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ANALYSIS OF THE WORK STATES OF A PULSE CURRENT ELECTRIC ARC FURNACE

ANALIZA STANÓW PRACY PIECA ŁUKOWEGO PRĄDU IMPULSOWEGO

Abstract

This article presents the results of the analysis of a six-electrode pulse current electric arc furnace (EAF). The characteristics of a power supply system for an EAF are presented for symmetrical states and the most probable asymmetrical states.

Keywords: *electric arc furnace*, *EAF*, *pulse current*, *six-electrode arc furnace*

Streszczenie

W artykule przedstawiono wyniki badań pracy sześcioelektrodowego pieca łukowego prądu impulsowego. Charakterystyki energetyczne układu zasilania pieca łukowego zostały przedstawione dla stanów symetrycznych oraz najbardziej prawdopodobnych stanów niesymetrycznych.

Słowa kluczowe: *elektryczny piec łukowy*, *prąd impulsowy*, *sześcioelektrodowy piec łukowy*

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1. Introduction

In recent years, direct-current EAFs have been competing within the steelmaking industry with three-phase alternating current EAFs in terms of their effect on power supply systems. However, the use of high-power direct-current EAFs is limited by certain factors, the most important of which are multiple overvoltages caused by dips in high-value technological current [1]. Short-term technological shutdowns of direct-current EAFs have to be performed while the EAF is under load. This creates additional requirements for circuit breakers installed on the side of the primary winding of the furnace transformer. Frequent shutdowns of furnace transformers directly under load reduce the technological viability of circuit breakers, sometimes even damaging them and prematurely excluding them from use [2, 3].

2. Analysis of the results

In order to partially solve the aforementioned issues in EAFs used in steelmaking, a design of a six-electrode pulse current EAF was developed in which the arc can be interrupted by raising the electrodes, and the furnace transformer was disconnected from the electrical power supply during the no-load state of the EAF. Figure 1 shows a schematic of the power supply system for the pulse current EAF [4]. An equivalent system was presented with a voltage of 230 kV and an equivalent reactance of 8 Ω. The power transformer was supplied with 230 kV via an overhead line, of length 7 km and cross-section 3×500 mm^2. The parameters of the power transformer are summarized in Table 1. The three--phase cable line of a length of 520 m, constructed of four cables 1×240 mm^2 was used to supply the furnace transformer (parameters summarized in Table 1). Rectifier diodes were modeled as resistance. When the diode was ON, resistance equaled R_{ON} $5\cdot 10^{-3}\Omega$, when OFF, $R_{OFF} = 10^6\Omega$.

In order to analyze the power system shown in Fig. 1, a mathematical model implemented in an DELPHI 6 environment was used. Developed software package based on the minimum input information (graph data and branch of graph parameters) forming in an automatic cycle of the system of equations.

Table 1

The parameters of the power and furnace transformers

Parameter	Power transformer	Furnace transformer
S_n	160 MVA	12.5 MVA
U_1/U_2	230 kV/35 kV	35 kV/0.2–0.4 kV
$u_{k\%}$	10%	11.5%
ΔP_{Fe}	450 kW	22 kW
ΔP_{Cu}	167 kW	90 kW
I_0	0.6%	0.5%

This solution enables much longer commutation breaks in circuit breakers and improves working conditions for the insulation of the EAF basic device. The technological operation involves six arcs with overlapping currents between individual electrodes. This requires estimating the power of each arc and the conditions for the transition to a continuous arc, and burning the arcs under the electrodes. These factors need to be taken into account when using EAFs of this type. In addition, the EAF energy conversion efficiency, the power factor, and the relationship between arc active power and the voltage between the electrode and charge need to be determined to help select the optimal method for regulating active power in the EAF.

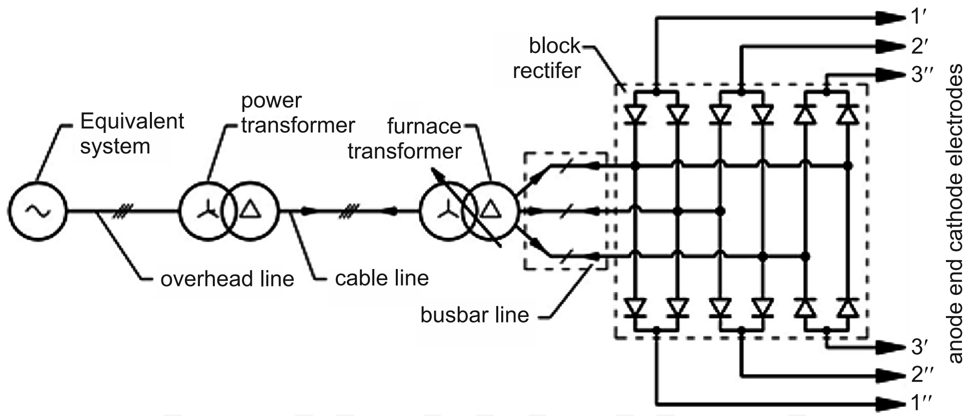

Fig. 1. Concept schematic of the power supply system for the pulse current EAF

In this case, the task involves testing the proposed six-electrode pulse current EAF, shown in Fig. 1. The testing should primarily concern steady states of the EAF in order to arrive at its operating characteristics. This will allow the effect on the power supply system and the most probable asymmetrical states to be determined from the viewpoint of the electrical power quality (higher harmonics generation [5, 6]), and will allow the conditions for continuous arc burning under electrodes to be obtained. The values of currents and voltages obtained based on model testing will help assess whether the choice of the electrical device and individual semiconductor elements is correct.

Research involved assessing the effect of a six-electrode pulse current EAF working in different states on the power supply system, it aimed to determine the distribution of the higher harmonics of current in the power network and assess the asymmetry of active power and passive power in phase wires. The obtained information will help select the methods and means of improving the quality of electrical power in the power network and improve the compatibility between the EAF and the power network.

To this end, research was proposed on the symmetrical states of EAF operation and the asymmetrical states with the greatest effect on the power network, i.e.:

– Interruption of an arc.
– Short-circuit between an electrode and charge.

– Interruption of one arc under the cathode and another arc under the anode.
– Simultaneous interruption of one arc and short-circuit between another electrode and charge.

Research on electromagnetic waveforms during an accidental change to the dynamic characteristics of an electrical arc haven't been performed. In a symmetrical state, instantaneous values of arc currents and voltages are identical (Fig. 2).

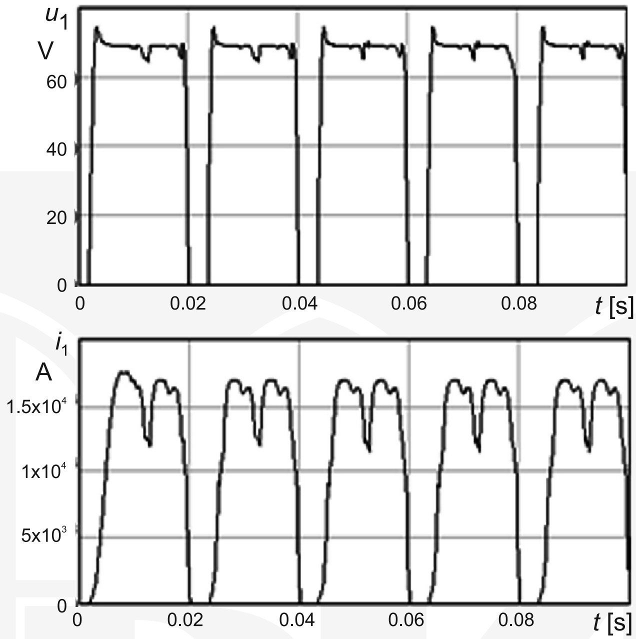

Fig. 2. Instantaneous values of arc currents (flowing through electrode 2', 1") and voltages (electrode 1") in the symmetrical state

As Figure 2 shows, each zero-current break in a single 50 Hz period lasts 3.3 μs, and the arc under each electrode last for 16.7 μs, which constitutes 83.55% of the entire period. This means that each electrode is highly efficient. The deformation of electrical arc currents and voltages depends on the *R* and *L* parameters of the power network. Once a choke is connected via a series circuit with the furnace transformer, the zero-current break shortens, and may even be eliminated completely. Figure 3 shows a graphical representation of the relationship between the zero-current break and a time constant, given by $\tau = L/R$. As can be seen in the figure, the value of the break decreases with an increase in *L*.

If the arc voltage reaches 110 V and the arc current in this state amounts to approx. 15 kA, the mean values of voltage and the current during each period amounts to approx. 75 V and 9 kA, respectively, which corresponds to 700 kW of power in each arc and to over 4 MW of total EAF power. Research showed that maximal power under each arc is 926 kW, which corresponds to approx. 6 MW of total power. If the arc voltage corresponding to maximal power increases or decreases, the power of the EAF slowly decreases.

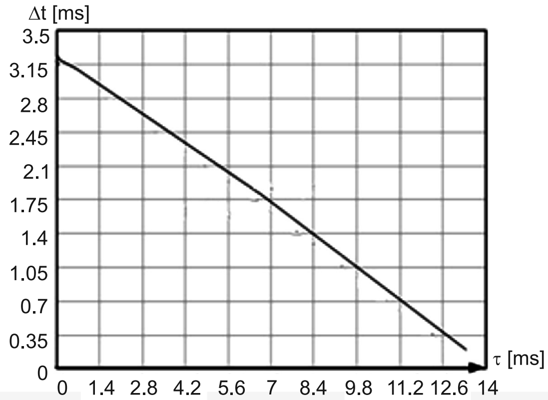

Fig. 3. Zero-current break duration as a function of the time constant

Figure 4a shows the power characteristics of an arc depending on its voltage (arc length). As can be seen in the figure, arc power depends parabolically on arc voltage. Therefore, arc electrical power can be adjusted by changing the arc length or transformer turns ratio (arc voltage), which is easily achievable in practice.

Note that in a symmetrical state, the EAF generates the fifth and seventh current harmonics into the power network. Figure 4b shows the relationship between the value of the fifth and seventh current harmonics and arc voltage. As can be seen in the figure, the value of the total harmonic distortion increases with an increase in arc voltage due to a decrease in the amplitude of the first harmonic and an increase in the amplitude of the fifth harmonic. The largest increase in the fifth current harmonic occurs when changes in arc voltage correspond to arc power of no less than 80% of maximal power. Further increase in arc voltage is accompanied by a slow increase in the relative value of the fifth harmonic and a decrease in the absolute value of the fifth harmonic. In a symetrical state the power factor of EAF falls between 0.75–0.8.

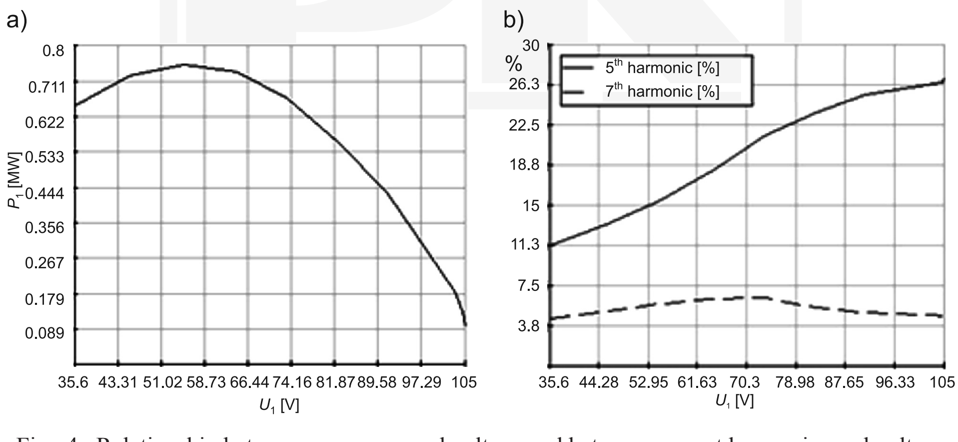

Fig. 4. Relationship between arc power and voltage and between current harmonics and voltage

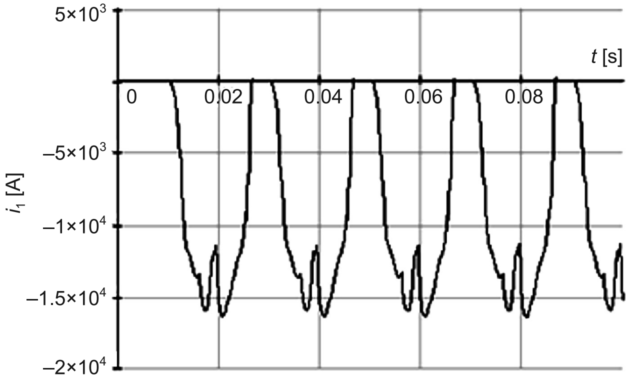

Fig. 5a. Oscillograms of currents in the case of the interrupt arc under the electrode 1' (currents of electrode 1' and 1")

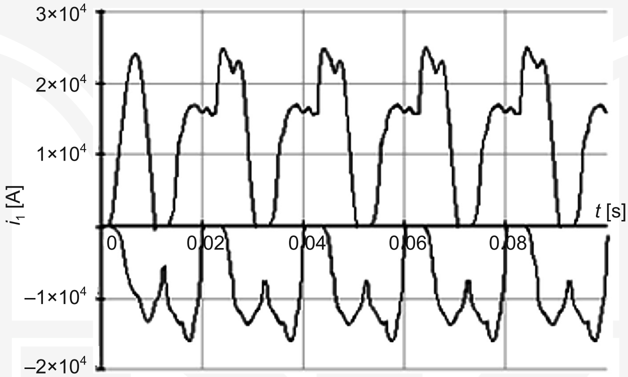

Fig. 5b. Oscillograms of currents in the case of the interrupt arc under the electrode 1' (currents of electrode 2' and 2")

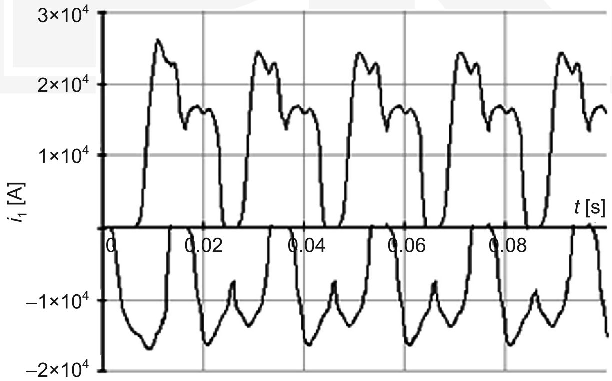

Fig. 5c. Oscillograms of currents in the case of the interrupt arc under the electrode 1' (currents of electrode 3' and 3")

If an arc is interrupted (in this case, under Electrode 1'), an asymmetric state occurs. Figure 5 shows oscillograms of currents in each electrode (in the following order: 1'/1"; 2'/2"; 3'/3") with current amplitudes in working arcs (1", 2" and 3"). The current of Electrode 1' equals zero, while current amplitudes in Electrodes 2' and 3' increase 1.7 times compared to the symmetrical state.

In this case, the voltage amplitudes of the arcs change. This affects the power of appropriate arcs, as shown in Table 2.

Table 2

Active power in each EAF arc (interrupt arc under the electrode 1')

Number of electrode	Active power [kW]
1'	0
2'	604
3'	627
1"	930
2"	601
3"	910
Total power EAF [kW]	3672

A short-circuit between an EAF electrode and charge (in this case, 1') causes the current of the electrode to nearly double compared to the symmetrical state, as shown in Fig. 6a (top). Other current amplitudes increase by 10% to 25% compared to current amplitudes during the symmetrical state.

Current harmonics in the power network in this state differ from the symmetrical state in that the second harmonic appears in addition to the fifth and seventh harmonics, albeit the fifth harmonic remains the highest. Moreover, it was noted that voltage amplitude between

Fig. 6a. Current oscillograms after a short-circuit between Electrode 1' and charge (currents of electrode 1' and 1")

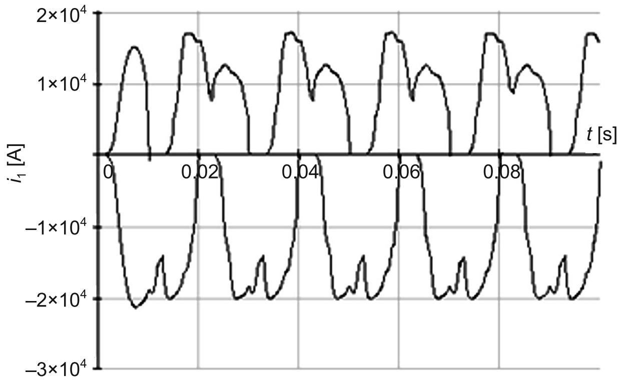

Fig. 6b. Current oscillograms after a short-circuit between Electrode 1' and charge (currents of electrode 2' and 2")

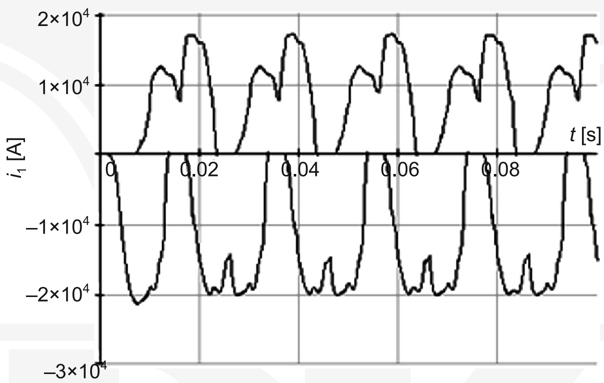

Fig. 6c. Current oscillograms after a short-circuit between Electrode 1' and charge (currents of electrode 3' and 3")

the electrode with the interrupted arc and charge increased 1.84 times, and mean value increased 1.76 times compared to the symmetrical state. Voltages under other electrodes do not change.

A short-circuit between an electrode and charge leads to considerable asymmetry in the currents of other arcs and currents in the power network. Figure 6 shows the instantaneous values of arc currents. It was noted that the circuit current of an electrode connected to a charge increased by only 2 times compared to the arc current of a given electrode in the symmetrical state when the circuit current in the three-phase EAF reaches a value 3 to 3.5 times greater than the normal value. In this case, the value of the circuit's current can be limited by arc resistance under the second electrode of the rectifier.

During a short-circuit in an EAF electrode, the apparent power input is 1.15 times lower than the apparent power input of the furnace after an arc is interrupted and amounts to 4.6 MVA, which is 1.3 times lower than in the symmetrical state. Active power and passive power decrease accordingly, and the range of changes in the apparent power of the furnace during a short-circuit between an electrode and charge falls between 1.7 MVA and 6.0 MVA. In this state, the EAF generates considerably more harmonics. The third, fourth, and sixth harmonics appear in addition to the second, fifth, and seventh harmonics, with the relative values of the fifth and seventh harmonics lower than in the symmetrical state due to an increase in the value of the first harmonic. In this case, the power factor of EAF falls between 0.45–0.6. In the other cases the power factor included in the range 0.55–0.75, depending of asymmetry type.

Table 3

Active power in each EAF arc (short circuit electrode 1' with charge material)

Number of electrode	Active power [kW]
1'	0
2'	603
3'	628
1"	931
2"	600
3"	911
Total power EAF [kW]	3673

If the arcs between an anode and charge, and between a cathode and charge are interrupted, an asymmetrical state occurs. As a result, the current amplitudes of other arcs decrease by approx. 1.5 times compared to the symmetrical state. Moreover, currents in the power network include the second, third, fourth, fifth, seventh, tenth, and eleventh harmonics, with the fifth harmonic of the phase current showing the highest value. Analysis of the instantaneous values of the currents of other arcs shows that the break interval between current pulses in individual electrodes does not change, i.e., the breaks do not depend on the states of the arcs of other rectifiers.

Table 4

Active power in each EAF arc (interruption of two arcs)

Number of electrode	Active power [kW]
1'	0
2'	772
3'	0
1"	771
2"	749
3"	748
Total power EAF [kW]	3040

The maximal voltage value under the electrode with the interrupted arc increases by 1.8 times, the mean value increases by 1.6 times, and the voltages of other arcs do not change. Because active power, passive power, and apparent power increase proportionally to the increase in the currents of other arcs, the total apparent power decreases by approx. 1.2 times compared to the symmetrical state.

Lastly, let us consider the working state of an EAF when two electrodes (one anode and one cathode, each from a different rectifier) short-circuit. In this state, the values of currents flowing through the short-circuited electrodes are 2.27 times greater than those in the symmetrical state. While the values of currents in other electrodes of the same rectifiers do not change, currents flowing through the third rectifier practically double.

Table 5 shows an overview of power values. As can be seen in the table, apparent power, and active power of the EAF decrease by two times compared to the symmetrical state. Because total passive power practically corresponds to the symmetrical state, the power factor decreases considerably, and must, therefore, be increased by compensating the reactive power.

Table 5

Active power in each EAF arc (short circuit of two arcs witch charge material)

Number of electrode	Active power [kW]
1'	0
2'	484
3'	0
1"	1002
2"	495
3"	1000
Total power EAF [kW]	2981

Figure 7 shows histograms of the total active power taken by the EAF to enable comparison between power inputs. As the figure indicates, active power depends on the work state of the EAF, while passive power remains almost constant.

Fig. 7. Active power in different arc work states

3. Conclusions

Analysis of results obtained by simulating different work states of a pulse current EAF with a furnace transformer of 12.5 MVA power leads to the following conclusions:

1. Results concerning steady states indicate that the fifth and seventh harmonics have the highest power in the power supply system, and that the share of other harmonics (third, sixth, ninth, eleventh, and thirteenth) does not exceed 1%. The amplitude of the seventh harmonic is practically independent from the arc voltage and reaches approx. 6%, while the amplitude of the fifth harmonic increases with an increase in the arc voltage and reaches 15% compared to the amplitude of the first harmonic.
2. The EAF arc power depends on the arc length and reaches its maximum voltage at which the arc resistance approaches the impedance of the EAF power supply system.
3. Interruptions in arc currents and short-circuits between electrodes and charge decrease the active power input of the EAF by 25–30% due to asymmetry between voltages and currents in the EAF power supply system. At the same time, a short-circuit between electrodes and charge increases the current in the components of the rectifier to 30%, and an interruption in the arc increases voltage on non-active semiconductors. All this should be taken into account when selecting rectifiers.
4. An increase in time constants in the arc profile decreases zero-current breaks under each electrode. This relationship is nearly linear. During operation, the time constant is adjusted by changing the arc length (arc resistance). This should be taken into account when selecting a method for automatically adjusting the position of electrodes, as it affects the power characteristics of the EAF.

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