

ADVANTAGES OF CHANGING 3-PHASE ARC FURNACES ASYMMETRY ESTIMATION CRITERIA IN INTERNATIONAL AND EUROPEAN STANDARDS¹⁾

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Summary: The criteria for estimating the asymmetry of arc furnace circuit impedances, referring to the theory of symmetrical components, have been presented. In contrast to the criteria recommended as yet by IEC and CENELEC, they give homogeneous estimation of asymmetry of circuit impedances, heating powers and unbalance of arc currents. Moreover they make it possible to take into account functional dependences among them and, consequently, to improve the analysis of unbalanced operation states of EAF, as well as their balancing.

Key words:
Arc furnaces
Current unbalance
Impedance asymmetry
Power asymmetry

1. INTRODUCTION

During the processes of the recent enlargement of the European Union, National Standards were coordinated with the Standards of EU member states, particularly with IEC and CENELEC Standards. This creates a good opportunity to reflect and perhaps correct some currently valid requirements. Therefore, the authors suggest reconsidering the proposal to change the estimation criteria for 3-phase arc furnace circuit asymmetry.

The criteria proposed by the authors are based on the method of asymmetry differential-angular coefficients [1], referring to the generally applied theory of symmetrical components [7, 13]. Consequently, they enable a complex analysis of asymmetry of different supply circuit parameters (impedances, source voltages), and different parameters determining EAF unbalanced operation states (arc resistances and currents as well as heating powers). The acceptance of these criteria for estimating EAF circuit asymmetry would enable relatively simple and clear estimation of e.g. heating power asymmetry expected during furnace operation.

2. ASYMMETRY OF ARC FURNACE CIRCUIT

An arc furnace circuit has been presented in a simplified form in Figure 1. Impedances $\underline{Z}_j = R_j + jX_j$ appearing in each phase j ($j = A, B, C$) of this circuit refer to an arc supply circuit (H.V. supply system, furnace transformer and secondary heavy current line), while heating resistances r_j refer to arcs, charge and, partially, electrodes (non-linearity of arcs is omitted for simplification).

If reactances and resistances in each phase are the same, the circuit is symmetric and, consequently, phase currents and heating powers are equal in each phase. However, in real furnaces (mainly in a heavy current line) phase resistances and reactances of supply circuit are not equal, due to different clearances between phase conductors and different distances between a transformer and electrode clamps in each phase. This leads to the appearance of the asymmetry phenomenon in the circuit; phase heating resistances depend upon the position of electrodes and may be equal or not.

According to the Standards: International CEI/IEC 60676 and European EN 60676:2002, as well as Polish Standard PN-EN 60676 estimation of supply circuit asymmetry is based on the maximal difference between phase impedances, while asymmetry factor K_{as-z} is defined by the formula:

$$K_{as-z} = \frac{Z_{max} - Z_{min}}{Z} \cdot 100\% \quad (1)$$

or, respectively for reactances:

$$K_{as-x} = \frac{X_{max} - X_{min}}{X} \cdot 100\% \quad (2)$$

(asymmetry of circuit resistances was also taken into consideration in the previous version of these Standards).

According to the method of asymmetry differential-angular coefficients [1, 3, 14, 21], the value in phase j , e.g. the value of reactance X_j , may be treated as a sum of mean value X and differential values determined by differential modulus W_X (equal in each phase) and differential angle α_X ($\alpha_{XA} = \alpha_X$, $\alpha_{XB} = \alpha_X - 120^\circ$, $\alpha_{XC} = \alpha_X + 120^\circ$) according to the formula:

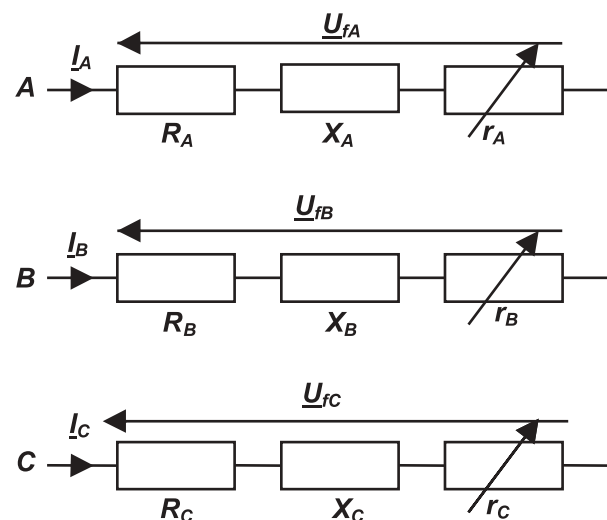


Fig. 1. Simplified circuit of 3-phase arc furnace and supply system

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$$X_j = X + W_X \cos \alpha_{Xj} \quad (3)$$

The values of W_X and α_X can be calculated from the formulas

$$W_X \cos \alpha_X = X_A - X, \quad W_X \sin \alpha_X = \frac{X_B - X_C}{\sqrt{3}} \quad (4a)$$

Additionally, the differential coefficient of reactance asymmetry $k_X = W_X/X$ can also be introduced. Similarly, we have R, W_R, k_R, α_R for circuit resistances and $r, W_r, k_r,$ and α_r for heating resistances.

The mean value of supply circuit impedances can be defined from the obvious formula

$$\underline{Z} = Z e^{j\varphi_z} = R + jX \quad (5)$$

while differential modulus D and differential angle δ defined below have been proposed for evaluation of their asymmetry

$$\underline{D} = D e^{j\delta} = W_R e^{j\alpha_R} + jW_X e^{j\alpha_X} \quad (6a)$$

In accordance with propositions of the authors [3, 19, 21] one can estimate the asymmetry of circuit supplying EAF impedances by means of asymmetry differential-angular coefficient \underline{k}_Z , treated as compound of two factors: differential coefficient k_Z ($k_Z = D/Z$) and differential angle δ :

$$\underline{k}_Z = k_Z e^{j\delta} = \frac{D}{Z} e^{j\delta} \quad (7a)$$

One can generalize this proposition also in the case of phase sequence A, C, B (apart from A, B, C). Then some corrections should be accepted: differential angle $\alpha_X'' = -\alpha_X$ instead of α_X (for each phase $\alpha_{Xj}'' = -\alpha_{Xj}$), determined from formulas:

$$W_X \cos \alpha_X'' = X_A - X; \quad W_X \sin \alpha_X'' = -\frac{X_B - X_C}{\sqrt{3}} \quad (4b)$$

(similarly $\alpha_R'' = -\alpha_R$ and $\alpha_r'' = -\alpha_r$), and consequently:

$$\underline{D}'' = D'' e^{j\delta''} = W_R e^{j\alpha_R''} + jW_X e^{j\alpha_X''} \quad (6b)$$

$$\underline{k}_Z'' = k_Z'' e^{j\delta''} = \frac{D''}{Z} e^{j\delta''} \quad (7b)$$

These parameters are closely connected with the theory of symmetrical components and they may be determined from the formulas:

$$\underline{D} = 2(\underline{Z}_A + a\underline{Z}_B + a^2\underline{Z}_C)/3 \quad (8a)$$

$$\underline{D}'' = 2(\underline{Z}_A + a^2\underline{Z}_B + a\underline{Z}_C)/3 \quad (8b)$$

In the case of ideal symmetry of supply circuit the values of asymmetry estimation criteria – both K_{as-z} (formula 1) and k_z or k_z'' (formulas 7a and 7b) equal zero; hence, they can be

treated as equivalent. However in the case of asymmetrical circuit, the criteria proposed by the authors, apart from estimation of circuit impedance asymmetry, make it possible to carry out a detailed analysis of current unbalance and heating power asymmetry generated during furnace operation.

3. FUNDAMENTAL DEPENDENCES

For the circuit presented in Figure 1 full circuit phase voltage in phase j equals:

$$\underline{U}_{jf} = I_j (\underline{Z}_j + r_j) = I_j \underline{Z}_{jf} \quad (9)$$

Expressing supply phase voltages (balanced) by means of positive sequence component U_{f1} , currents by means of positive sequence component I_1 and negative sequence component I_2 , and total phase impedances together with heating resistances, by mean value:

$$\underline{Z}_f = \underline{Z} + r \quad (10)$$

and their asymmetry (for both phase sequences) by:

$$\underline{D}_f = D_f e^{j\delta_f} = D e^{j\delta} + W_r e^{j\alpha_r} \quad (11a)$$

$$\underline{D}_f'' = D_f'' e^{j\delta_f''} = D'' e^{j\delta''} + W_r e^{-j\alpha_r} \quad (11b)$$

we obtain the following two equations from (9):

$$\underline{U}_{f1} = I_1 \underline{Z}_f + 0,5 I_2 \underline{D}_f'' \quad (12a)$$

$$0 = 0,5 I_1 \underline{D}_f + I_2 \underline{Z}_f \quad (12b)$$

From equation (12b) we obtain the relation determining current unbalance generated in the circuit:

$$\underline{k}_i = k_i e^{j\psi_i} = \frac{I_2}{I_1} = -0,5(D e^{j\delta} + W_r e^{j\alpha_r}) / (Z_f e^{j\varphi_f}) \quad (13)$$

from which it results immediately that operation with equal heating resistances in each phase provokes current unbalance defined by unbalance factor $k_i = 0,5D/Z_f$ and angle of phase shift between positive- and negative-sequence components $\psi_i = \delta - \varphi_f \pm 180^\circ$, operation with current balance requires introduction of asymmetry of heating resistances defined by $W_r = D$ and $\alpha_r = \delta \pm 180^\circ$.

Heating power in phase j is defined by:

$$P_j = I_j^2 r_j \quad (14a)$$

or, applying the proposed method:

$$P_j = P + W_p \cos \alpha_{pj} = P(1 + k_p \cos \alpha_{pj}) \quad (14b)$$

For estimation asymmetry of heating powers the authors propose a differential coefficient of asymmetry $k_p = W_p/P$, enabling evaluation of the size of power asymmetry, i.e. differences between phase heating powers and the mean value of them, and differential angle α_p determining the manner of division these differences among three phases (e.g. the greatest heating power appears in phase *A* when $\alpha_p = -60 \dots 60^\circ$) creating together differential-angular coefficient of heating power asymmetry:

$$\underline{k}_p = k_p e^{j\alpha_p} \quad (15)$$

Asymmetry of heating powers depends upon current unbalance and heating resistance asymmetry, according to the formula:

$$\underline{k}_p = \frac{I_1^2 r}{P} [2\underline{k}_i + (1 + k_i^2)\underline{k}_r + \underline{k}_i^* \underline{k}_r^*] \quad (16)$$

and their mean value:

$$P = I_1^2 r [1 + k_i^2 + k_i k_r \cos(\psi_i - \alpha_r)] \quad (17)$$

It follows from the formulas above that operation with equal heating resistances will lead to generation of heating power asymmetry defined by differential modulus $W_p = 2I_1^2 r k_i$ or differential coefficient $k_p = 2k_i/(1 + k_i^2)$ and differential angle $\alpha_p = \psi_i$. Whereas operation with current balance will be connected with heating power asymmetry defined by $W_p = I_1^2 D$ or $k_p = D/r$ and $\alpha_p = \delta + 180^\circ$.

Formulas (16), (17) and (13) make it possible also to determine operation conditions ensuring the symmetry of heating powers or, if necessary, their favourable asymmetry (e.g. to decharge preheated phase *A* it is recommended to decrease power in this phase: $P_A < P_B = P_C$, it corresponds to condition $\alpha_p = 180^\circ$). An iteration method [15, 17], has been proposed to solve this and similar problems.

4. ADVANTAGES OF THE PROPOSED CRITERIA

The proposed method for the estimation of the asymmetry of 3-phase circuit parameters is connected with the traditional method of symmetrical components, in effect, they give similar and compatible criteria for the evaluation of asymmetry of circuit impedances and heating powers and unbalance of arc currents (also asymmetry of other parameters if needed). The need for this homogeneity is confirmed by asymmetry factors in the form analogical to formulas (1) and (2), recommended in various publications, concerning phase inductances [11], heating powers [4, 5, 6, 7, 8, 9], RMS values of arc currents and voltages [6], and even the values of network voltages [12].

The essential advantage of the acceptance of the new criteria would be obtaining functional dependences among parameters defining circuit impedance, heating resistance and power asymmetry and current unbalance – see formulas (16) and (13). In effect, the furnace user can quickly perform a preliminary analysis of furnace unbalanced operation states in a more simple and clear way than it is possible using previous criteria.

The apparatus for measurements and control as well as computerized control systems used in steelworks provide all the necessary metrological information and no new additional measurements are necessary [2].

The proposed criteria and iteration method may be easily adapted for the estimation of operation conditions ensuring e.g.

- dynamic symmetrisation of refractory wear (indexes of Schwabe) – experimentally verified by thermographic measurements on the 50-ton furnace [20],
- maximisation of heating powers or minimisation of unit losses [17, 18],
- choice of phase transformation ratios of Yd11 transformer supplying carbide furnace for the purpose of heating powers symmetrisation [14, 22], (importance of such subjects can be confirmed by the Thesis [10] presented recently in Germany), or supply network currents balancing [14, 16].

5. CONCLUSION

It seems that a convincing argument for the acceptance of the proposed criteria for the estimation of supply circuit impedance asymmetry of 3-phase EAF is their connection, by functional relations, with parameters defining current unbalance and heating power and resistance asymmetry (if necessary, also voltage unbalance or asymmetry of other convenient parameters), so they would be more useful indeed for arc furnace users, than the criteria currently recommended in International, European and National Standards.

An additional argument is a possibility to extend these criteria on other 3-phase receivers and arrangements – for instance they make considerably easier the choice of transformation ratios in each phase of a transformer supplying asymmetrical 3-phase receivers in order to decrease voltage unbalance in power supply systems (EMC problems) [16].

6. LIST OF SYMBOLS

a	120° turn operator
A, B, C	phases of furnace
D, D''	differential modulus of supply circuit phase impedance asymmetry (phase sequence <i>ABC</i> or <i>ACB</i>)
D_f, D_f''	differential modulus of full circuit phase impedance asymmetry (phase sequence <i>ABC</i> or <i>ACB</i>)
I_j	current of any phase ($j = A, B, C$)
I_1, I_2	positive and negative sequence components of currents
j	quadrature operator
k_i	unbalance coefficient of currents
k_p	differential coefficient of heating power asymmetry
k_r, k_R, k_X	differential coefficient of heating resistance and of supply circuit resistance and reactance asymmetry
k_z, k_z''	differential coefficient of supply circuit impedance asymmetry (phase sequence <i>ABC</i> or <i>ACB</i>)

K_{as-z}, K_{as-x}	asymmetry factor of supply circuit impedances and reactances
P_j, P	heating power in any phase j and their mean value
r_j, r	heating resistance in any phase j and their mean value
R_j, R	supply circuit resistance in any phase j and their mean value
U_{ff}	phase voltage of any phase j
U_{f1}	positive sequence component of phase voltages
W_P	differential modulus of heating power asymmetry
W_r, W_R, W_X	differential modulus of heating resistance and of supply circuit resistance and reactance asymmetry
X_j, X	supply circuit reactance of any phase j and their mean value
X_{max}, X_{min}	maximal and minimal value of supply circuit reactances
Z	mean value of supply circuit impedances
Z_{ff}, Z_f	impedances of full circuit in any phase j and their mean value
Z_{max}, Z_{min}	maximal and minimal value of supply circuit impedances
α_P	differential angle of heating power asymmetry
$\alpha_r, \alpha_R, \alpha_X$	differential angle of heating resistance and of supply circuit resistance and reactance asymmetry
δ, δ''	differential angle of supply circuit impedance asymmetry (phase sequence ABC or ACB)
δ_f, δ_f''	differential angle of full circuit impedance asymmetry (phase sequence ABC or ACB)
ψ_i	angle of phase shift between positive and negative sequence components of currents
$-, *$	(under symbol) complex value, complex conjugate value.

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