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

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CONSIDERATIONS ON DIRECT BALANCING OF ULTRA-HIGH-POWER AC ARC FURNACES IN UNEASY STATE

A Thesis

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ABSTRACT

During the operation of ultra-high-power ac arc furnace the negative effects of unbalance mostly occur in the secondary terminals of the transformer connected to the load. Hence balancing and compensating the furnace at this terminal will not only improve the transformer efficiency but also reduce energy losses that do occur.

In this thesis a computer modeling of a reference ac arc furnace in both balanced and unbalanced states were simulated, and the effects of a reactive balancing compensator installed on the secondary side of the furnace transformer was evaluated to see how much delivered energy improvement can be obtained.

The balancing compensator used is synthesized using the Currents' Physical Components (CPC) based power theory, which is also used to evaluate our obtained results. The results obtained provide a platform for developing an adaptive balancing compensator for ac arc furnace operating in uneasy mode, with thyristor switched inductors used for compensator susceptances control.

CHAPTER 1. INTRODUCTION

Steel is mainly produced in industries using electric arc furnaces. During their operation they cause or are sources of electrical disturbance in the grid network they are connected to. The energy consumption of a single electric arc furnace could be in the range from as little as 2.5MVA to 1GVA, this is comparable to amount of power consumed by half a million customers. Therefore, finding ways to make sure the operate efficiently can help improve quality of the supply system and output of the furnace.

Arc furnaces operate mainly in three modes, boring mode, melting mode and refining mode. In the refining mode, the load at this point is a homogenous mixture of scrap, for most of the operation time during this period all arc are ignited, and a very few unbalance conditions can be encountered during this phase of operation. This phase is mainly regarded as the balanced state. Whereas in the boring and melting phases the arc current continuously changes due to the load being made up of clumps of scraps and metals which are randomly distributed and change positions. During this stage, the unbalanced stage, intervals where one or two arcs are not fired which creates asymmetry in the supply current and reduces power factor.

1.1 Causes of unbalance

Due to random ignition of arcs, ac arc furnaces are powerful sources of asymmetry in distribution systems particularly in the boring and melting phases of the arc operation. This period is described as the furnace being in an uneasy mode. It applies, in particular, to ultra-high-power arc furnaces, with power that reaches the level of 750MVA. A simplified structure of an ac arc furnace, along with the furnace transformer, is shown in Fig. 1.

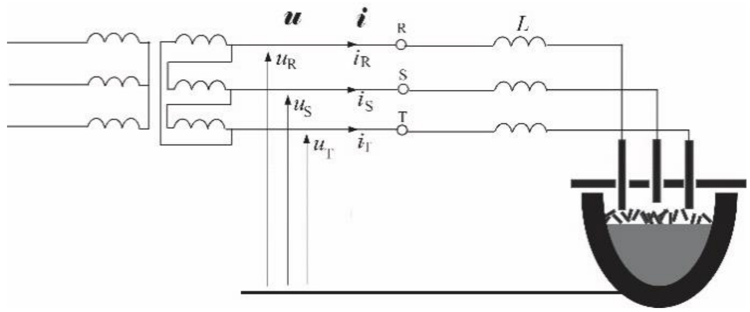

Figure 1: A structure of an ac arc furnace with a transformer

Apart from negative effects of asymmetry, a furnace in an unbalanced state, draws not only the active and reactive currents, but also 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 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.

1.2 Current methodology

Compensators needed for the improvement of power factor in ac arc furnaces are commonly installed at the primary side of the furnace transformer. It means, they operate at a higher voltage, but a lower current. Current technology and practices used for power factor correction involves using a STATCOM which is a voltage synchronous converter-based device for cancelation of fast current transients and a detuned filter for reactive power compensation installed parallel to the arc furnace but connected to the same voltage bus. 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 considered, moreover, that arc furnaces of the ultra-high power are supplied from transformers of relatively low power as compared to the furnace power. Therefore, their windings resistance is relatively high, which would result in more energy loss in transformer's windings.

1.3 Objective

An arc furnace in 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, adaptive balancing with TSI is not possible at lower thyristor power rating when used in ultra-high ac arc furnace, but when a single thyristor can switch currents of the rms value above 50 kA, it seems that the main technological obstacle can be overcome.

Arc furnace imbalance is caused be different reasons and demonstrates itself in different ways. It could be as a result of mechanical and electrical asymmetry of electrodes and the furnace charge, but it is mainly due to the imbalance is caused by arcs random extinction. The furnace can operate with only two arcs ignited or even with unidirectional arcs. In effect of this, furnace can operate in different states. These states 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 if it possible to balance such a device and what our goals are. These issues should be clarified before any attempt of implementing TSI for adaptive arc furnace direct balancing is considered. This thesis presents results and conclusion drawn from modeling a reactive balancing compensator installed directly at the arc furnace terminals. The reactive balancing compensator is synthesized, and its performance is evaluated using the Currents' Physical Components (CPC) – based power theory, developed by L.S. Czarnecki, whose material has been referenced in this thesis. This theory is currently the only one which provides fundamentals for such balancing compensator synthesis

CHAPTER 2. 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 at the level of 0.71, meaning, the reactive power *Q* is kept on a level of the active power *P* of the furnace.

2.1 Electric arc reference

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

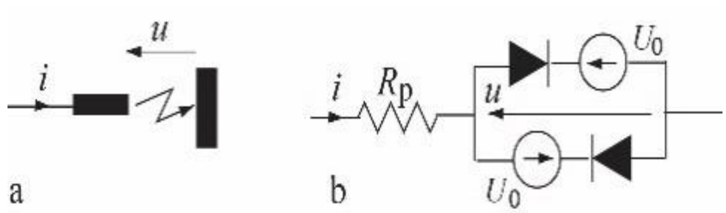

Figure 2: A circuit (b) that approximates the arc (a).

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.

2.2 Electric arc furnace model

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 with the furnace power or a few times higher.

The studies in this project 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.

2.3 Furnace operation in state s0

It is assumed in this report that a reference arc furnace has the line resistance, including the resistance of the arc plasma and the melted steel, equal to R = 0.25Ω, the line reactance equal to w_1L = 1Ω, 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 assumed that the dc voltage on the arc is U_0 = 300V.

The results of modeling of the furnace which operates at the power factor λ = 0.71 are shown in Fig. 3.

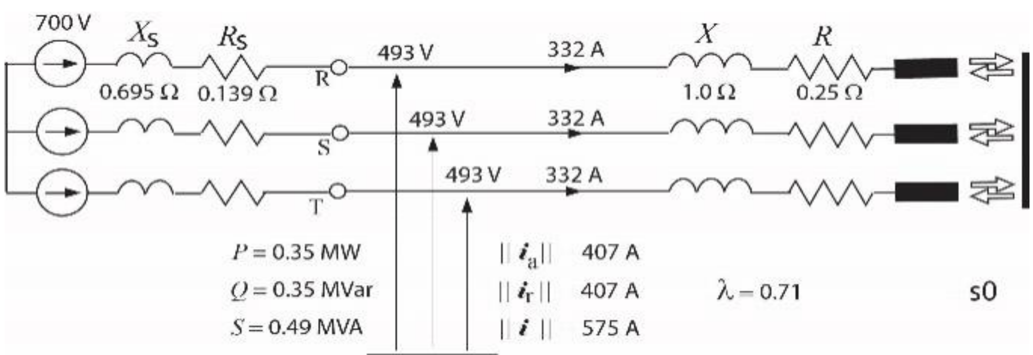

Figure 3: The results of modeling of a furnace which operates

at the power factor l = 0.71 in state s0.

The state s0 in Fig. 3 denotes a balanced state of the furnace. The supply current distortion at such a state of the furnace is δ_c = 1.9%. The waveforms of furnace voltage at R terminal and the line R current are shown in Fig. 4.

As long as the supply voltage rms value E = 700V and the relative transformer ratio S_s/S remain unchanged, the furnace currents rms values shown for the reference furnace in Fig. 3, can be recalculated to any furnace of the power S, multiplying the furnace current rms value be the scaling coefficient $a = S/0.49$.

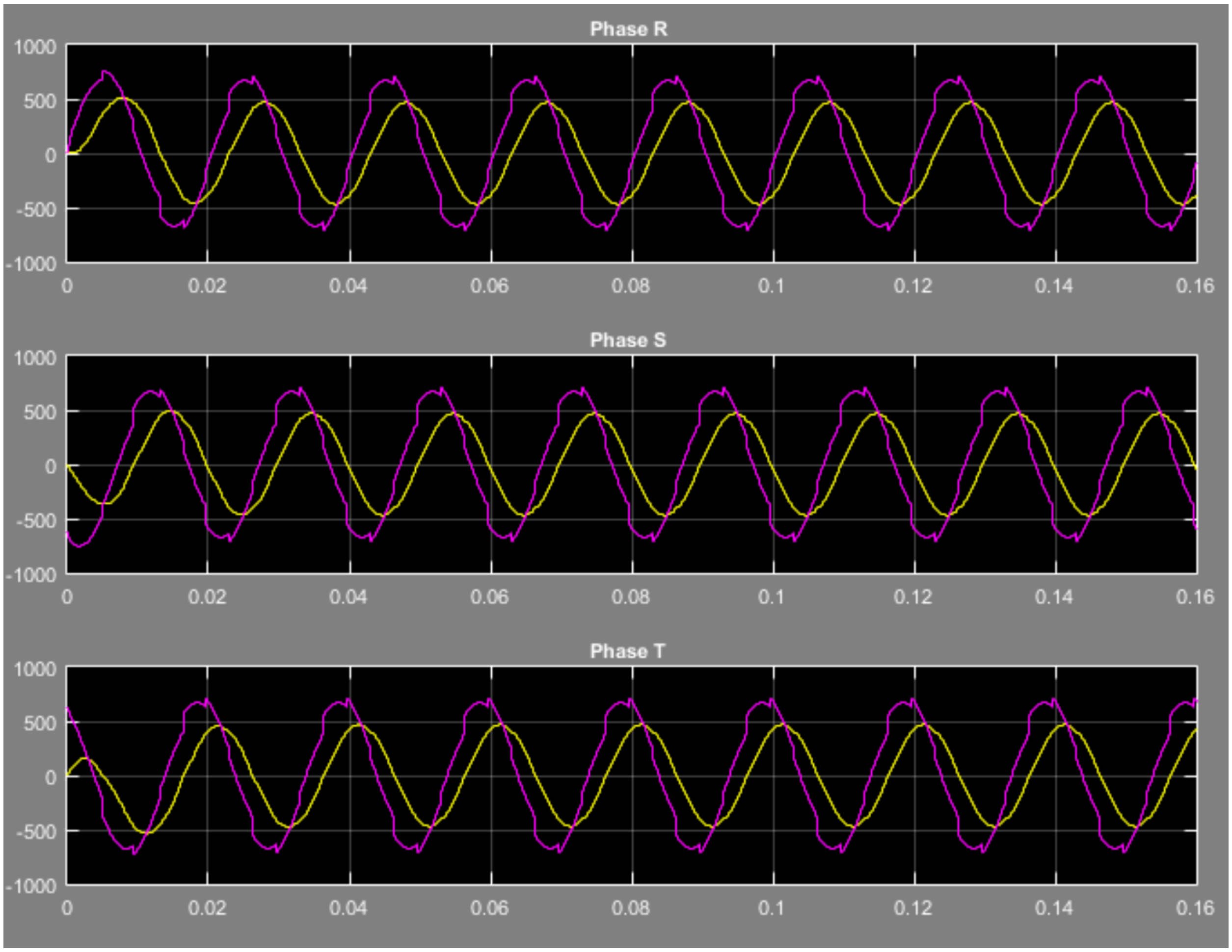

Figure 4: Waveforms of phase R, S, T, voltages and currents at balanced furnace operation.

For example, for S = 750 MVA, this coefficient is a = 1531. At a different supply voltage E the scaling coefficient $a = S/0.49\text{x}700/E$, provides only approximate values of the furnace currents because the arc is nonlinear.

2.4 Simulink Electric arc furnace model

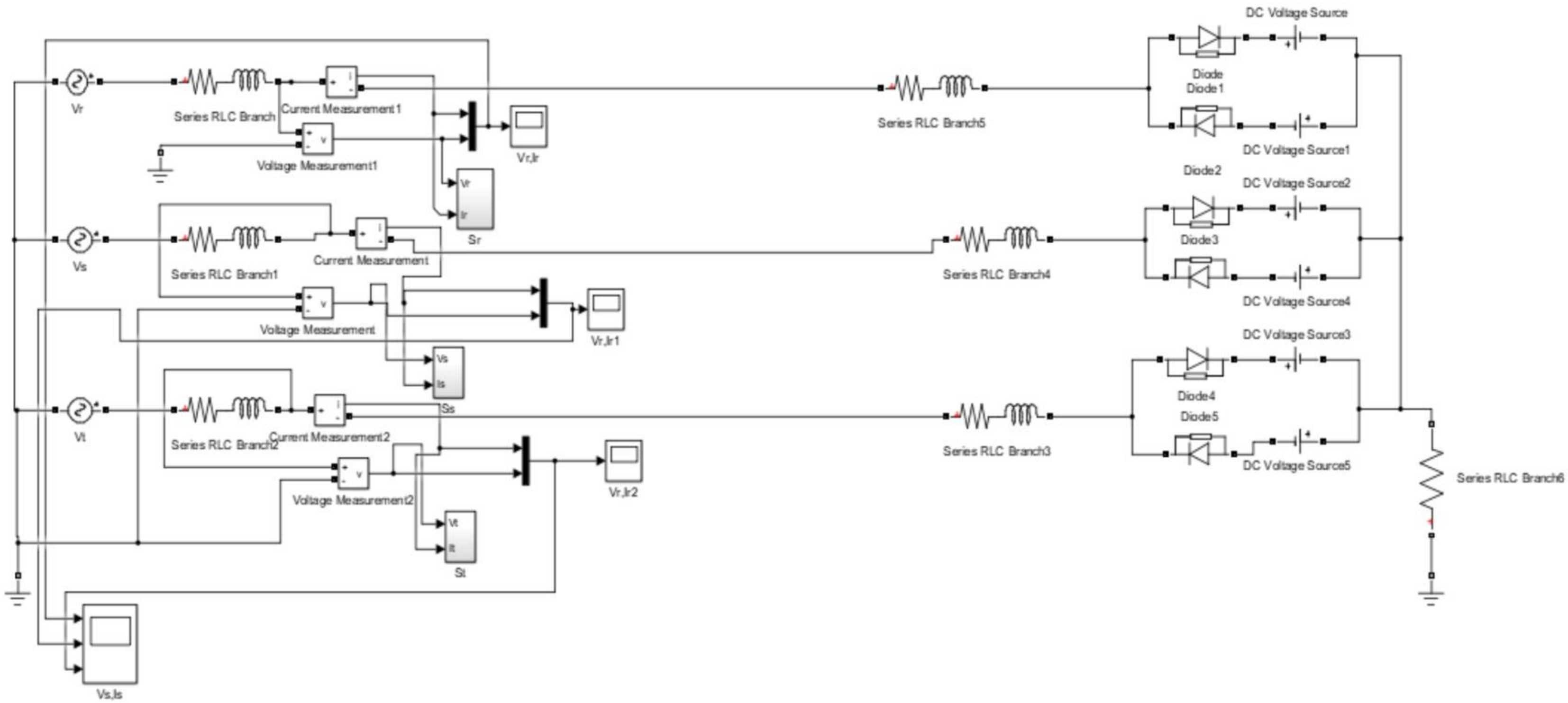

Figure 5: Simulink electric arc furnace model

CHAPTER 3. POWER PROPERTIES OF AC ARC FURNACE

3.1 CPC Power Theory arc furnace power properties

Arc furnaces of the ultra-high power are often supplied from dedicated power plants or dedicated transmission/ distribution lines with sinusoidal and symmetrical voltage. Therefore, as compared to the level of waveform distortion and asymmetry produced by the furnace, it can be assumed that they are 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 lines. At such an assumption, the vector of the arc furnace supply current

$$\boldsymbol{i} = [i_{\mathrm{R}}, i_{\mathrm{S}}, i_{\mathrm{T}}]^{\mathrm{T}} = \sum_{n=0}^{\infty} \boldsymbol{i}_n \approx \begin{bmatrix} I_{\mathrm{R}0} \\ I_{\mathrm{S}0} \\ I_{\mathrm{T}0} \end{bmatrix} + \sqrt{2}\mathrm{Re}\sum_{n\in N} \begin{bmatrix} \boldsymbol{I}_{\mathrm{R}n} \\ \boldsymbol{I}_{\mathrm{S}n} \\ \boldsymbol{I}_{\mathrm{T}n} \end{bmatrix} e^{jn\omega_1 t} =$$

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

can be decomposed into four Currents' Physical Components (CPC), namely

$$\boldsymbol{i} = \boldsymbol{i}_1 + \boldsymbol{i}_{\mathrm{G}} = \boldsymbol{i}_{\mathrm{a}1} + \boldsymbol{i}_{\mathrm{r}1} + \boldsymbol{i}_{\mathrm{u}1} + \boldsymbol{i}_{\mathrm{G}}\,. \tag{2}$$

Symbol N in (1) denotes the set of the current harmonics order n, including the fundamental harmonic, $n = 1$. Symbols $\boldsymbol{i}_{\mathrm{a}1}$, $\boldsymbol{i}_{\mathrm{r}1}$ and $\boldsymbol{i}_{\mathrm{u}1}$ denote the active, reactive and the unbalanced currents of the fundamental frequency respectively, while $\boldsymbol{i}_{\mathrm{G}}$ 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 u can be presented in the form.

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

$$= \boldsymbol{U}_0 + \sqrt{2}\,\mathrm{Re} \sum_{n \in N} \boldsymbol{U}_n e^{jn\omega_1 t}. \qquad (3)$$

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

$$\boldsymbol{u} = \boldsymbol{u}_1 + \boldsymbol{u}_{\mathrm{G}} \qquad (4)$$

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

$$\boldsymbol{u} = \boldsymbol{u}_1^{\mathrm{p}} + \boldsymbol{u}_1^{\mathrm{n}} + \boldsymbol{u}_{\mathrm{G}} \qquad (5)$$

In this decomposition

$$\boldsymbol{u}_1^{\mathrm{p}} = \begin{bmatrix} u_{\mathrm{R}1}^{\mathrm{p}} \\ u_{\mathrm{S}1}^{\mathrm{p}} \\ u_{\mathrm{T}1}^{\mathrm{p}} \end{bmatrix} = \sqrt{2}\,\mathrm{Re} \begin{bmatrix} 1 \\ \alpha^* \\ \alpha \end{bmatrix} \boldsymbol{U}_1^{\mathrm{p}}\, e^{j\omega_1 t} = \sqrt{2}\,\mathrm{Re}\{\mathbf{1}^{\mathrm{p}} \boldsymbol{U}_1^{\mathrm{p}} e^{j\omega_1 t}\} \qquad (6)$$

where

$$\boldsymbol{U}_1^{\mathrm{p}} = \frac{1}{3}[1, \alpha, \alpha^*] \begin{bmatrix} \boldsymbol{U}_{\mathrm{R}1} \\ \boldsymbol{U}_{\mathrm{S}1} \\ \boldsymbol{U}_{\mathrm{T}1} \end{bmatrix}, \quad \alpha = 1 e^{j2\pi/3} \qquad (7)$$

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

The scalar product of three-phase vectors, defined generally as

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

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 zero. In particular, 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 can be expressed as

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

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

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

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

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

with

$$G_{\mathrm{e}1} = \frac{P_1^{\mathrm{p}}}{||\boldsymbol{u}_1^{\mathrm{p}}||^2} \tag{14}$$

is the fundamental harmonic of the active current or the “working” active current. The current component

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

with

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

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

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

with

$$\mathbf{1}^{\mathrm{n}} = \begin{bmatrix} 1 \\ \alpha \\ \alpha^* \end{bmatrix} \qquad (18)$$

is the ***unbalanced current*** of the furnace. The symbol $\boldsymbol{Y}_{1\mathrm{u}}$ in (17) stands for an unbalanced admittance of the furnace for the fundamental harmonic. This admittance can be calculated 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.

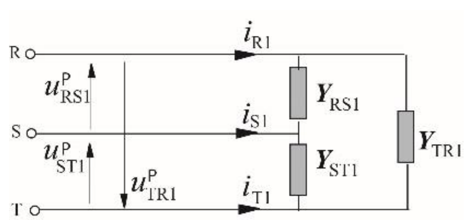

Figure 6: General structure of equivalent circuit of the arc furnace for the fundamental harmonic

With these admittances

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

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, zero. Assuming that Y_{RS1} = 0, i.e., the equivalent circuit has the structure shown in Fig. 6,

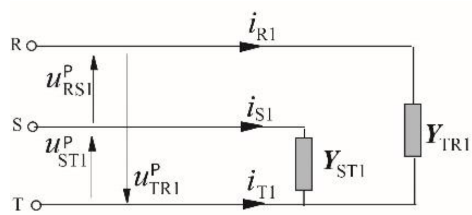

Figure 7: Specific structure of equivalent circuit of the arc furnace for the fundamental harmonic

with

$$\boldsymbol{Y}_{TR1} = \frac{\boldsymbol{I}_{R1}}{\boldsymbol{U}^{p}_{R1} - \boldsymbol{U}^{p}_{T1}} \tag{20}$$

$$\boldsymbol{Y}_{ST1} = \frac{\boldsymbol{I}_{S1}}{\boldsymbol{U}^{p}_{S1} - \boldsymbol{U}^{p}_{T1}} \tag{21}$$

the furnace equivalent admittance is equal to

$$\boldsymbol{Y}_{u1} = -(\boldsymbol{Y}_{ST1} + \alpha \boldsymbol{Y}_{TR1})\,. \tag{22}$$

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

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

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

$$||\boldsymbol{i}_{\mathrm{u1}}|| = Y_{\mathrm{u1}}\,||\boldsymbol{u}_1^{\mathrm{p}}|| \tag{26}$$

$$||\boldsymbol{i}_{\mathrm{G}}|| = \sqrt{\sum_{n\in N_{\mathrm{h}}} ||\boldsymbol{i}_n||^2} \tag{27}$$

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

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

The power factor is commonly defined as $\lambda = P/S$. In the presence of the load generated current $\boldsymbol{i}_{\mathrm{G}}$, 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

$$\lambda = \frac{P_1^{\mathrm{p}}}{S} \tag{29}$$

3.2 Current harmonic content

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

$$\delta_{\mathrm{c}} = \frac{||\boldsymbol{i}_{\mathrm{h}}||}{||\boldsymbol{i}_1||} \tag{30}$$

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.

CHAPTER 4. 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 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.

4.1 Furnace operation in State s1

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. 8 and Fig. 9, respectively.

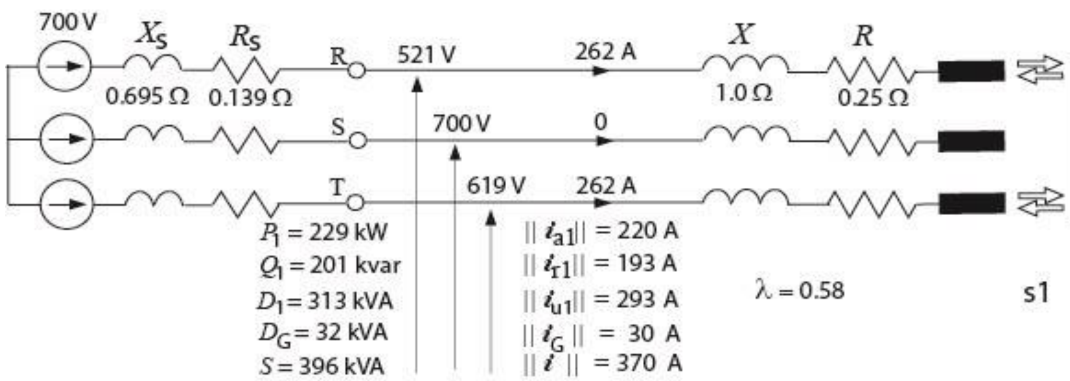

Figure 8: The results of modeling of a reference arc furnace in state s1

Let us observe that the unbalanced current i_{u1} is the dominating current component of the furnace current. It is even much higher than the reactive current i_{r1}.

The line currents are distorted by odd order harmonics with the 3rd order being the most dominating. It can occur in the supply lines because of line currents asymmetry. Harmonic distortion of the line currents at such state amounts to d_c = 8.0%.

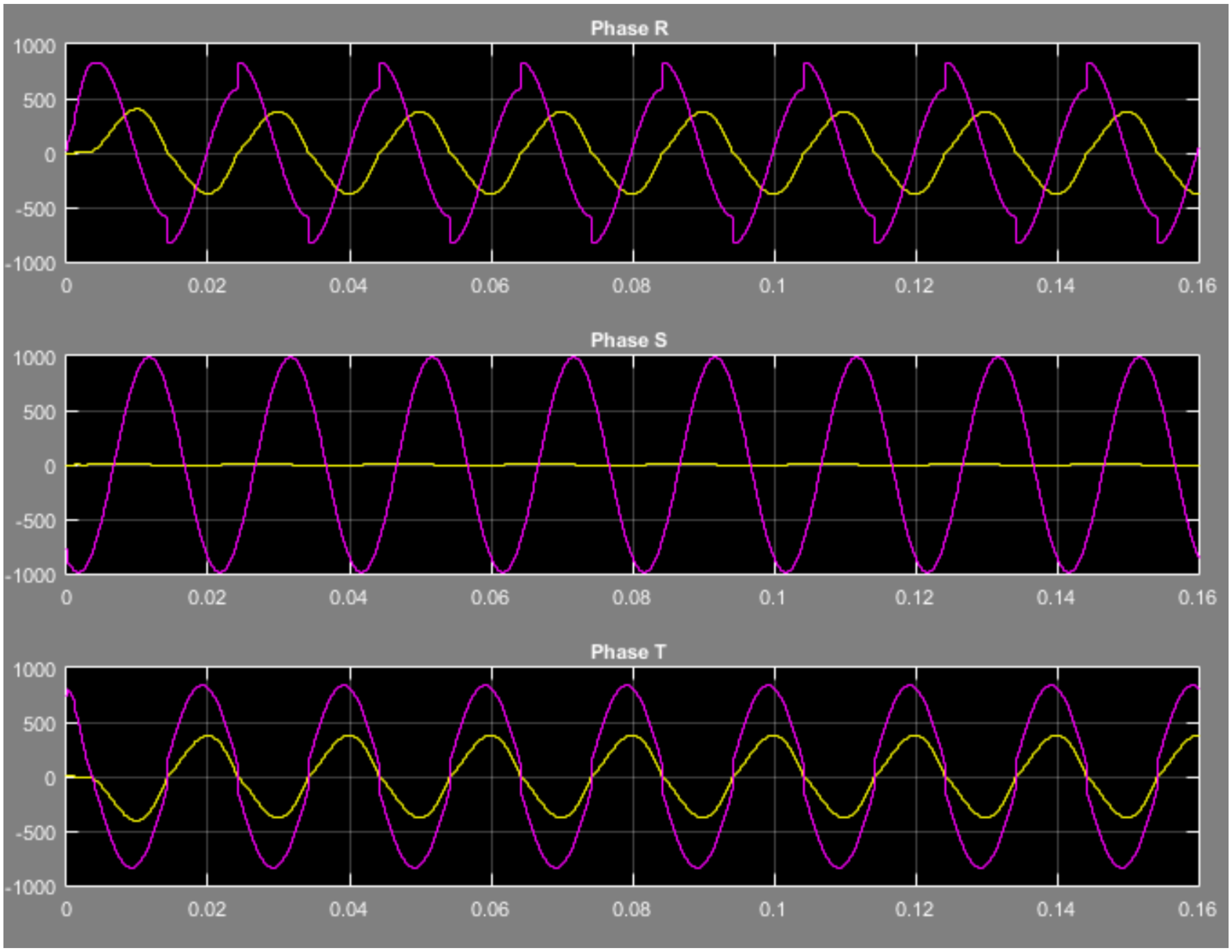

Figure 9: Waveforms of Phase R, S, T, voltages and currents in state s1

4.2 Furnace operation in state s2

A presence of unidirectional arc (state s2) in the furnace is not well documented in the literature of the subject. We can conclude, indirectly, that such states can occur from the presence of the even order harmonics, mainly the second order harmonic, in the furnace current. They cannot occur neither in state s0 nor in state 1.

The results of modeling the reference furnace in state s2 are shown in Figs. 10 and 11.

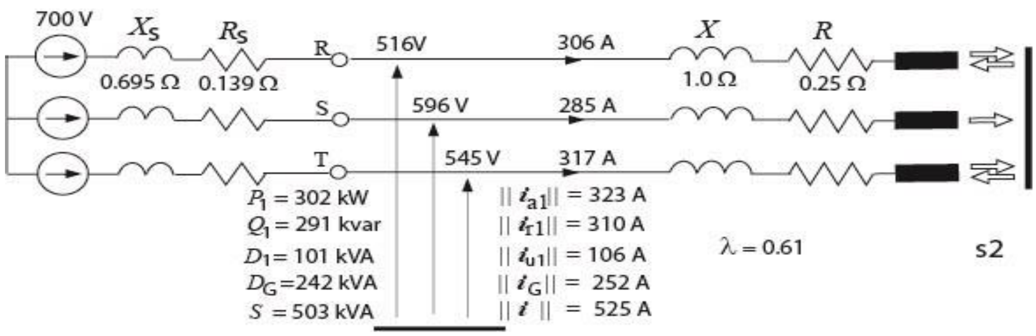

Figure 10: The results of modeling of arc furnace in state s2

It is worth to observe that the furnace generated current i_G has the three-phase rms value $||i_G||$ comparable with the active and the reactive currents.

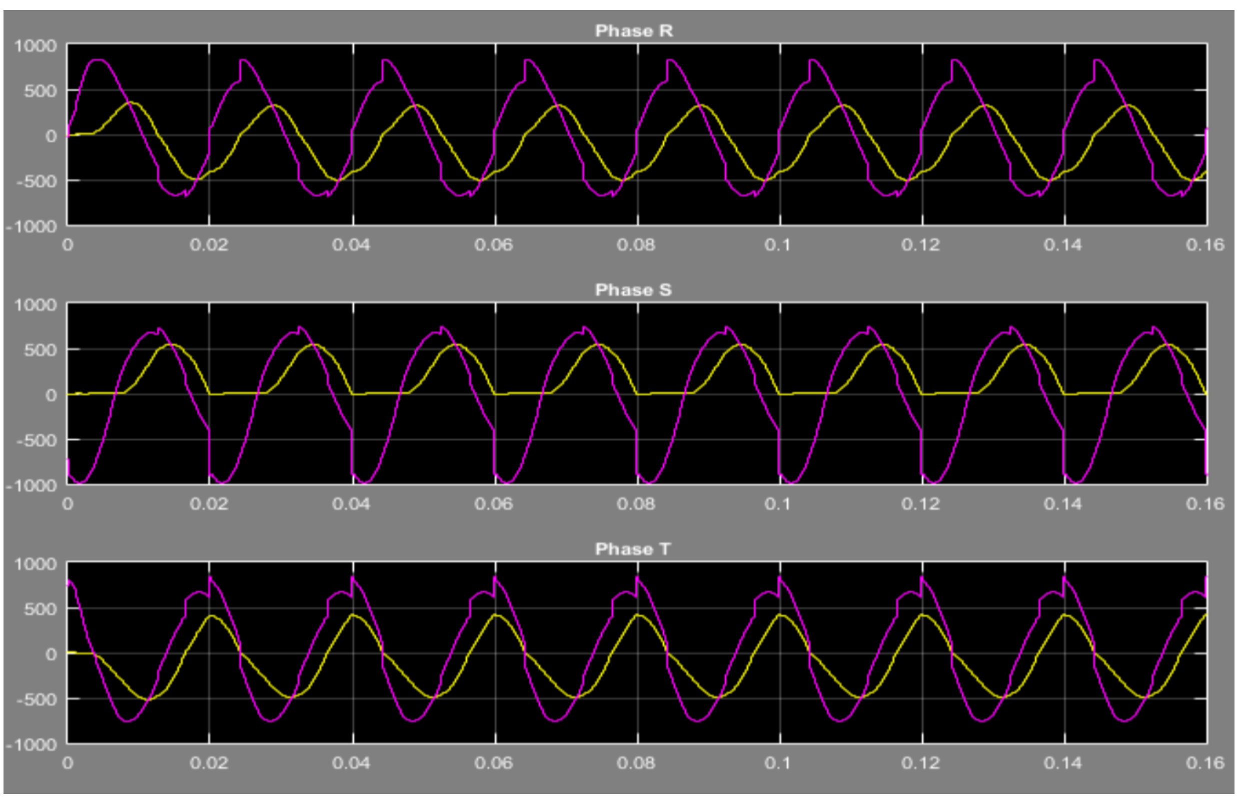

Figure 11: Waveforms of voltages and currents of Phase R, S, T, at the furnace operation with unidirectional arc

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

CHAPTER 5. REACTIVE CURRENT COMPENSATION

The arc furnace loads the supply source with a reactive current because inductors have to be connected for keeping arc stability. Since the value of these inductors is selected such that the reactive power is comparable with the active power, the arc furnace operates in its steady and balanced state approximately at the power factor $\lambda = 0.7$. Thus, to reduce the furnace supply current, compensation of the reactive current is need.

5.1 Reactive compensation in state s0

Compensation of the reactive current can be achieved along with filtering of harmonics by resonant harmonic filters (RHFs). The 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. This is achieved by a capacitor bank connected in D structure as shown in Fig. 12.

Compensation of the furnace reactive current changes the voltage at the furnace terminals. This changes the working point of the furnace. Consequently, this changes the capacitance C of the bank needed for reactive current compensation. Because the furnace is nonlinear, the value of this capacitance cannot be found analytically. An iterative process is needed for that.

At the assumption that the reactive current should be compensated entirely, this iterative process for the reference arc furnace resulted in C = 0.631mF. It was assumed that capacitors of the bank are connected between lines, i.e., in D configuration. To-ground capacitors, they have to be connected in Y configuration, and, the capacitance of the bank has to be recalculated from D to Y configuration.

The capacitance C, as specified above, could be the capacitance of the bank, and the equivalent capacitance of harmonic filters for the fundamental frequency. It will not affect the furnace performance at the fundamental frequency.

The results of modeling of the arc furnace in state s0 with compensated reactive current are shown in Fig. 12.

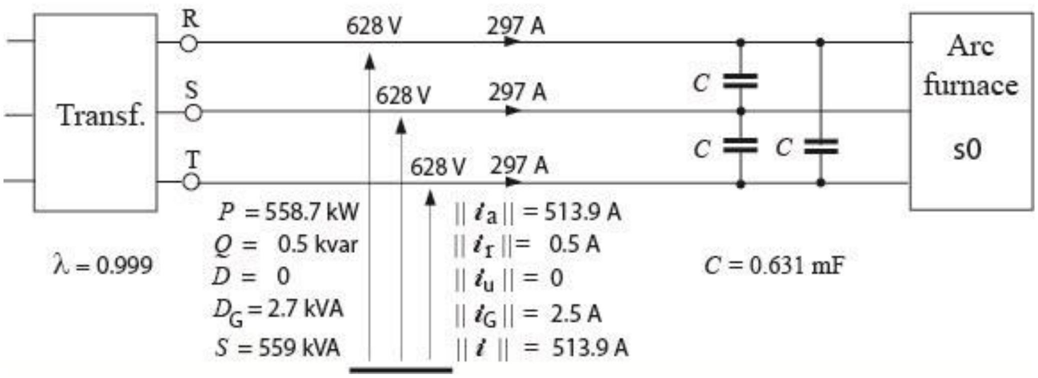

Figure 12: The results of modeling of reference furnace in state s0

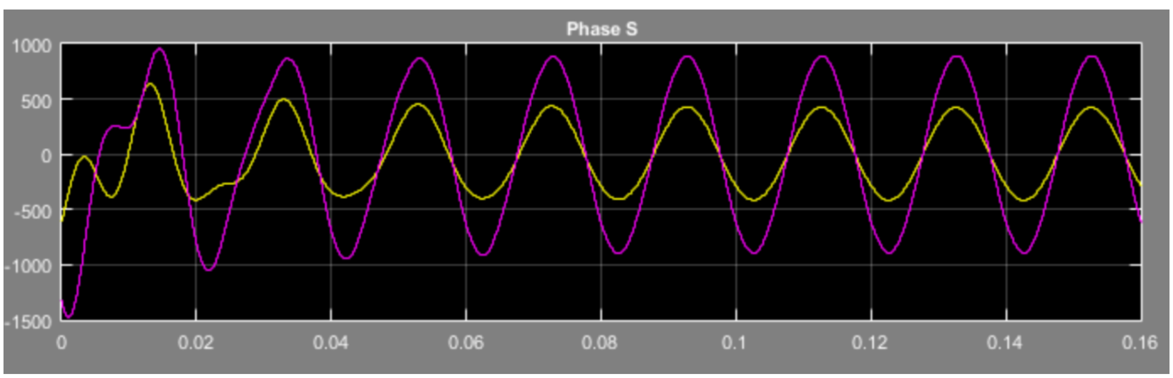

Figure 13: Phase S compensated voltage and current waveform in state s0

The compensated furnace operates at almost unity power factor, with the current distortion on the level dc = 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 with C = 0.631mF.

5.2 Reactive compensation in state s1

When one arc of the furnace is not ignited, i.e., it operates in the state s1, the furnace become overcompensated. Power quantities change to values shown in Fig. 14.

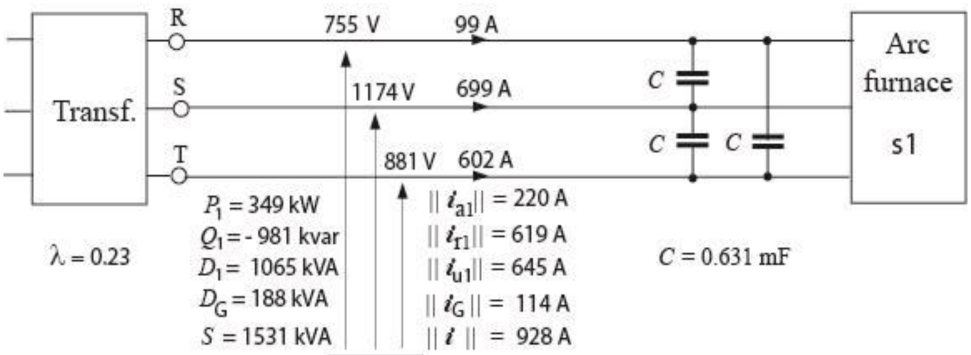

Figure 14: The results of modeling of reference furnace in state s1

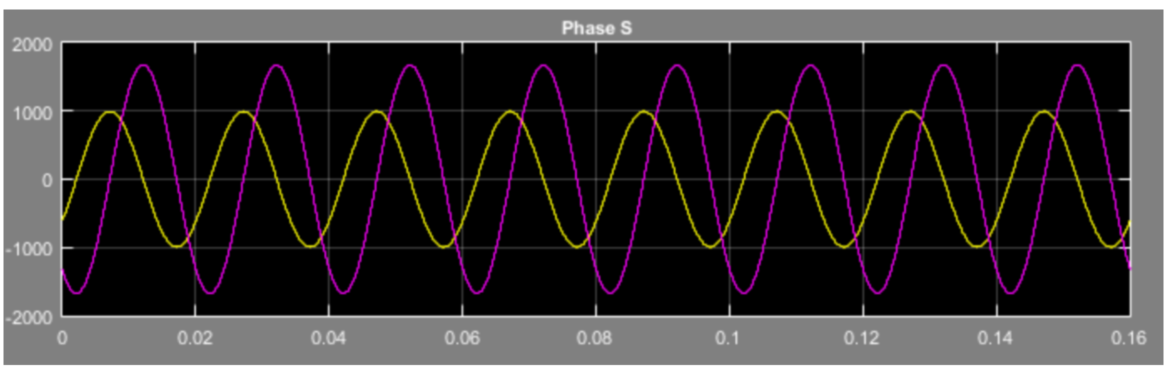

Figure 15: Phase S overcompensated voltage and current waveform in state s1

Thus, as it can be seen from Fig. 14, an arc extinction in a totally compensated furnace causes dramatic increase of the reactive current and decline of the power factor 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.

5.3 Reactive compensation in state s2

The same is observed at unidirectional arc, i.e. in state s2, as shown in Fig. 16, although in a lower degree.

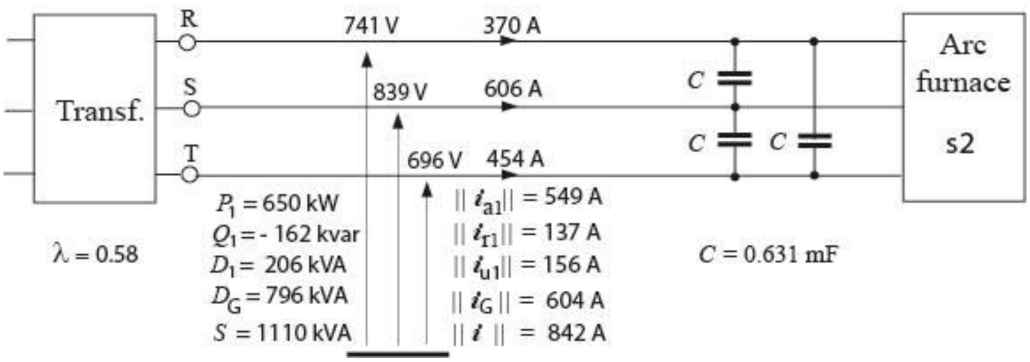

Figure 16: The results of modeling of reference furnace in state s2

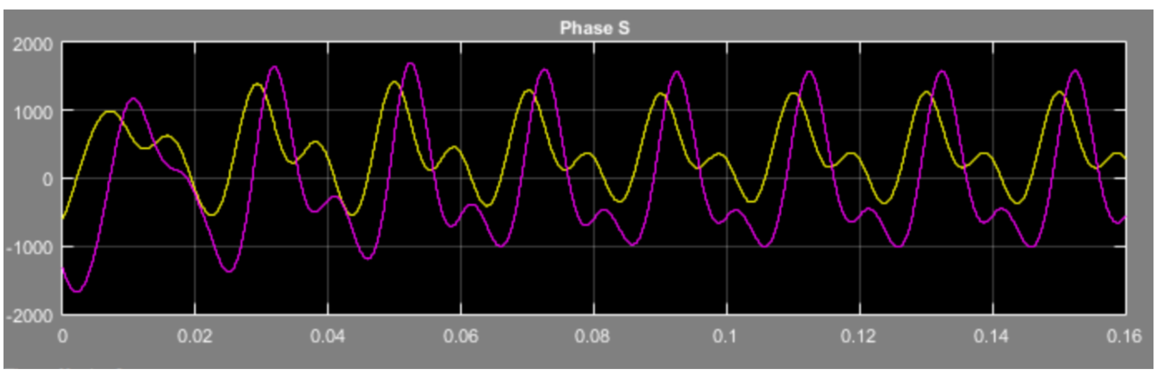

Figure 17: Phase S compensated voltage and current waveform in state s2

At fixed furnace transformer parameters, meaning its stray inductance is fixed, 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, cannot be compensated to 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.

CHAPTER 6. UNBLANCED CURRENT COMPENSATION

6.1 Thyristor switched inductor model

Thyristor switched inductors, connected in parallel with a capacitor, as shown in Fig. 18a, 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 for the fundamental harmonic T_1 and a current source of the current $j(t)$, as shown in Fig. 18b. 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 18c. These two values depend on the selection of the inductance L and capacitance C. The one-port shown in Fig. 17a, will be referred to in this paper as a thyristor controlled susceptance (TCS)

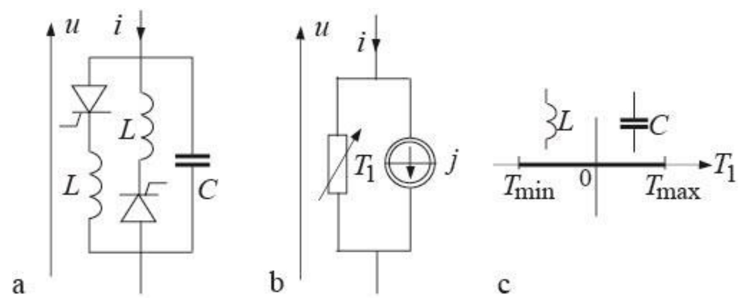

Figure 18: Thyristor switched inductors (a), equivalent circuit (b) and the susceptance T_1 control range

Reduction of harmonics generated by TCSs, along with those harmonics generated by the arc furnace, although necessary, is a separate issue. Now, let us check whether balancing at the fundamental harmonic in a situation illustrated in Fig. 14, 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 $\boldsymbol{Y}_{u1}$, of the furnace can be calculated from formulae (16) and (20) – (22).

6.2 Reactive balancing compensator and its parameters

A reactive balancing compensator (RBC), can have a structure and parameters shown in Fig. 19.

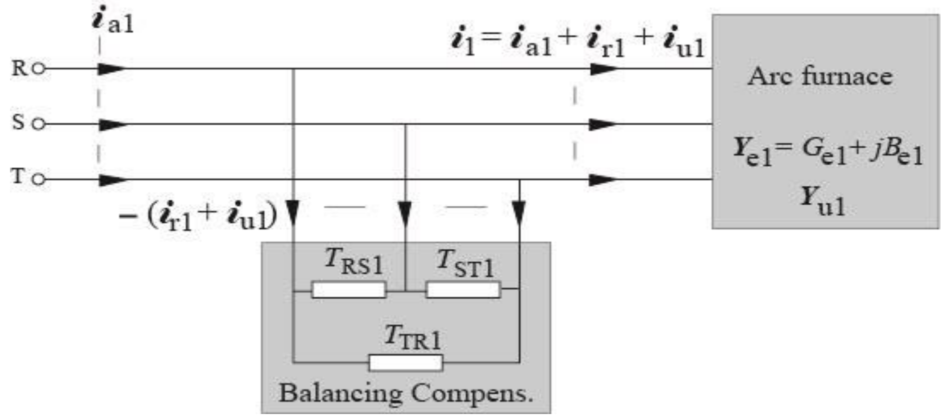

Figure 19: Structure and parameters of reactive balancing compensator connected at the furnace terminals

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

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

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

These equations have with respect to the compensator susceptances the solution

$$T_{RS1} = (\sqrt{3}\,\mathrm{Re}\,\boldsymbol{Y}_{u1} - \mathrm{Im}\,\boldsymbol{Y}_{u1} - B_{e1})/3$$

$$T_{ST1} = (2\mathrm{Im}\,\boldsymbol{Y}_{u1} - B_{e1})/3 \qquad (33)$$

$$T_{TR1} = (\sqrt{3}\,\mathrm{Re}\,\boldsymbol{Y}_{u1} - \mathrm{Im}\,\boldsymbol{Y}_{u1} - B_{e1})/3$$

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

$$C_{XY} = \frac{T_{XY1}}{\omega_1} \qquad (34)$$

should be connected between X and Y terminals.

When this susceptance is negative, then inductor of inductance

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

Compensation of the reactive and unbalanced currents changes the voltage on the furnace. Because it 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.

6.3 Balancing compensator in state s1

The result of balancing the furnace in state 1 are shown in Fig. 20. Both the reactive and unbalanced current were reduced to a negligible value.

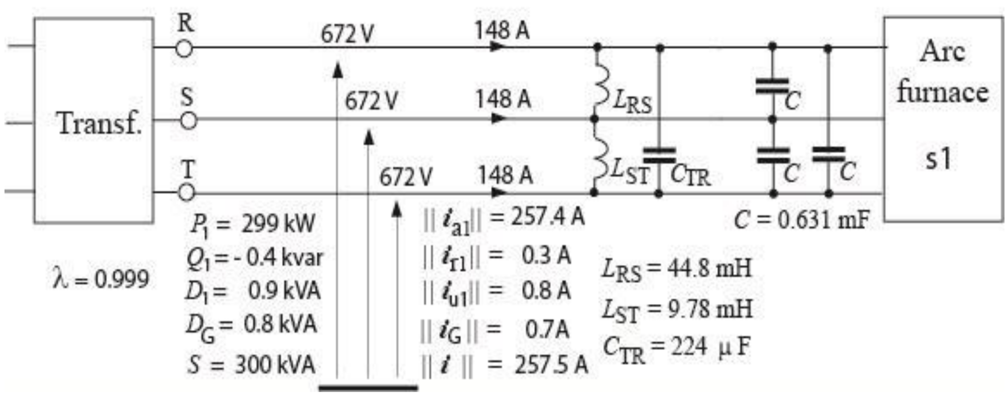

Figure 20: The results furnace in the state s1 balancing

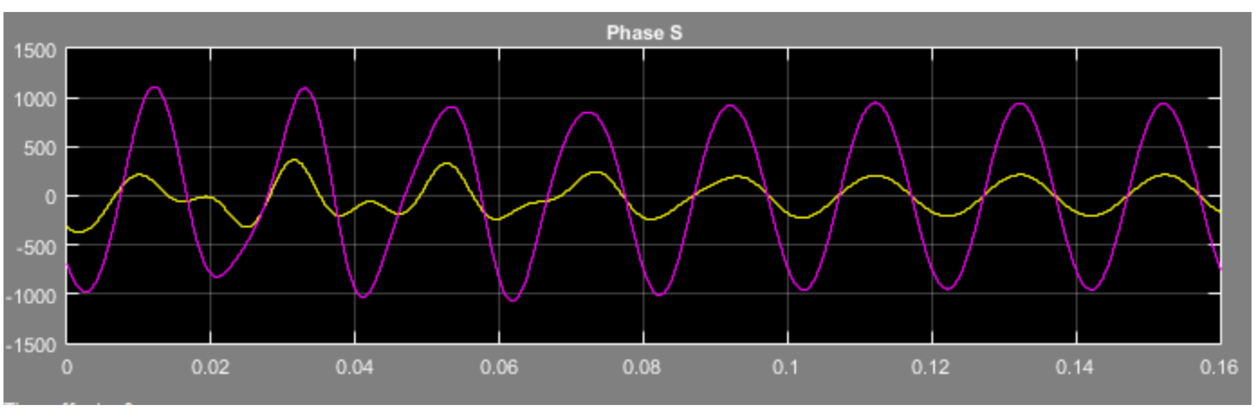

Figure 21: Phase S compensated voltage and current waveform in state s1 balancing

6.4 Balancing compensator in state s2

The result of balancing the furnace in state 2 are shown in Fig. 22.

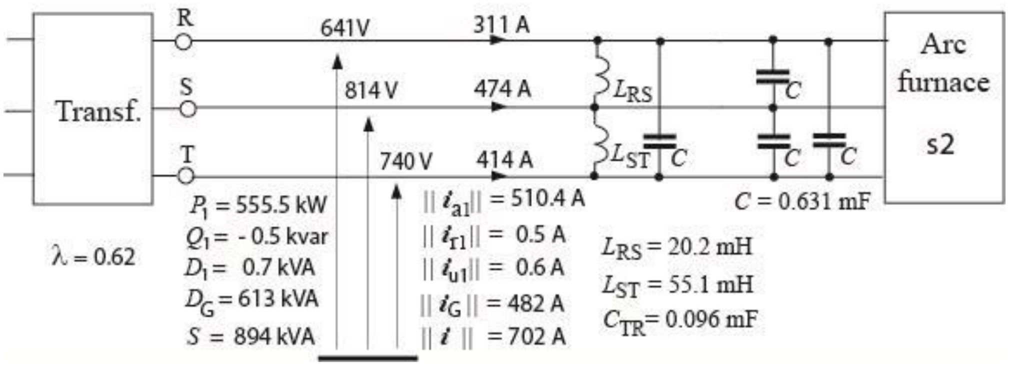

Figure 22: The results furnace in the state s2 balancing

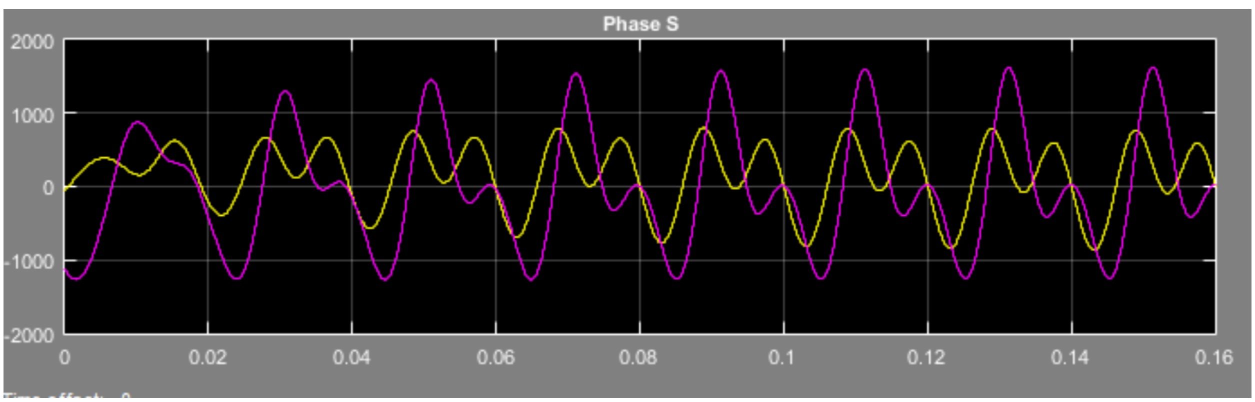

Figure 23: Phase S voltage and current waveform in state s2 balancing

These results show that in spite almost total compensation of the reactive and unbalanced currents, the power factor 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, its balancing without harmonics filtering seems do not provide any benefits.

6.5 RHF equivalent balancing compensator

Let us replace the capacitive compensator with a resonant harmonic filter (RHF) of the same reactive power 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. 12 is built of two resonant branches tuned to the frequency of the 2nd and the 3rd order harmonics. It is assumed moreover and 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 to 50. Such a filter with parameters is shown in Fig. 24.

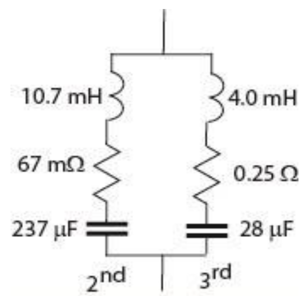

Figure 24: Structure and parameters of a filter of the 2nd and the 3rd order harmonics

6.6 RHF equivalent balancing compensator in state s1

The results of balancing the furnace in the state s1, with the capacitor bank with capacitance C = 632µF, connected as show in Fig.14, replaced by RHF shown in Fig. 24, are shown in Fig. 25.

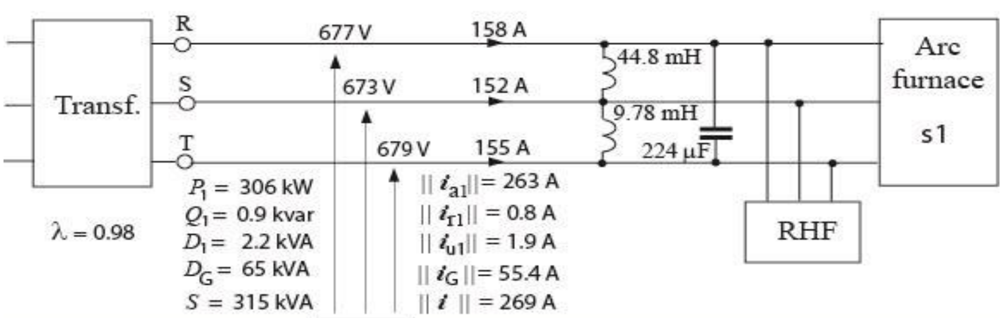

Figure 25: The results of balancing a furnace in the state s1 with a RHF of the 2nd and the 3rd harmonic

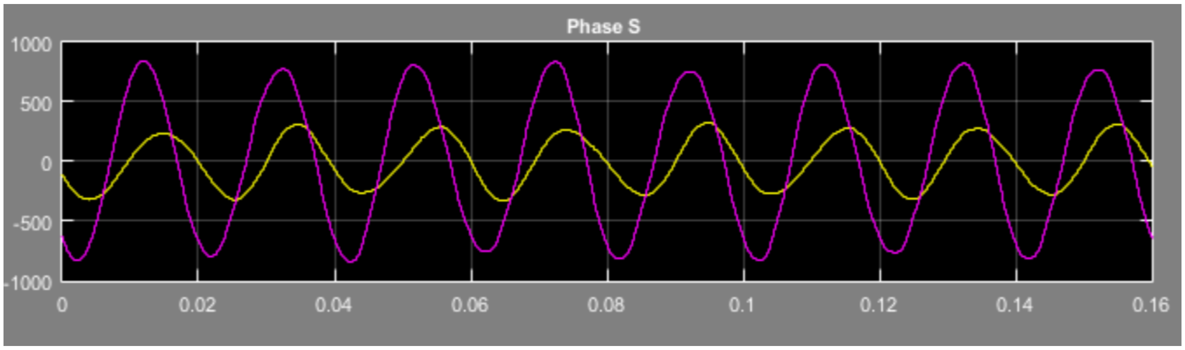

Figure 26: Phase S voltage and current waveform in state s1 balancing with RHF

As can be observed, 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 the voltage on arcs is nonsinusoidal.

6.7 RHF equivalent balancing compensator in state s2

When the state of the furnace changes to s2, then the furnace can be balanced with results shown in Fig. 27.

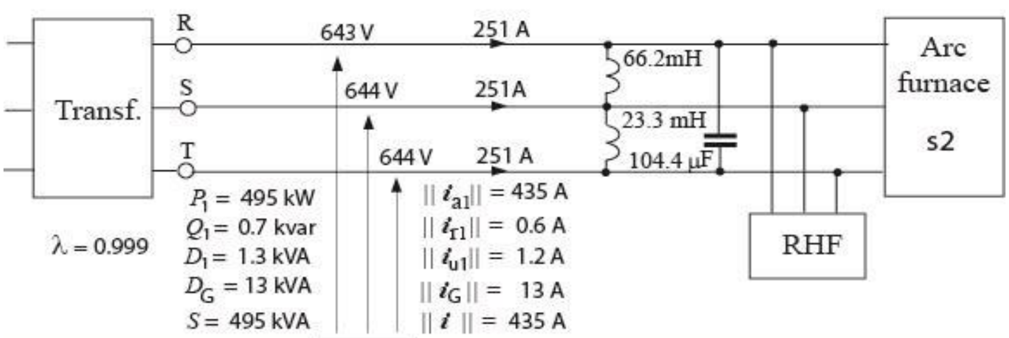

Figure 27: The results of balancing a furnace in the state s2 with a RHF of the 2nd and the 3rd harmonic

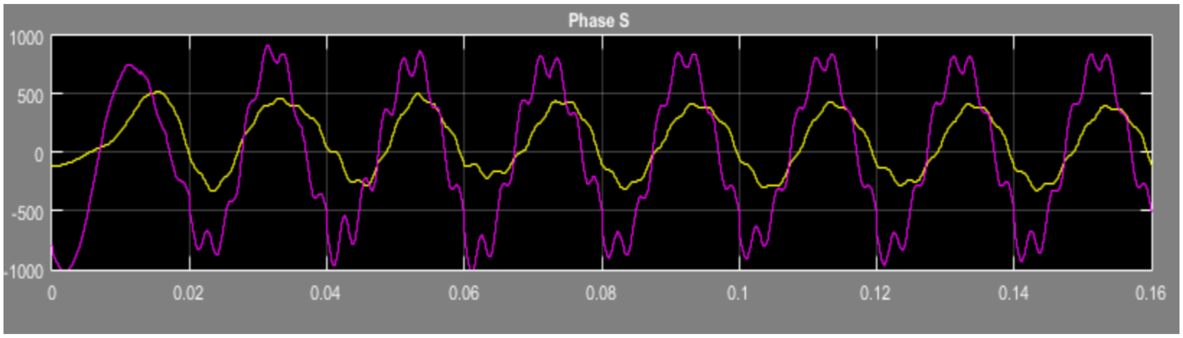

Figure 28: Phase S voltage and current waveform in state s2 balancing with RHF

CHAPTER 7. CONCLUSION

The results presented in this research shows 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 this 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 presently allow of using switching compensators, built of power transistors.

If the conclusions drawn in this paper are right, and other research supports and confirms 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 must be taken into account in the design of resonant harmonic filters integrated with the compensator. This problem presents an area for further studies into arc furnace compensation.

It will good to note that these results and conclusions made on this thesis do not take into account practical and economic aspects of such balancing, it is only a theoretical approach to balancing compensator.

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APPENDIX: SIMULINK LAYOUT

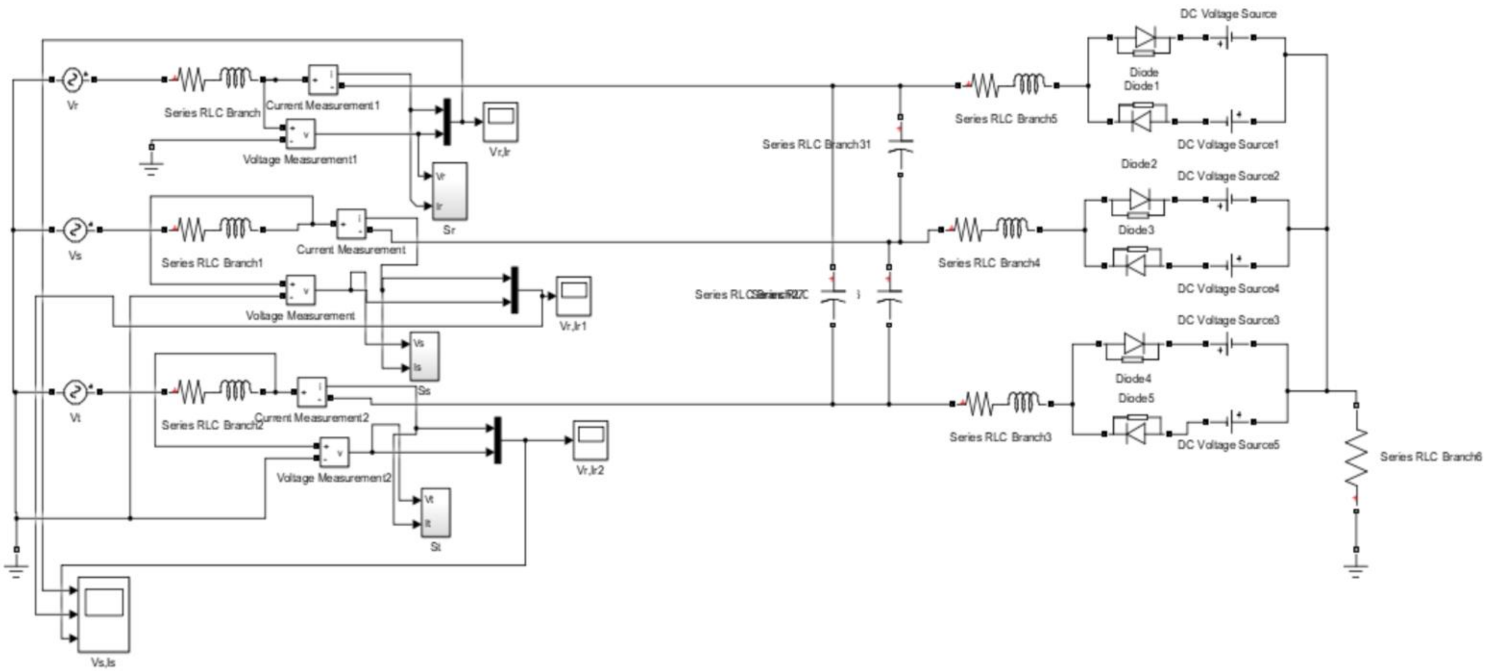

Figure 29: Simulink layout with reactive compensators

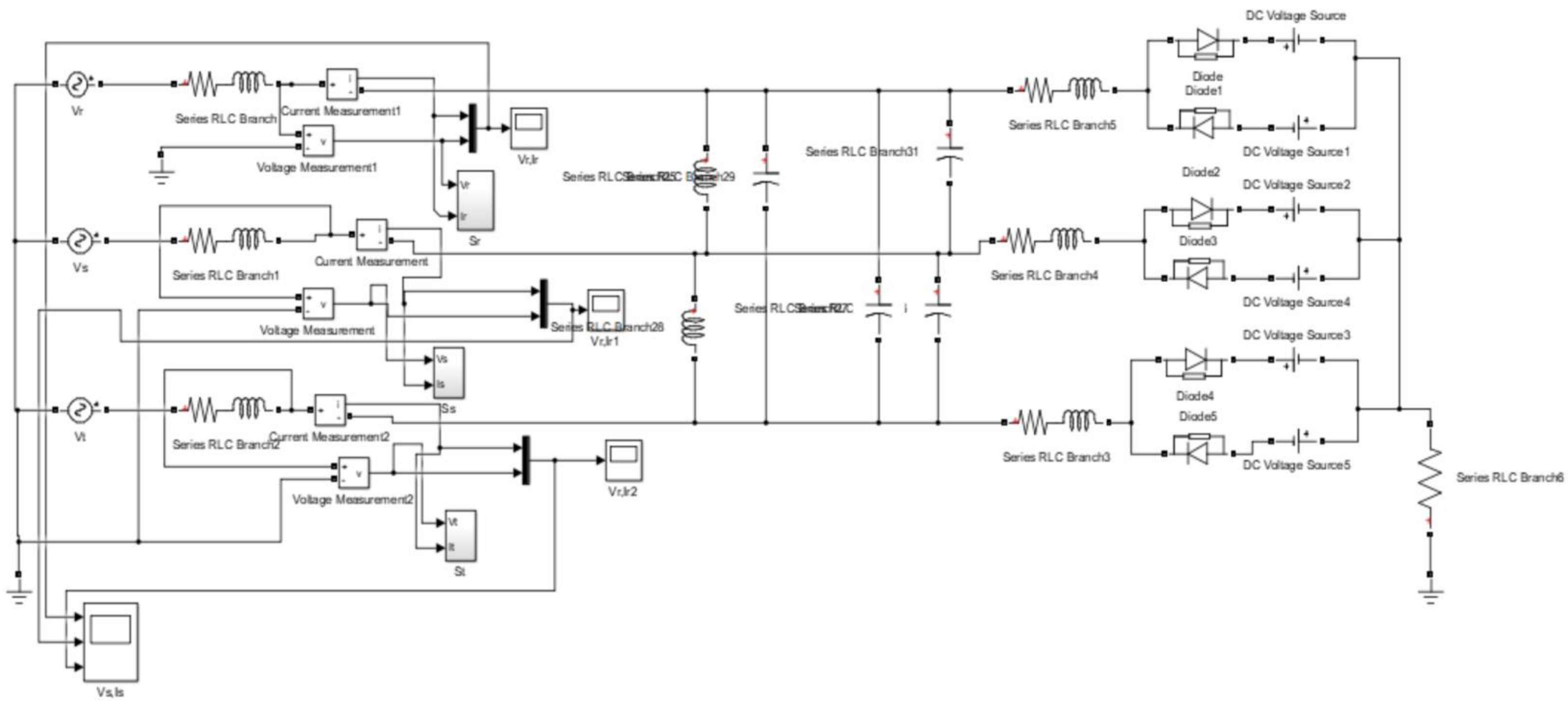

Figure 30: Simulink simulation with balancing compensators

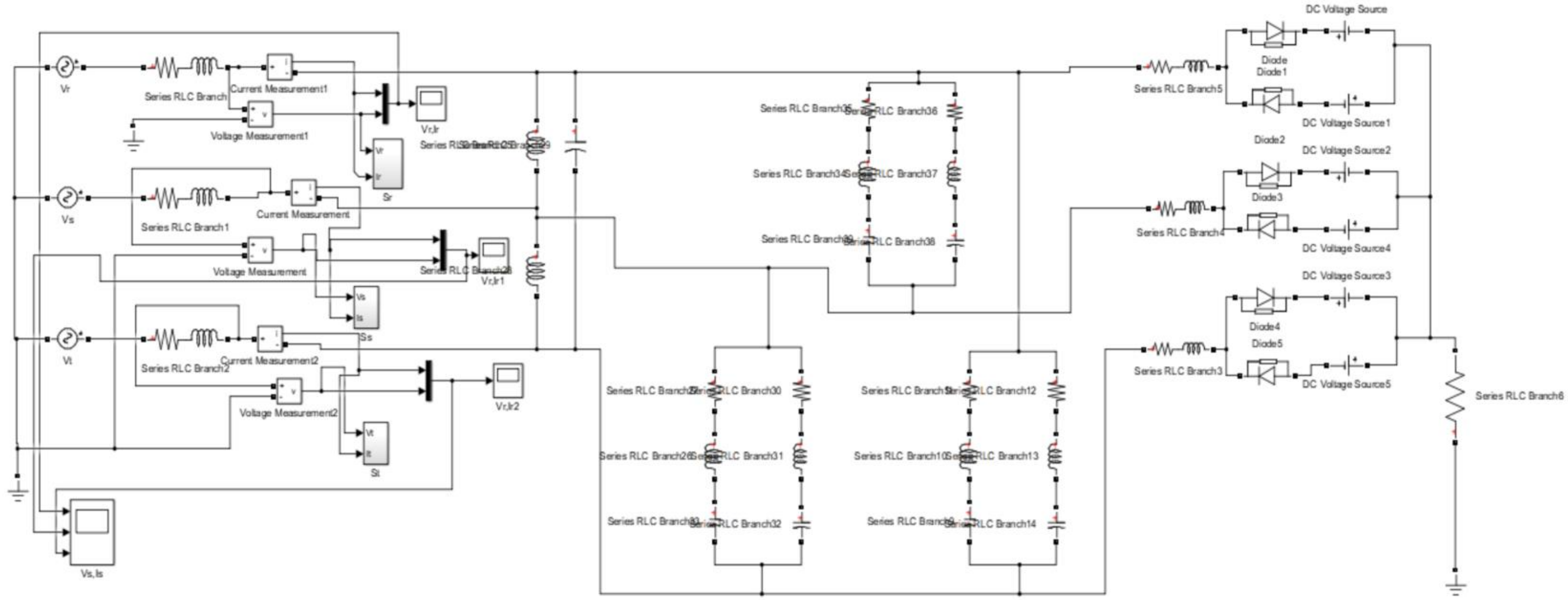

Figure 31: Simulink simulation with balancing compensators and equivalent RHF circuit

VITA

Ikenna Louis Ezeonwumelu was born in 1991, in Port Harcourt, Nigeria. He received his Bachelor of Science from Kwame Nkrumah University of Science and Technology, Ghana in 2013. He began his career as a City Council Engineer. As his interest in power grew, he decided to further his studies at Louisiana State University where he anticipates being awarded the degree of Master of Science in Electrical Engineering.