Modeling of asymmetrical operating states of AC electric arc furnace in the power system

Marek Gała
Faculty of Electrical Engineering
Czestochowa University of Technology
SEP Association of Polish
Electrical Engineers
Częstochowa, Poland
m.gala@el.pcz.czest.pl

Antoni Sawicki
Faculty of Electrical Engineering
Czestochowa University of Technology
SEP Association of Polish
Electrical Engineers
Częstochowa, Poland
sawicki.a7@gmail.com

Kazimierz Jagieła
Faculty of Mechanical Engineering
and Computer Science
University of Bielsko-Biala
SEP Association of Polish
Electrical Engineers
SEP Honorary Member
Częstochowa, Poland
kazimierz.jagiela@gmail.com

***Abstract*— The structural and operational factors influencing the asymmetrical work of steel arc furnaces in the power system are presented. In order to map the asymmetry of network load using a system of three electric arcs, the Pentegov mathematical model with different static-voltage characteristics was used. In addition, the asymmetry of the high-current path was taken into account by increasing the phase impedances under conditions of symmetrical arcing load. The simulation method examined the effect of load asymmetry on the values of asymmetry indicators, determined on the primary and secondary side of the furnace transformer.**

***Keywords*— arc furnaces, voltage and current asymmetry, arc model, power quality**

I. INTRODUCTION

Typical analyzes of the operation state of arc furnaces use the assumption of full load symmetry of the power grid. Obtaining such a condition is possible after fulfilling several conditions. They include a stable technological stage, in which the impact of the batch material on the states of arcing is small. The uniform distribution of the charge and its even melting in the boiler of the furnace corresponds to this. In addition to the appropriate uniform loading of steel scrap into the batch basket, it should also be ensured an even thermal effect of burners, often mounted in the boiler walls. Permanent wear of graphite electrodes (due to oxidation and sublimation) requires periodic replenishment, which, despite moving the electrode holders, does not guarantee their equal length. In addition, the operation of an efficient electrode positioning system should ensure a rapid reaction of the electrode movement on the resulting disturbances of the load position and, therefore, on the different lengths of the plasma columns and thus on the arc forces. For this reason, the control and movement of graphite electrodes is separate. Despite these measures, it is very difficult to achieve full load symmetry due to the rapidly changing furnace operating conditions. Electrode movements are also accompanied by changes in the position of the cables supplying them with electricity from the furnace transformer. As a result of various effects: skin effect, mutual inductance, approximation and power transfer between phases, impedance (and current) asymmetry arises, which is very difficult to eliminate despite very developed theoretical research and construction solutions of high-current tracks [1, 2]. Asymmetry results in strong and weak phases. They cause not only an uneven distribution of currents in the supply phases, but also uneven melting of the batch material, accelerated erosion of liner wall linings, accelerated and uneven wear of graphite electrodes, prolonged process time, increased wear and uneven distribution of alloy additions in molten metal, etc. Small effects of asymmetry in three-phase furnaces can be considered typical, especially at the stage of melting the loaded cold batch. As the melting time passes, the furnace operation should be calmed down and the phase currents symmetrical. If the current asymmetry states are excessive and they do not decrease as the technological process progresses, such states may indicate improper construction of the high-current track or incorrect operation of the electrode position regulators [3, 4].

The energy effects of the asymmetric operation of the furnace are not only the asymmetry in the operation of the furnace transformer, but also the disturbances of the passive harmonic filters, reactive power compensators and other devices of the high voltage side. Electricity grid operators also allow only a limited degree of asymmetry and oblige the recipients to apply appropriate technical measures.

II. THE ELECTRIC ARC MODELS USED TO SIMULATE THE OPERATING STATES OF STEELMAKING FURNACES

In simulation tests of steel arc furnaces of alternating current, it is usually assumed that electric arcs in all phases are described by selected identical mathematical models, which are also deterministic. Such descriptions are close to reality in the activities of some well-constructed ovens, especially those working in the final stages of steel melting.

In numerical simulations of steelmaking furnaces, a set of mathematical models of the arc and its voltage-current characteristics are limited by the lower current values. Due to very high currents, the Mayr model and its various modifications are usually omitted. However, the Cassie model is relatively often used:

$$\frac{1}{g}\frac{dg}{dt}=\frac{1}{\theta_C}\left[\frac{u_{col}^2(t)}{U_C^2}-1\right] \qquad (1)$$

where:
θ_C - time constant of the Cassie model,
U_C - constant voltage value of the Cassie model.

The static characteristics of this model are flat and have the form of a function:

$$U = U_C \operatorname{sgn} I = U_C \frac{I}{|I|} \tag{2}$$

The generalized mathematical model of the arc column proposed by Pentegov and then developed along with Sidorec has a much wider possibilities of mapping electrical processes [5]. It meets the power balance equation. In this model, instead of a real arc, a hypothetical arc is considered in which the conductance of the arc column is defined as a function of the fictitious (virtual) current $i_\theta(t)$, changing with a specific time constant θ [6]. The Pentegov model reproduces a non-linear two-terminal circuit, which is: energetically balanced, thermal inertia of the first order, linear, stationary and electrically without a header:

$$\frac{i}{u} = \frac{i_\theta}{U} = g \tag{3}$$

The relationship between the square of the state current i_θ and the square of the actual arc current i describes the first order linear differential equation:

$$\theta \frac{di_\theta^2}{dt} + i_\theta^2 = i^2 \tag{4}$$

In the general case, the voltage on the arc column determines the relationship:

$$u = \frac{U(i_\theta)}{i_\theta} i \tag{5}$$

Various analytical functions are used to approximate the static-voltage characteristics [6-8]. If the circuit power is supplied by a direct or alternating current of a rectangular bipolar wave with $|i(t)| = \text{const}$, then determining the parameters of these functions is relatively easy. The use of direct or rectangular current is common in welding equipment. However, direct current has recently been used to power modern steel arc furnaces of high power DC [9]. In such cases, determining the static characteristics of the high-power arc can be relatively easy. However, in the case of devices with AC arcs, there may be very big difficulties with the selection of a DC power supply system and adequate working conditions in relation to those that occur during the implemented standard technologies.

To date, many analytical and numerical methods have been developed to determine the parameters of static characteristics based on experimental studies of dynamic arcs supplied with alternating current. This applies in particular to cases in which periodic current of a sinusoidal or rectangular shape is used [8, 10, 11]. Based on simulation studies, [12] it has been shown that developed analytical dependencies for determining the parameters of sinusoidal arc models can also be applied to real cases in which non-ideal current sources with distorted current waves are used.

If during the experimental tests a specific set of formulas for approximating the shape of the static characteristic was selected and the arc supply is carried out with sinusoidal or rectangular current, spectral or integral methods can be used to determine the parameters of $U(I)$ and time constant of the Pentegov model [11, 13] . From among the variants obtained in this way, you can choose the best approximation. The basis is the implementation of model identification, in accordance with the optimization procedure [14].

Both the Mayr and Cassie models are special cases of the Pentegov model [15, 16]. This model may contain a static-voltage quasi hyperbolic-flat static characteristic with a specific ignition voltage:

$$U_{col} = \frac{P_M I}{I^2 + I_W^2} + U_{CP} \tag{6}$$

The extreme residual conductance corresponds to the cut off I_W of the extreme point.

III. STUDY OF THE IMPACT OF ASYMMETRIC OPERATING STATES OF ARC FURNACES ON THE POWER SYSTEM

Experimental tests of arcing in steelmaking furnaces usually take place in industrial conditions. This limits the choice of characteristics of the available power source, availability of measuring points in the high-current circuit, ranges of changes in source and load parameters. Compared to AC ERF three-phase AC furnaces, testing DC steel arc furnaces (DC-EAF) is easier. The reason is easier control over the characteristics of the power electronics rectifier. In some ranges they may be similar to the characteristics of ideal current sources. Rectifiers are built and controlled as symmetrical circuits. They can bring the set amplitude level and the frequency range of disturbances to the network. Interferences are limited by special structure of circuits and properly selected operating states of rectifiers. Due to the fixed range of disturbances, it is relatively easy to filter and eliminate them. A single arc does not affect the asymmetry of the power system. In the case of AC arc furnaces, the control of the source characteristics is most often performed electromechanically and in a limited way: by means of the tap changer of the furnace transformer, the inductive hitch tap changer switch or the bypass switch additional chokes. Despite the use of special furnace transformers with increased magnetic flux dispersion and additional induction chokes, even in the narrow current ranges, the characteristics of the arcs supply system usually deviate from the characteristics of the ideal current sources. Therefore, under the influence of arcs nonlinearity, the currents waveforms may be distorted and may not be sinusoidal, which affects further distortion of voltage waveforms. Therefore, dynamically determined dynamic curves of arcs are often strongly distorted. Data obtained in available places on the network (e.g. in a transformer station) show that arches are elements capable of preserving energy, which completely contradicts the dislodging properties of arcs. In addition, differences in the physical properties of the three arcs and in the impedances of the three phases of the high-current path affect the formation of asymmetry.

Figure 1 shows the substitute diagram of the arc furnace steel (AC-EAF) feed circuit. Measurement systems have been introduced into its structure. Measurements of effective values of arc currents and voltages are most often made on the primary side of the furnace transformer. Thanks to the lower values of currents, it is easier to choose a set of measuring equipment (current transformers) and obtain greater accuracy. Then, the determination of the value of the electrical quantities of the secondary side takes place by calculation. For this purpose, approximate mathematical models of both the transformer and the high-current track are used [17]. Obtaining the dynamic characteristics of the arcs is then difficult due to the high inertia and non-linearity of both the high-current path and the furnace transformer. In connection with some renovation works (e.g. replacement of flexible cables), appropriate scaling factors are determined experimentally during short-circuits on a "dry" oven lined with steel plate. Despite these efforts, the measurements should be considered approximate, as the parameters of the components of the high-current track are affected by random cable routing, accidental distribution and composition of the steel charge, current lengths of graphite electrodes and temperature distributions on their surface. The case in which the connection of the measuring apparatus takes place on the secondary side of the furnace transformer can be considered more advantageous in recording real dynamic waveforms. The actual dynamic waveforms are captured by connecting the measuring equipment on the secondary side of the furnace transformer, using, among others, Rogowski coils to measure the instantaneous currents.

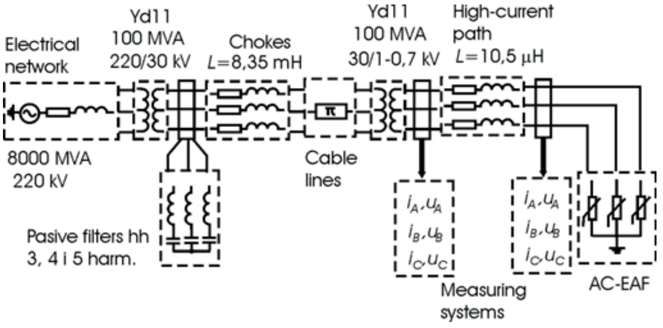

Fig. 1. Alternating circuit diagram of the AC-EAF arc supply circuits

Figure 2 shows the arc dynamic voltage and current characteristics described in the Pentegov model (4) - (6) determined in two different measurement locations. The parameters of the model were: P_{MP} = 1000 W, I_W = 50 A, $\theta = 5\cdot 10^{-4}$ s. In the first case (Fig. 2a), the voltage covers the area of the arc between the electrodes. It can be seen that the hysteresis loop is relatively narrow and passes through the origin of the coordinate system. The second case (Fig. 2b) concerns the output voltage of the furnace transformer. It includes both arc voltage and high-current path values. Compared with the previous graph, the obtained loop is characterized not only by higher values of the maximum voltage, but also by a significant widening, rounding of the vertices, and most importantly does not pass through the origin of the coordinate system. Examples of such characteristics are often presented in publications.

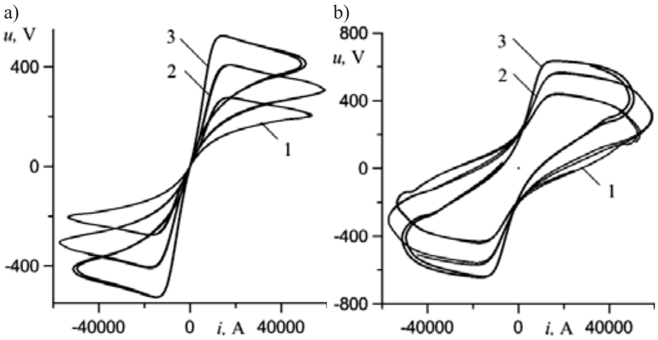

Fig. 2. Dynamic characteristics of non-linear and asymmetric network load: a) electric arc; b) furnace transformer loaded with electric arc (1 - U_C = 200 V, 2 - U_C = 300 V, 3 - U_C = 400 V)

IV. STUDY OF THE INFLUENCE OF THE ASYMMETRY OF ARC FURNACES ON THE OPERATION OF THE POWER SUPPLY SYSTEM

Evaluation of the asymmetry of three-phase systems is performed using asymmetric indicators. As an indicator describing the asymmetry of phase voltages, the following values are used:

- opposite asymmetry indicator

$$k_{u2} = \frac{|\underline{U}_2|}{|\underline{U}_1|}\cdot 100\% \tag{7}$$

- zero asymmetry indicator

$$k_{u0} = \frac{|\underline{U}_0|}{|\underline{U}_1|}\cdot 100\% \tag{8}$$

- total asymmetry indicator

$$k_u = \frac{|\underline{U}_2 + \underline{U}_0|}{|\underline{U}_1|}\cdot 100\% \tag{9}$$

where:

$\underline{U}_0$ - voltage zero sequence component;
$\underline{U}_1$ - voltage sequence order;
$\underline{U}_2$ - voltage reverse sequence component.

Similar relationships apply in the case of wire currents.

In the case of interfacial voltages, their symmetry disturbance is caused by the occurrence of the opposite symmetrical component. Then, the zero component does not occur. Therefore, only one asymmetry of line voltages is introduced:

$$k_{um} = \frac{|\underline{U}_{m2}|}{|\underline{U}_{m1}|}\cdot 100\% \tag{10}$$

where:

U_{m1}, U_{m2} - symmetrical components of voltage in the order of compliant, opposite and zero order;
k_{um} - coefficient of asymmetry of wire voltages.

In symmetry states of the system, these coefficients should decrease to zero. According to Polish standards, voltage asymmetry indices should meet the conditions of $k_{u2} \leq 2\%$, $k_{u0} \leq 2\%$, and current asymmetry indicators should not exceed 5%.

The electric arc is a strongly non-linear element of the electrical circuit. In addition, there is a relatively high level of random disturbances. Therefore, the steel plant's power systems are non-linear. In such systems, the superposition method is not used. The distribution of voltage and current waveforms to symmetrical components requires the assumption of good filtration of voltage and current waveforms in order to obtain fundamental harmonics [18]. In relation to such harmonics, numerical determination of asymmetric coefficients has been used. The results are presented in Tables 1 and 2. In the first stage of the research differences in U_C voltage values were introduced causing differences in the static and dynamic characteristics of individual arcs. Significant changes in the values of k_{u2} and k_u were observed. The asymmetry indicators calculated on the basis of the primary side voltages of the furnace transformer were significantly higher compared to the indicators concerning the secondary voltages of the power transformer. It proves, among others on the effective operation of sub-systems of the medium-voltage 30 kV network and the power network with low short-circuit impedance. At the second stage of the research, differences in the impedance values of the high-current track were introduced. Also in this case, higher voltage asymmetry indices were noted at the furnace transformer input compared to the voltage at the output of the network transformer. The lowest value was achieved by the k_{u0} asymmetry index. In addition, its value oscillated during the calculation.

TABLE I. ASYMMETRY INDICATORS OF THE PHASE VOLTAGES OF THE GRID FEEDING THE FURNACE WITH ASYMMETRICAL ELECTRIC ARCS

Voltage of the arc model			**The primary side of the furnace transformer**			**Secondary side of the network transformer**		
U_{CP1}, V	U_{CP2}, V	U_{CP3}, V	k_{u2}, %	k_{u0}, %	k_u, %	k_{u2}, %	k_{u0}, %	k_u, %
400	400	400	0.025	$5.52\cdot10^{-13}$	0.016	0.018	$1.53\cdot10^{-12}$	0.0112
300	400	400	3.524	$5.21\cdot10^{-13}$	3.533	1.234	$2.10\cdot10^{-12}$	1.253
300	300	400	3.773	$3.55\cdot10^{-13}$	3.842	3.316	$2.02\cdot10^{-12}$	1.052
300	300	300	0.057	$1.07\cdot10^{-13}$	0.042	0.017	$1.94\cdot10^{-12}$	0.017
200	400	400	7.343	$5.11\cdot10^{-13}$	7.334	2.547	$2.57\cdot10^{-12}$	2.533
200	200	400	8.682	$6.63\cdot10^{-13}$	8.685	2.801	$2.65\cdot10^{-12}$	2.801
200	300	300	4.171	$3.05\cdot10^{-13}$	4.169	1.346	$2.22\cdot10^{-12}$	1.345
200	200	300	4.561	$5.13\cdot10^{-13}$	4.557	1.419	$2.82\cdot10^{-12}$	1.423
200	200	200	0.022	$7.32\cdot10^{-13}$	0.019	0.007	$2.70\cdot10^{-12}$	0.007
200	300	400	7.391	$1{,}12\cdot10^{-12}$	7.391	2.464	$3.44\cdot10^{-12}$	2.464

TABLE II. TABLE 2. INDICATORS OF ASYMMETRY IN THE PHASE VOLTAGES OF THE GRID FEEDING THE FURNACE WITH ASYMMETRICAL LOAD IMPEDANCE OF THE HIGH-CURRENT TRACK $U_C = 300$ V)

Additional resistance of high-current track			**The primary side of the furnace transformer**			**Secondary side of the network transformer**		
R_1, Ω	R_2, Ω	R_3, Ω	k_{u2}, %	k_{u0}, %	k$_u$, %	k_{u2}, %	k_{u0}, %	k_u, %
$1\cdot10^{-3}$	0	0	1.584	$5.13\cdot10^{-13}$	1.585	0.52	$2.33\cdot10^{-12}$	0.533
$2\cdot10^{-3}$	0	0	2.975	$5.73\cdot10^{-13}$	2.974	1.013	$2.34\cdot10^{-12}$	1.014
$3\cdot10^{-3}$	0	0	4.287	$2.65\cdot10^{-13}$	4.291	1.472	$2.06\cdot10^{-12}$	1.476
0	$1\cdot10^{-3}$	$2\cdot10^{-3}$	2.522	$7.34\cdot10^{-13}$	2.531	0.867	$1.91\cdot10^{-12}$	0.869

V. SUMMARY

1. The mathematical model of the Pentegov arc allows relatively easy mapping of the load asymmetry of the arc furnaces.
2. Determining the asymmetry indicators of three-phase systems supplying steel-fired furnaces requires taking into account the deformation of time courses of voltages and currents (due to the non-linearity of arcs) and the relatively high level of interference.
3. Both differences in voltage-current curves of individual phases as well as differences in impedances of phases of high-current tracks can lead to asymmetry indicators exceeding the permissible values.
4. The use of a rigid network to power electrostatic plant and passive systems improving the quality of electricity only to a certain extent allows to reduce the impact of phase asymmetry (caused by different voltage and current characteristics of arcs and various parameters of high-current tracks) on the quality of electricity.

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