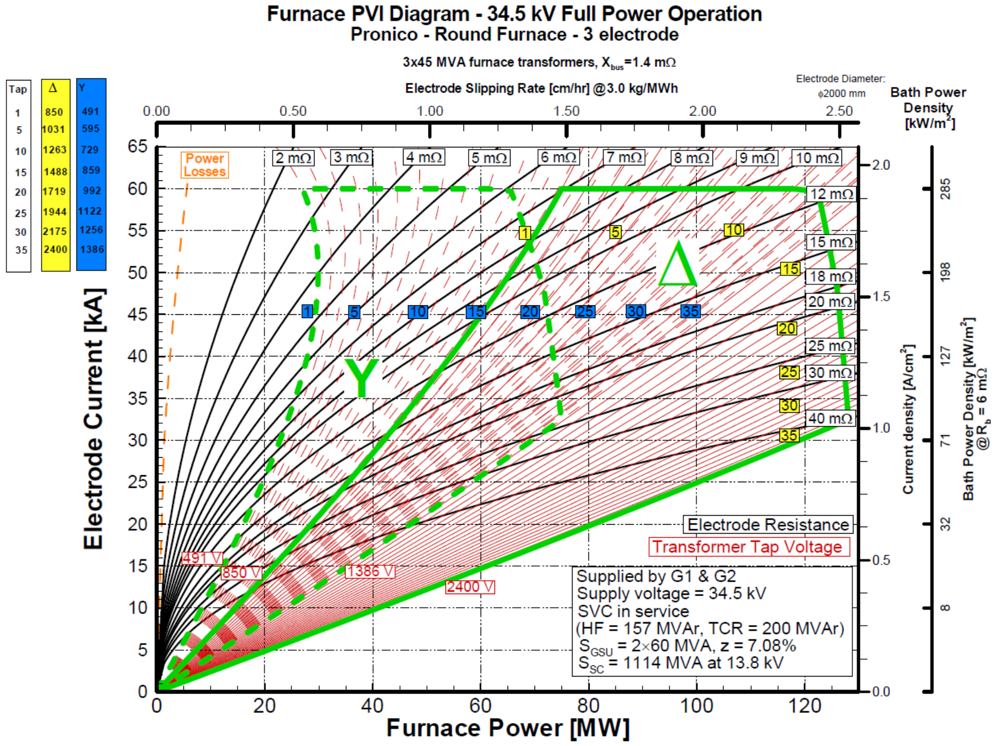


Fig. 14 – 34,5 kV Operation on two turbogenerators

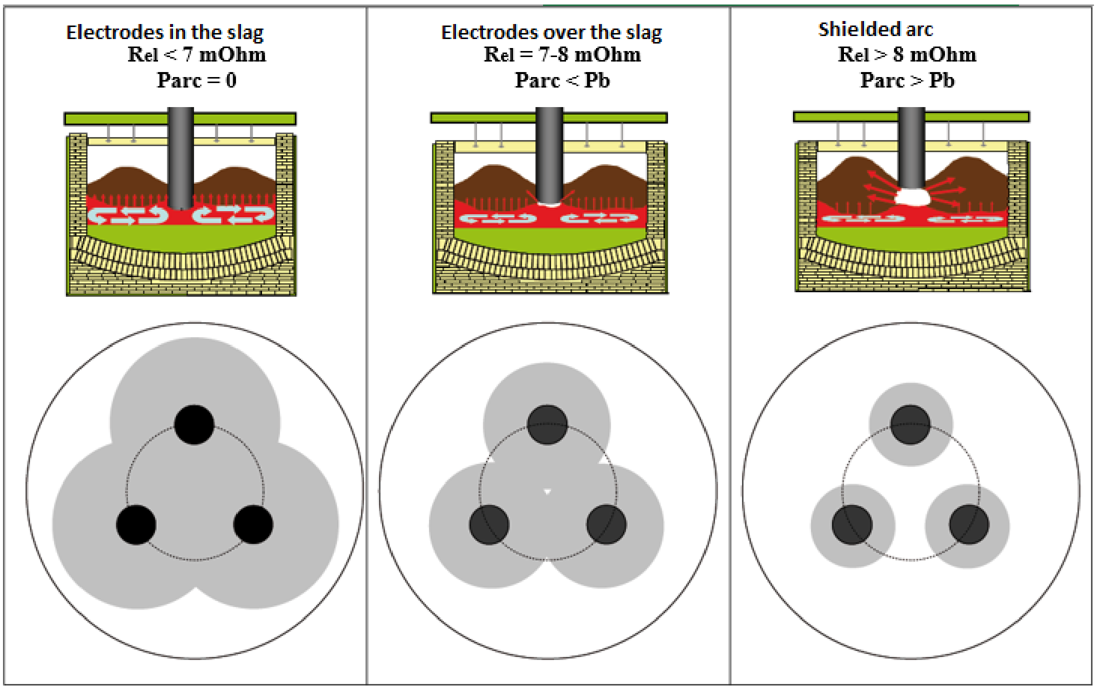


Fig. 15 – Area of active melting zone depending on R_{el}, P_{arc} and P_b

The resistance at the electrodes (R_{el}) determines the position of the working end of the electrode in relation to the slag surface (Figure 16) and the ratio of the power (or heat) generated in the arc to the power released in the slag bath due to the resistance of the slag.

The resistance or electrical conductivity of the slag depends on its composition (k – electrical conductivity, 1/Ohm·cm):

$\ln(k) = -4{,}45+9{,}152\cdot FeO+5{,}34\cdot(CaO+MgO)$ at 1500 °C.

As can be seen from the equation, MgO and especially FeO increases electrical conductivity or reduces resistance. It is also known that SiO2 and Al_2O_3 increase the resistance of the slag.

The total power released in the furnace consists of the power released in the arc (P_{arc}) and the power released in the slag bath (P_b). The ratio P_{arc} / P_b is an important technological parameter. Insufficient power of the slag bath P_b will lead to low slag temperature, more viscous slag and difficulties with its release. Too high a power of the slag bath will increase the thermal load on the lining of the furnace walls, due to the increased temperature of the slag (increased overheating), and will lead to more intense mixing of the slag in the furnace (wear of the lining and high heat losses).

The resistance value on the electrodes (R_{el}) is determined by the furnace operator depending on the target ratio P_{arc} / P_b. As the resistance value increases, the penetration of the electrodes into the slag decreases (or the distance from the end of the electrode to the surface of the slag increases), and the area of the active melting zone of the slag bath changes.

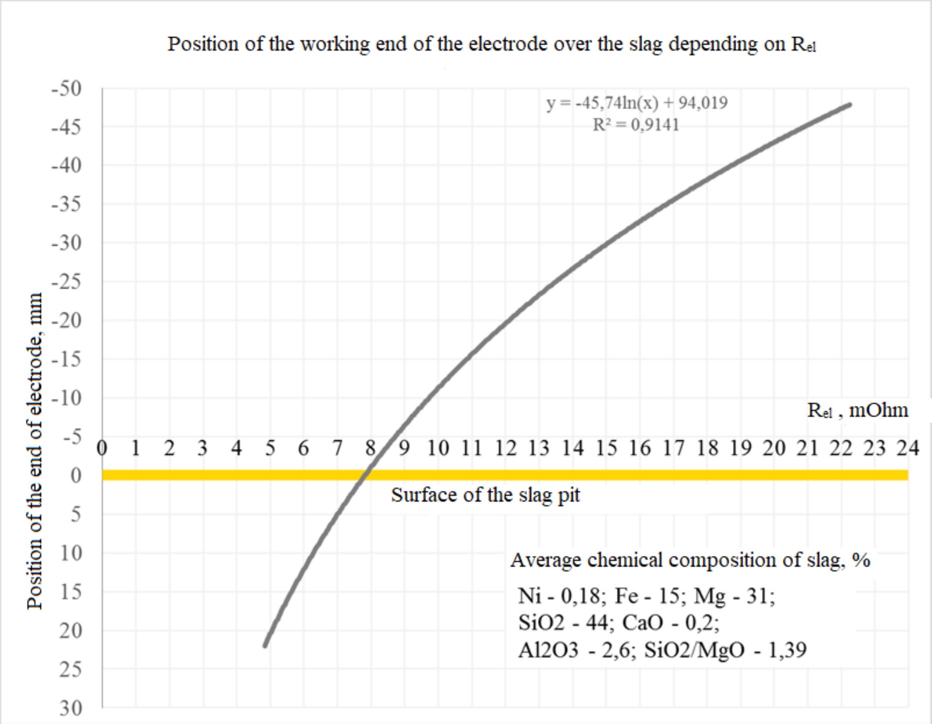


Fig. 16 – Position of the working end of the electrode depending on R_{el}

Table 5. Operating modes and electrical parameters of the OTF

Operating mode	Power, MW	R_{el} , mOhm	Average P_{arc} / P_b
Idling	<7	3-10	0
Warming up	7-20	7-14	1,4
Normal operation	20-30	10-16	1,7
Normal operation	30-40	12-18	2,0
Normal operation	40-50	15-20	2,3
Normal operation	50-60	18-22	2,7
Normal operation	>60	>18	>2,9

Table 6. Electric mode of the furnace in 24 hours

Parameter	One-time parameter	Parameter range for 24 hours
P [MW]	84	79-87,0
P [MW] one phase	28	16,6-49,9
cos φ	0,91	0,58-0,95
I [kA]	43,7	16,6-54,5
U [V]	664,3	450-1204
Stage	13	12-15
Electrode bypass [mm]	575,5	126-835
Active resistance R [mOhM]	15,7	9,2-87,3

Conclusions

Electrical parameters of ore reduction furnaces with a capacity of 46-90 MW with a rectangular (six-electrode) and round (three-electrode) bath are characterized by a significant difference in the distribution of electric current in the bath of smelting units - in rectangular furnaces there is a power imbalance in the half-phases, and in round furnaces - on the electrodes when operating at different phase voltages. The authors of the current paper are working to improve the electrical parameters of ore reduction furnaces and develop new sources of their energy supply.

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