2018 IEEE Int. Conference on Environment and Electrical Engineering, EEEIC, Palermo, Sicily

Considerations on Direct Balancing of Ultra-High Power Ac Arc Furnaces in Uneasy State

Leszek S. Czarnecki, Ikenna L. Ezeonwumelu
School of Electrical Engineering and Computer Science, Louisiana State University,
Baton Rouge, USA
lsczar@cox.net, www.lsczar.info; iezeon1@lsu.edu

Abstract **- The paper presents some observations and opinions for a discussion on a possibility of balancing ultra-high power ac arc furnace directly at the furnace terminals, i.e., on the secondary side of the furnace transformer. The negative effects of the furnace unbalance reveal themselves, first of all, in the furnace transformer. Therefore, balancing the furnace directly on its terminals could be beneficial for the transformer performance and, first of all, for reduction of the energy loss. Some technical issues have to be solved and several theoretical questions need to be clarified for that. Some of them are discussed in this paper.**

Key words **– compensation, unbalanced current, power factor, asymmetry, Current's Physical Components, CPC.**

I. INTRODUCTION

Due to random ignition of arcs, ac arc furnaces are powerful sources asymmetry in distribution systems, in particular in the first, boring and melting phases of the arc operation, when the furnace charge is on a continuous move, meaning, the furnace is an uneasy mode. It applies, in particular, to ultra-high power arc furnaces, with power that reaches now the level of 750MVA. A simplified structure of an ac arc furnace, along with the furnace transformer, is shown in Fig. 1.

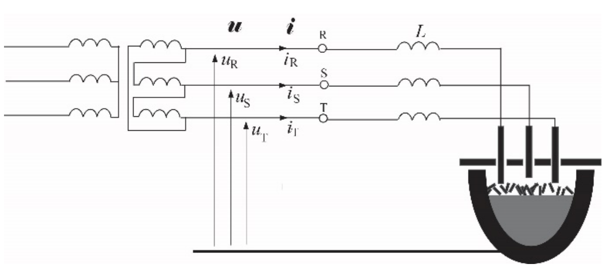

Fig. 1. A structure of an ac arc furnace with a transformer.

Apart from negative effects of asymmetry, a furnace in an unbalanced state draws not only the active and reactive currents but also an unbalanced current, which causes energy loss at delivery, thus it contributes to an increase in the bill for the energy needed for the furnace operation. Taking into account that the annual bill for the energy of ultra-high power arc furnaces, i.e., of the order of power 750MVA, could be at the level of $500 million, the cost of energy dissipated in the furnace transformer could be significant.

Compensators needed for the power factor of arc furnaces improvement are commonly [1] – [4] installed on the primary side of the furnace transformer. It means, they operate at a higher voltage, but a lower current. The reactive and unbalanced currents of the furnace cause the energy loss mainly in the furnace transformer, however. To reduce this loss of energy, a compensator installed on the secondary side of the furnace transformer is needed. It should be taken into account, moreover, that arc furnaces of the ultra-high power are supplied from transformers or relatively low power as compared to the furnace power. Consequently, their windings resistance is relatively high, meaning, also high is the energy loss in transformer's windings.

An arc furnace in an uneasy state of operation stands for a load with fast varying parameters. A balancing compensator of such a load has to have an adaptive property. It can be built of thyristor switched inductors (TSI). The possibility of using thyristors for the arc furnace balancing depends on their switching power, however. When this power was low, adaptive balancing with TSI was not possible. Now, when a single thyristor can switch currents of the rms value above 50 kA, it seems that the main technological obstacle can be overcome.

The furnace imbalance is caused by different reasons and demonstrates itself in different ways. It could be mechanical and electrical asymmetry of electrodes and the furnace charge, but first of all, the imbalance is caused by the arcs random extinction. The arc can operate with only two arcs ignited or even with unidirectional arcs. In effect of this, the furnace can operate in different states. They are unpredictable and of random duration. Some of them can be regarded as steady-state, some as transient.

This raises a number of issues as to balancing goals and even its possibility. They should be clarified before any attempt of implementation of TSI for arc furnace direct adaptive balancing. This paper presents some results and opinions drawn from modeling a reduced power furnace, regarded as a reference furnace, with a reactive balancing compensator, but with fixed parameters, installed directly at the furnace terminals.

The compensator is synthesized, and its performance is evaluated using the Currents' Physical Components (CPC) – based power theory [8]-[12], This theory is currently the only one which provides fundamentals for compensator synthesis.

Description of EAF in power terms is discussed in [6], [7].

II. A Reference Ac Arc Furnace

The line reactance L, shown in Fig. 1, is commonly selected by the furnace operator to keep the power factor (PF) at the level of 0.71, meaning, the reactive power Q is kept on a level of the active power P of the furnace.

The electric arc is a nonlinear phenomenon and there are several different simplified physical models [5] of it. Its selection has a secondary importance from the point of view of this paper. Therefore, a relatively simple model, discussed in [5], is adopted here. It is assumed that the voltage on the arc has a constant value U_0. It is shown in Fig. 2.

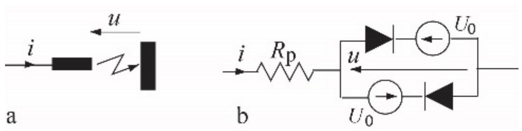

Fig. 2. A circuit (b) that approximates the arc (a).

The symbol R_p in this model stands for the arc plasma resistance. The dc voltage on the arc U_0 and the arc plasma resistance R_p, depend on the arc length and its geometry, are slowly varying parameters. It can be assumed that in short intervals of time, comparable with the period T, both R_p and U_0 are constant.

From the electrical system perspective, ac arc furnaces differ mainly as to power, furnace supply voltage rms value and the furnace transformer. The furnace supply voltage rms value can be in a range of 400 V to 1300 V. The furnace transformers could have a power comparable to the furnace power or a few times higher.

The studies in this paper are not on a specific arc furnace. They are carried with an intention that conclusions obtained would apply to the arc furnaces of ultra-high power. At the same time, it is much more convenient to analyze relatively low power furnace, regarded as a ***reference furnace,*** and recalculate the obtained results to a specific furnace.

It is assumed in this paper that a reference arc furnace, as shown in Fig. 3,

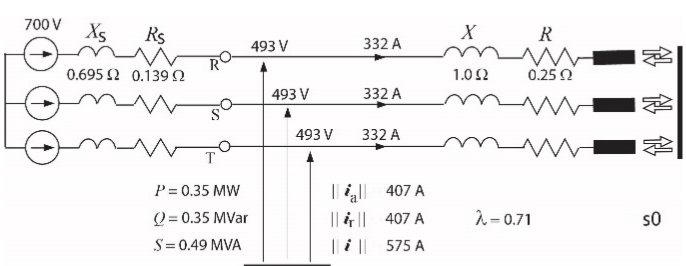

Fig. 3. The results of modeling of a furnace which operates at the power factor $\lambda = 0.71$ in state s0.

has the line resistance, including the resistance of the arc plasma and the melted steel, equal to $R = 0.25\Omega$, the line reactance equal to $\omega_1 L = 1\Omega$, and it is supplied with the voltage of rms value $U = 700$ V, from a transformer of the power ratings $S_s = 0.69$ MVA. The reactance-to-resistance ratio of the transformer was assumed to be $X_s/R_s = 5$. It is also assumed that the dc voltage on the arc is $U_0 = 300$V.

The results of modeling, shown in Fig. 3, apply to a furnace which operates at the power factor $\lambda = 0.71$, The state s0 denotes a balanced state of the furnace. The waveforms of the voltage at R terminal and the line R current are shown in Fig. 4. The current distortion at such a state is $\delta_c = 1.9\%$. Observe, that the furnace voltage u_R is substantially distorted. This is caused by the low power of the furnace transformer.

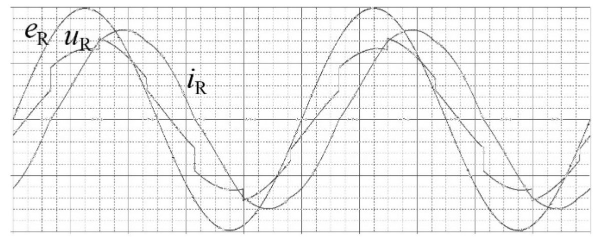

Fig. 4. Waveforms of voltages and line R current at balanced furnace operation.

As long as the supply voltage rms value $E = 700$V and the ratio of the transformer and the furnace power, S_s/S, remain unchanged, the reference furnace currents rms values can be recalculated to any furnace of the power S, multiplying the furnace current rms value be the scaling coefficient $a = S/0.49$. For example, for $S = 750$ MVA, this scaling coefficient is equal to $a = 1531$. At a different supply voltage rms value E, the scaling coefficient $a = S/0.49\text{x}700/E$ provides only an approximate value of the furnace currents because the arc is nonlinear, however.

III. Power Properties Of Ac Arc Furnaces

Arc furnaces of the ultra-high power are often supplied from dedicated power plants or dedicated transmission lines with sinusoidal and symmetrical voltage. Consequently, as compared to the waveform distortion and asymmetry produced by the furnace itself, it can be assumed that it is supplied with a sinusoidal and symmetrical voltage.

Therefore, ultra-high power arc furnace can be classified as an unbalanced Harmonics Generating Loads (HGL) supplied with a sinusoidal and symmetrical voltage by a three-wire line. At such an assumption, the vector of the arc furnace supply current

$$\boldsymbol{i} = [i_R, i_S, i_T]^T = \sum_{n=0}^{\infty} \boldsymbol{i}_n \approx \begin{bmatrix} I_{R0} \\ I_{S0} \\ I_{T0} \end{bmatrix} + \sqrt{2}\text{Re}\sum_{n\in N} \begin{bmatrix} \boldsymbol{I}_{Rn} \\ \boldsymbol{I}_{Sn} \\ \boldsymbol{I}_{Tn} \end{bmatrix} e^{jn\omega_1 t} =$$

$$= \boldsymbol{I}_0 + \sqrt{2}\text{Re}\sum_{n\in N} \boldsymbol{I}_n e^{jn\omega_1 t} \tag{1}$$

can be decomposed into four Currents' Physical Components (CPC) [8], [10], namely

$$\boldsymbol{i} = \boldsymbol{i}_1 + \boldsymbol{i}_G = \boldsymbol{i}_{a1} + \boldsymbol{i}_{r1} + \boldsymbol{i}_{u1} + \boldsymbol{i}_G\,. \tag{2}$$

Symbol N in (1) denotes the set of the current harmonics orders n, including the fundamental harmonic, $n = 1$. Symbols $\boldsymbol{i}_{a1}$, $\boldsymbol{i}_{r1}$ and $\boldsymbol{i}_{u1}$ denote the active, reactive and the unbalanced currents of the fundamental frequency, while $\boldsymbol{i}_G$ is the vector of all higher order current harmonics generated in the furnace.

Due to the furnace currents asymmetry and harmonics, the furnace voltage is asymmetrical and distorted. Its vector $\boldsymbol{u}$ can be presented in the form.

$$\boldsymbol{u} = [u_{\mathrm{R}}, u_{\mathrm{S}}, u_{\mathrm{T}}]^{\mathrm{T}} = \sum_{n=0}^{\infty} \boldsymbol{u}_n \approx \begin{bmatrix} U_{\mathrm{R0}} \\ U_{\mathrm{S0}} \\ U_{\mathrm{T0}} \end{bmatrix} + \sqrt{2}\mathrm{Re}\sum_{n\in N} \begin{bmatrix} \boldsymbol{U}_{\mathrm{R}n} \\ \boldsymbol{U}_{\mathrm{S}n} \\ \boldsymbol{U}_{\mathrm{T}n} \end{bmatrix} e^{jn\omega_1 t} = U_0 + \sqrt{2}\mathrm{Re}\sum_{n\in N} U_n e^{jn\omega_1 t}. \tag{3}$$

The distorted component of the voltage, as a response to the furnace current harmonics, can be separated from the furnace voltage, so that it can be decomposed to

$$\boldsymbol{u} = \boldsymbol{u}_1 + \boldsymbol{u}_{\mathrm{G}} \tag{4}$$

where $\boldsymbol{u}_1$ is the fundamental component of this voltage. It is asymmetrical so that it can be decomposed into components of the positive and negative sequences, namely

$$\boldsymbol{u} = \boldsymbol{u}_1^{\mathrm{p}} + \boldsymbol{u}_1^{\mathrm{n}} + \boldsymbol{u}_{\mathrm{G}}\,. \tag{5}$$

In this decomposition

$$\boldsymbol{u}_1^{\mathrm{p}} = \begin{bmatrix} u_{\mathrm{R1}}^{\mathrm{p}} \\ u_{\mathrm{S1}}^{\mathrm{p}} \\ u_{\mathrm{T1}}^{\mathrm{p}} \end{bmatrix} = \sqrt{2}\mathrm{Re}\begin{bmatrix} 1 \\ \alpha^* \\ \alpha \end{bmatrix} \boldsymbol{U}_1^{\mathrm{p}}\, e^{j\omega_1 t} = \sqrt{2}\mathrm{Re}\{1^{\mathrm{p}}\boldsymbol{U}_1^{\mathrm{p}} e^{j\omega_1 t}\} \tag{6}$$

where

$$\boldsymbol{U}_1^{\mathrm{p}} = \frac{1}{3}[1, \alpha, \alpha^*] \begin{bmatrix} \boldsymbol{U}_{\mathrm{R1}} \\ \boldsymbol{U}_{\mathrm{S1}} \\ \boldsymbol{U}_{\mathrm{T1}} \end{bmatrix}, \quad \alpha = 1e^{j2\pi/3}. \tag{7}$$

For describing power properties of a load with the voltage and current vectors decomposed, as shown above, the concept of a scalar product and mutual orthogonality is needed.

The scalar product of three-phase vectors is defined as

$$(\boldsymbol{x}, \boldsymbol{y}) = \frac{1}{T}\int_0^T \boldsymbol{x}^{\mathrm{T}}(t)\, \boldsymbol{y}(t)\, dt\,. \tag{8}$$

A three-phase rms value $\|.\|$ of three-phase vectors $\boldsymbol{x}$ and $\boldsymbol{y}$ satisfies the relationship

$$\|\boldsymbol{x} + \boldsymbol{y}\|^2 = \|\boldsymbol{x}\|^2 + \|\boldsymbol{y}\|^2 \tag{9}$$

on the condition that they are mutually orthogonal, i.e., their scalar product $(\boldsymbol{x}, \boldsymbol{y})$ is equal to zero. It can be checked that vectors of quantities shifted by $\pi/2$, such as the active and reactive currents, and three-phase quantities of a different sequence are mutually orthogonal. Taking this into account, the active power of the fundamental harmonic at the furnace terminals P_1 can be expressed as

$$P_1 = \frac{1}{T}\int_0^T \boldsymbol{u}_1^{\mathrm{T}}\, \boldsymbol{i}_1\, dt = \frac{1}{T}\int_0^T (\boldsymbol{u}_1^{\mathrm{p}} + \boldsymbol{u}_1^{\mathrm{n}})^{\mathrm{T}} (\boldsymbol{i}_{\mathrm{a1}} + \boldsymbol{i}_{\mathrm{r1}} + \boldsymbol{i}_{\mathrm{u1}})\, dt = \frac{1}{T}\int_0^T \boldsymbol{u}_1^{\mathrm{pT}} \boldsymbol{i}_{\mathrm{a1}} dt + \frac{1}{T}\int_0^T \boldsymbol{u}_1^{\mathrm{nT}} \boldsymbol{i}_{\mathrm{u1}}\, dt = P_1^{\mathrm{p}} + P_1^{\mathrm{n}}. \tag{10}$$

The active power of the voltage and current fundamental harmonic positive sequence can be calculated as

$$P_1^{\mathrm{p}} = \frac{1}{T}\int_0^T \boldsymbol{u}_1^{\mathrm{pT}} \boldsymbol{i}_{\mathrm{a1}} dt = 3\mathrm{Re}\{\boldsymbol{U}_1^{\mathrm{p}}\, \boldsymbol{I}_1^{\mathrm{p}*}\} = 3U_1^{\mathrm{p}}\, I_1^{\mathrm{p}} \cos\varphi_1^{\mathrm{p}}. \tag{11}$$

The reactive power of the fundamental harmonic of the positive sequence can be defined as

$$Q_1^{\mathrm{p}} = 3\mathrm{Im}\{\boldsymbol{U}_1^{\mathrm{p}}\, \boldsymbol{I}_1^{\mathrm{p}*}\} = 3U_1^{\mathrm{p}}\, I_1^{\mathrm{p}} \sin\varphi_1^{\mathrm{p}}. \tag{12}$$

Having these two powers, the active and reactive currents of the fundamental harmonic is defined as

$$\boldsymbol{i}_{\mathrm{a1}} = G_{\mathrm{e1}}\, \boldsymbol{u}_1^{\mathrm{p}} = \sqrt{2}\mathrm{Re}\{G_{\mathrm{e1}}\, 1^{\mathrm{p}} \boldsymbol{U}_1^{\mathrm{p}} e^{j\omega_1 t}\} \tag{13}$$

with

$$G_{\mathrm{e1}} = \frac{P_1^{\mathrm{p}}}{\|\boldsymbol{u}_1^{\mathrm{p}}\|^2} \tag{14}$$

is the fundamental harmonic of the active current or the ***working active current*** [12]. The current component

$$\boldsymbol{i}_{\mathrm{r1}} = \sqrt{2}\mathrm{Re}\{\, jB_{\mathrm{e1}}\, 1^{\mathrm{p}} \boldsymbol{U}_1^{\mathrm{p}}\, e^{j\omega_1 t}\} \tag{15}$$

with

$$B_{\mathrm{e1}} = -\frac{Q_1^{\mathrm{p}}}{\|\boldsymbol{u}_1^{\mathrm{p}}\|^2} \tag{16}$$

is the ***reactive current***, and

$$\boldsymbol{i}_{\mathrm{u1}} = \sqrt{2}\mathrm{Re}\{\boldsymbol{Y}_{\mathrm{u1}}\, 1^{\mathrm{n}} \boldsymbol{U}_1^{\mathrm{p}}\, e^{j\omega_1 t}\} \tag{17}$$

with

$$1^{\mathrm{n}} = \begin{bmatrix} 1 \\ \alpha \\ \alpha^* \end{bmatrix} \tag{18}$$

is the ***unbalanced current*** of the furnace. The symbol $\boldsymbol{Y}_{1\mathrm{u}}$ in formula (17) stands for an unbalanced admittance of the furnace for the fundamental harmonic. This admittance can be calculated [13] having known the values of the line-to-line equivalent admittances of the furnace for the fundamental harmonic, $\boldsymbol{Y}_{\mathrm{RS1}}$, $\boldsymbol{Y}_{\mathrm{ST1}}$ and $\boldsymbol{Y}_{\mathrm{TS1}}$, shown in Fig. 5.

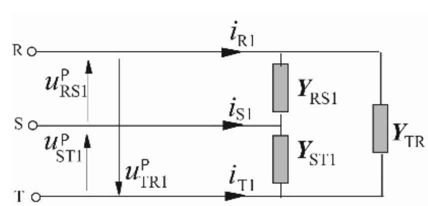

Fig. 5. A general structure of an equivalent circuit of the arc furnace for the fundamental harmonic.

With these admittances

$$\boldsymbol{Y}_{\mathrm{u1}} = -(\boldsymbol{Y}_{\mathrm{ST1}} + \alpha\boldsymbol{Y}_{\mathrm{TR1}} + \alpha^*\boldsymbol{Y}_{\mathrm{RS1}}). \tag{19}$$

Unbalanced loads have an infinite number of such equivalent circuits, as shown in Fig. 5, so that one of these three admittances can have any value, in particular, zero. Assuming that $Y_{\mathrm{RS1}} = 0$, i.e., the equivalent circuit has the structure shown in Fig. 6,

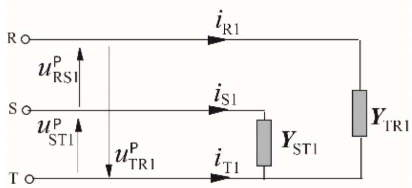

Fig. 6. A specific structure of an equivalent circuit of the arc furnace for the fundamental harmonic.

with

$$Y_{TR1} = \frac{I_{R1}}{U^{p}_{R1} - U^{p}_{T1}} \tag{20}$$

$$Y_{ST1} = \frac{I_{S1}}{U^{p}_{S1} - U^{p}_{T1}} \tag{21}$$

the furnace equivalent admittance is equal to

$$Y_{u1} = -(Y_{ST1} + \alpha Y_{TR1}). \tag{22}$$

The last current component in decomposition (2)

$$\boldsymbol{i}_{G} = \sum_{n \in N_h} \boldsymbol{i}_n \tag{23}$$

is the ***load generated harmonic current***. The symbol N_h denotes the set of all orders harmonics of the furnace supply current, including the dc component, but without the fundamental one.

The three-phase rms values of the current components in decomposition (2) are

$$||\boldsymbol{i}_{a1}|| = G_{e1} ||\boldsymbol{u}^{p}_{1}|| \tag{24}$$

$$||\boldsymbol{i}_{r1}|| = |B_{e1}| \, ||\boldsymbol{u}^{p}_{1}|| \tag{25}$$

$$||\boldsymbol{i}_{u1}|| = Y_{u1} \, ||\boldsymbol{u}^{p}_{1}|| \tag{26}$$

$$||\boldsymbol{i}_{G}|| = \sqrt{\sum_{n \in N_h} ||\boldsymbol{i}_n||^2}. \tag{27}$$

Currents' Physical Components in (2) are mutually [8, 10] orthogonal and consequently, their three-phase rms values satisfy the relationship

$$||\boldsymbol{i}||^2 = ||\boldsymbol{i}_{a1}||^2 + ||\boldsymbol{i}_{r1}||^2 + ||\boldsymbol{i}_{u1}||^2 + ||\boldsymbol{i}_{G}||^2. \tag{28}$$

The power factor is commonly defined as $\lambda = P/S$. In the presence of the load generated current $\boldsymbol{i}_G$, only the active power of the fundamental harmonic of the positive sequence contributes to the energy transfer from the supply source to the load. Therefore, the effectiveness of this transfer is better characterized by the power factor defined as

$$\lambda = \frac{P^{p}_{1}}{S}. \tag{29}$$

Harmonic distortion of the three-phase current vector is specified in this paper as the ratio of three-phase rms values of harmonic current $\boldsymbol{i}_h$ and the current fundamental harmonic $\boldsymbol{i}_1$, namely

$$\delta_c = \frac{||\boldsymbol{i}_h||}{||\boldsymbol{i}_1||}. \tag{30}$$

Observe that distortion coefficient δ_c is defined in such a way that it characterizes distortion of the whole three-phase current vector, but not individual line currents. It applies to three-phase load regarded as a unit, but not as three single-phase units.

IV. Furnace In Unbalanced States

The position of the furnace electrodes and arc currents are controlled individually, which can cause some level of the furnace electric imbalance. However, the main cause of a substantial imbalance of the furnace could be an extinction of one of three arcs, due to the furnace charge movement. When an electrode is too far from the charge then the arc cannot be ignited (state s1), or it is ignited but only in one direction (state s2). Such situations occur mainly in the uneasy mode of the furnace operation.

Let us suppose that the arc not ignited or ignited in only one direction is in the line S. The results of modeling the arc furnace in state s1, with parameters as shown in Fig. 3, are shown in Fig. 7 and Fig. 8, respectively.

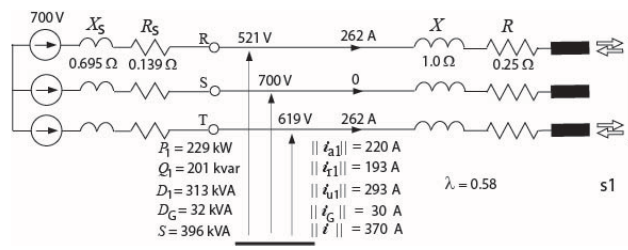

Fig. 7. The results of modeling of a reference arc furnace in state s1.

Let us observe that the unbalanced current $\boldsymbol{i}_{u1}$ is the dominating current component of the furnace current. It is even much higher than the active and reactive currents $\boldsymbol{i}_{a1}$ and $\boldsymbol{i}_{r1}$.

The line currents are distorted by odd-order harmonics with dominating the 3rd one. It can occur in the supply lines because of line currents asymmetry. Harmonic distortion of the line currents at such state amounts for the reference arc furnace to $\delta_c = 8.0\%$.

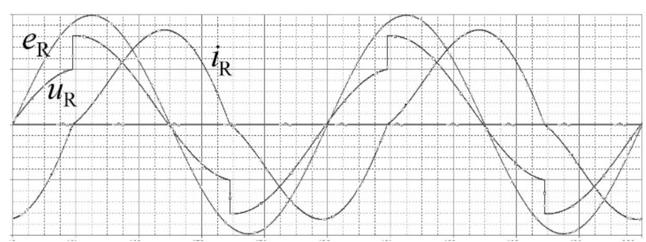

Fig. 8. Waveforms of voltages and line R current in state s1.

A presence of a unidirectional arc (state s2) in the furnace is not well documented in the literature of the subject. We can conclude a presence of such a state, indirectly, from the presence of the even order harmonics in the furnace current, first of all, the second order harmonic in the furnace current. Such order current harmonics should not occur either in state s0 nor in state s1.

The results of modeling the reference furnace in state s2 are shown in Figs. 9 and in Fig.10.

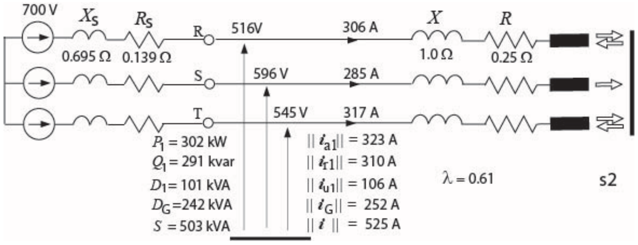

Fig. 9. The results of modeling of arc furnace in state s2.

It is worth to observe that the furnace generated current $\boldsymbol{i}_G$ has the three-phase rms value $||\boldsymbol{i}_G||$ comparable with the active and the reactive currents.

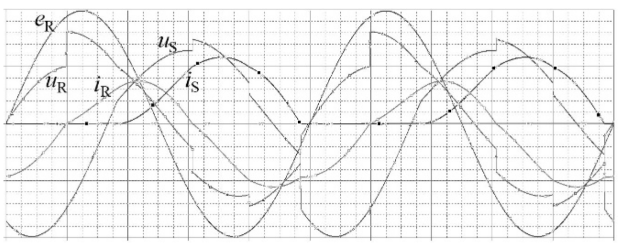

Fig. 10. Waveforms of voltages and lines R and S currents at the furnace operation with the unidirectional arc.

Distortion coefficient of the furnace current is on the level of δ_c = 55%. The dc component and the second order harmonic contribute mainly to this distortion.

V. Reactive Current Compensation

The supply current of a furnace contains a reactive component due to inductors in supply lines installed for keeping arcs stability. The value of these inductors is selected such that the reactive power is comparable with the active power. Consequently, the furnace operates in its steady state (s0) approximately at the PF of λ = 0.7. Thus, to reduce the furnace supply current, compensation of the reactive current is needed.

Compensation of the reactive current can be achieved along with filtering by resonant harmonic filters (RHFs). Technology and effectiveness of RHFs is a separate issue, and therefore, let us assume tentatively that compensation of the reactive current is separated from harmonics reduction, namely, it is done by a capacitor bank. It was assumed that it is connected in Δ structure as shown in Fig. 11.

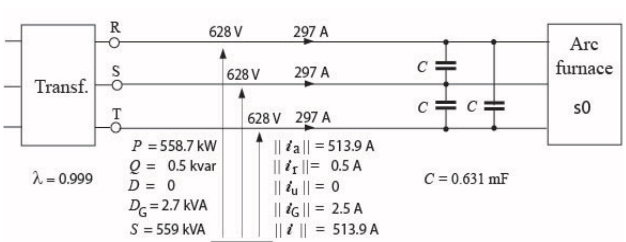

Fig. 11. The results of modeling of reference furnace in state s0.

Compensation of reactive current changes the voltage at the furnace terminals. Consequently, this changes the capacitance

C of the bank needed for reactive current compensation. The furnace is nonlinear, thus the value of this capacitance cannot be found analytically. An iterative process is needed for that.

At the assumption that the reactive current is compensated entirely, this process resulted in *C* = 0.631mF. It was assumed that capacitors of the bank are connected between lines. To ground capacitors, they should be connected in Y.

The found capacitance *C* could be directly the capacitance of the bank, but also this could be the equivalent capacitance of RHF for the fundamental frequency. It will not affect the furnace performance at the fundamental frequency.

The results of modeling the arc furnace in state s0, with totally compensated reactive current are shown in Fig. 11. The furnace operates at almost unity power factor, with the current distortion on the level δ_c = 0.5%.

The state s0 is the main state of a furnace operation and the furnace should be compensated in this state permanently and in the most economically justified way. Maybe, the capacitance found above is not the economically optimum value, nonetheless, let us assume that the furnace is compensated permanently by a capacitor bank which compensates the furnace in the state s0 to unity PF.

When one of the furnace arcs is not ignited, i.e., it operates in the state s1, the furnace becomes overcompensated. Power quantities change to values shown in Fig. 12.

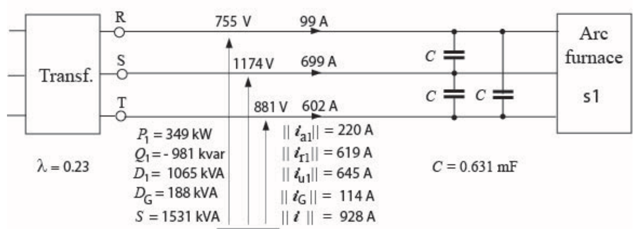

Fig. 12. The results of modeling of reference furnace in state s1.

As it can be seen from Fig. 12, an arc extinction of entirely compensated furnace causes a dramatic increase of the reactive current and the PF decline to λ = 0.23. The unbalanced current occurs to be even higher than the reactive current. A resonance of the capacitor bank with the transformer inductance is responsible for such an increase in the furnace current. A substantial increase of the voltage at the furnace terminals occurs because of that.

The same is observed at the unidirectional arc, i.e., in state s2, as shown in Fig. 13, although to a lower degree.

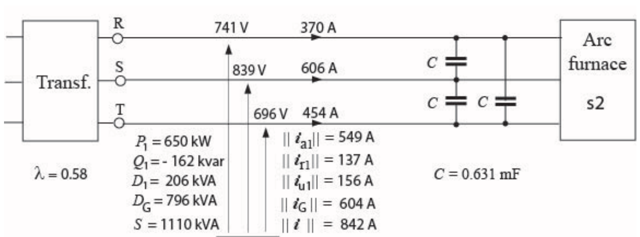

Fig. 13. The results of modeling of reference furnace in state s2.

At fixed furnace transformer *parameters*, meaning fixed its stray inductance, this response of the system to an arc extinction can be reduced by reduction of the compensator capacitance C. It means, however, that the furnace in the basic state, s0, would not be compensated to a unity power factor.

Use of thyristor switch inductors (TSI), which can change compensator parameters in time of one period T, could be another solution of the problem.

VI. Unbalanced Current Compensation

Thyristor-switched inductors, connected in parallel with a capacitor, as shown in Fig. 14a, are nonlinear, harmonic generating one-ports. They can be approximated in a working point specified by the supply voltage $u(t)$, by a linear branch of a susceptance T_1 for the fundamental harmonic, and a current source of the current $j(t)$, as shown in Fig. 14b. The susceptance T_1 can be controlled by changing the firing angle of thyristor in a range from T_{min} to T_{max}, as shown in Fig 14c. These two values depend on the selection of the inductance L and capacitance C. The one-port shown in Fig. 14a will be referred to as a thyristor controlled susceptance (TCS)

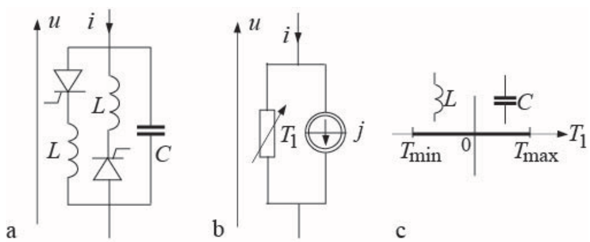

Fig. 14. Thyristor-switched inductors (a), an equivalent circuit (b) and the susceptance T_1 control range.

Reduction of harmonics generated by TCSs, along with those harmonics generated by the arc furnace, although necessary, is a separate issue, however. Now, let us check whether balancing at the fundamental harmonic, in a situation illustrated in Fig. 12, i.e., in state s1, is possible or not, meaning ignoring harmonics generated by TCSs of the compensator.

Having the crms values of the fundamental harmonic $\boldsymbol{U}_{R1}$, $\boldsymbol{U}_{S1}$, $\boldsymbol{U}_{T1}$, $\boldsymbol{I}_{R1}$, $\boldsymbol{I}_{S1}$ and $\boldsymbol{I}_{T1}$ of the furnace voltages and currents, the equivalent susceptance B_{e1} and unbalanced admittance $\boldsymbol{Y}_{u1}$, can be calculated from formulae (16) and (20) – (22).

A reactive balancing compensator (RBC), can have a structure and parameters shown in Fig. 15.

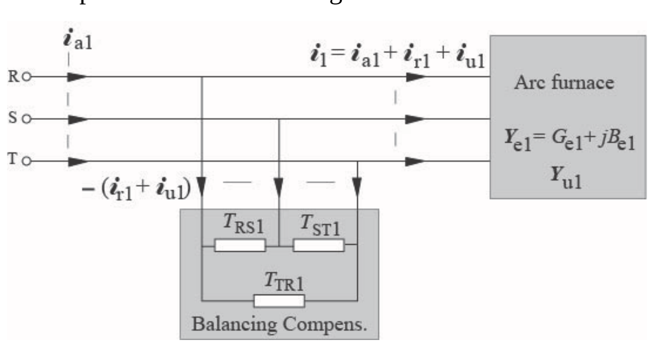

Fig. 15. Structure and parameters of reactive balancing compensator connected at the furnace terminals.

It compensates the reactive and the unbalanced currents of the fundamental harmonic on the condition that

$$B_{e1} - (T_{ST1}+T_{ST1}+T_{TR1}) = 0 \tag{31}$$

$$\boldsymbol{Y}_{u1} + j\,(T_{ST1}+\alpha\, T_{ST1}+\alpha^{*}\, T_{TR1}) = 0. \tag{32}$$

These equations, with respect to the compensator susceptances T_{XY1}, have the solution [9], [13]

$$\begin{aligned} T_{RS1} &= (\sqrt{3}\,\mathrm{Re}\boldsymbol{Y}_{u1} - \mathrm{Im}\,\boldsymbol{Y}_{u1} - B_{e1})/3 \\ T_{ST1} &= (2\,\mathrm{Im}\,\boldsymbol{Y}_{u1} - B_{e1})/3 \\ T_{TR1} &= (\sqrt{3}\,\mathrm{Re}\boldsymbol{Y}_{u1} - \mathrm{Im}\,\boldsymbol{Y}_{u1} - B_{e1})/3\,. \end{aligned} \tag{33}$$

When susceptance T_{XY1}, calculated from eqn. (33), is positive, then a capacitor of capacitance

$$C_{XY} = \frac{T_{XY1}}{\omega_1} \tag{34}$$

should be connected between X and Y terminals. When this susceptance is negative, then inductor of inductance

$$L_{XY} = -\,\frac{1}{\omega_1 T_{XY1}} \tag{35}$$

should be connected between the line X and Y.

Compensation of the reactive and unbalanced currents changes the voltage on the furnace. Because the furnace is nonlinear, this changes the susceptance B_{e1} and unbalanced admittance $\boldsymbol{Y}_{u1}$. Therefore, parameters of the compensator can be found in an iteration process.

The result of balancing the furnace in state 1 are shown in Fig. 16. Both the reactive and unbalanced currents were reduced to a negligible value.

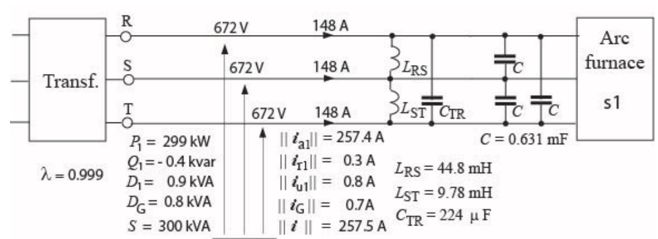

Fig. 16. The results furnace in the state s1 balancing.

The result of balancing in state 2 are shown in Fig. 17.

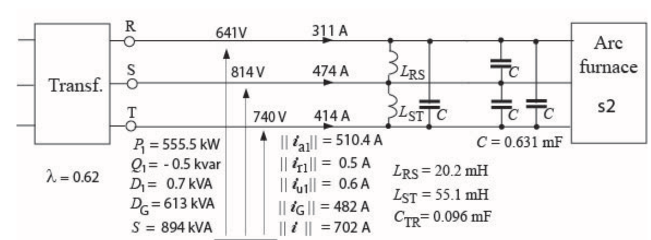

Fig. 17. The results furnace in the state s2 balancing.

These results show that in spite almost total compensation of the reactive and unbalanced currents, the PF remains practically unchanged. This is because of an increase in the harmonic distortion caused by harmonics generated in the furnace when it operates with a unidirectional arc.

Results of modeling a compensated furnace in states s0 and s1 show that the level of the supply current distortion, caused by the furnace, is on such a low level that filtering of harmonics might not be needed. However, when a furnace is in state s2, the furnace balancing without harmonics filtering seems do not provide any benefits.

Let us replace the capacitive compensator with a resonant harmonic filter (RHF) of the same reactive power Q_1 for the fundamental harmonic. Since harmonics of the 2nd and the 3rd order are dominating ones in the state s2, let us assume that the filter which replaces capacitors in Fig. 11 is built of two resonant branches tuned to the frequency of the 2nd and the 3rd order harmonics. It is assumed moreover that each branch compensates the same reactive power, i.e., $Q_1/2$. The q-factor of inductors, $q = \omega_1 L/R$, it is assumed to be equal 50. Such a filter with parameters is shown in Fig. 18.

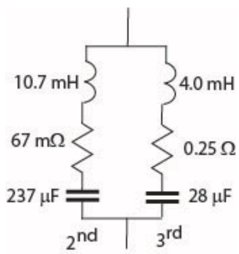

Fig. 18. Structure and parameters of a filter of the 2nd and the 3rd order harmonics.

The results of balancing in the state s1, with capacitors of $C = 631\mu$F, replaced by RHFs, are shown in Fig. 19.

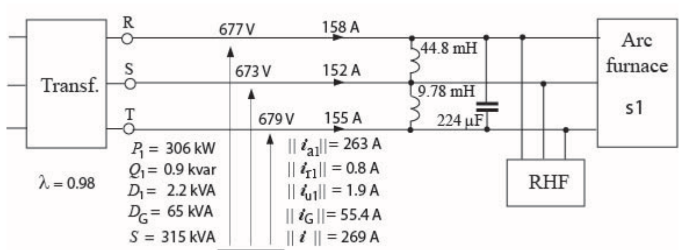

Fig. 19. The results of balancing a furnace in the state s1. with an RHF of the 2nd and the 3rd harmonic.

It can be observed, that a relatively high generated current $\boldsymbol{i}_G$ remains after compensation. A dc component $\boldsymbol{i}_0$ is the main component of this current. It occurs because voltages on arcs are nonsinusoidal.

When the state of the furnace changes to s2, then the furnace can be balanced with results shown in Fig. 20.

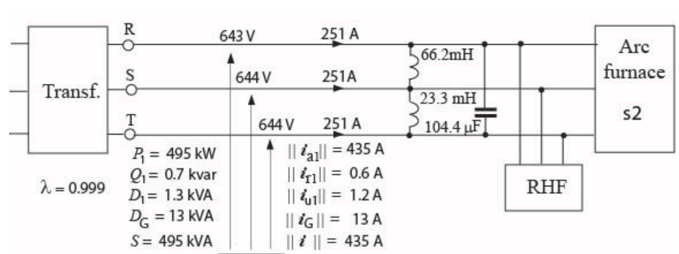

Fig. 20. The results of balancing a furnace in the state s2 with an RHF of the 2nd and the 3rd harmonic.

VII. Conclusions

The results presented in this paper show that balancing ac arc furnaces directly at their terminals seem to be possible. The Currents' Physical Component-based power theory seems to provide a useful tool for synthesis of the reactive balancing compensator for such a purpose. These conclusions are drawn having in mind their implementation for balancing ultra-high power furnaces, which, due to the level of currents, do not make presently allow of using switching compensators, built of power transistors.

These conclusions are formulated only at a theoretical level but do not take practical and, economic aspects of such balancing into account.

Assuming that the conclusions drawn in this paper are right, and other research will confirm the merits of direct balancing, the studies should be continued towards using thyristors for the balancing compensator control. Thyristor-switched inductors will be sources of additional distortion of the supply current and this has to be taken into account at a synthesis of resonant harmonic filters integrated with the compensator. Continuation of research on furnace balancing is needed for that, however.

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