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The Effectiveness of Reactive Harmonic Filters of Ac Arc Furnaces in Uneasy Mode

Leszek S. Czarnecki, Venkata M. Gadiraju, Aditi Shinde
School of Electrical Engineering and Computer Science, Louisiana State University,
Baton Rouge, USA
lsczar@cox.net; www.lsczar.info; vgadir@lsu.edu; shindeaditi92@gmail.com

Abstract: – Resonant harmonic filters are commonly installed on the primary side of the arc furnace transformer, and consequently, the transformer is exposed to the furnace generated current harmonics, the furnace reactive and unbalanced currents.

The effectiveness of resonant harmonic filters installed directly at the furnace terminals, i.e., on the secondary side of the furnace transformer, is investigated in this paper. Such filters operate in conditions of fast varying parameters of the furnace. This can cause a decline in the filter effectiveness of harmonics reduction and a decline in the effectiveness of the power factor improvement. This paper investigates the effectiveness of resonant harmonic filters in an uneasy mode of an arc furnace operation. This study should enable us to draw some quantitative conclusions on the usefulness of resonant harmonic filters installed directly on the furnace.

Key words: ***resonant harmonic filters, Current's Physical Components, CPC***

I. INTRODUCTION

Resonant harmonic filters (RHF) needed for reducing the voltage and current distortion of AC arc furnaces are commonly installed on the primary side of the arc furnace transformer [1, 3, 6]. When installed in such a way, they can reduce not only harmonic originated in the furnace, but also originated in the furnace transformer. It is advantageous, but the transformer is exposed to current harmonics originated in the furnace arcs nonlinearity. It is also exposed to the reactive current, which can be compensated along with the current harmonics.

Installation of harmonic filters on the primary side of the transformer is supported by a tradition, how-now, and by a filter technology developed for that. Moreover, the needed capacitance of harmonic filters is lower when the filter operates at a higher voltage as compared to the capacitance which is needed when the filter operates at the lower voltage

The energy loss in the furnace transformer can be reduced, however, when the reactive as well as, the unbalanced power of the furnace is compensated on the secondary side of the transformer. The same applies to the energy loss in the transformer, caused by the furnace current harmonics. To protect the transformer against current harmonics, filters on its secondary side are needed. Therefore, a sort of discussion as to the place of filters location seems to be justified. Maybe, the present state of technology makes installation of filters on the secondary side of the furnace transformer possible.

The basic structure of an AC arc furnace with a transformer and a resonant harmonic filter under study in this paper is shown in Fig. 1.

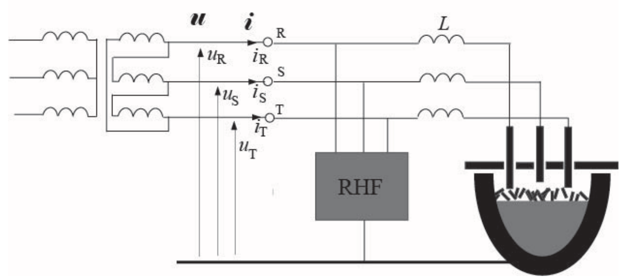

Fig. 1. Ac arc furnace with a furnace transformer and an RHF in Y configuration.

Compensation of the reactive power on the secondary side of the transformer could be also beneficial for the arc furnace melting operation. Such compensation increases the voltage rms value on the furnace arcs to a larger degree when the reactive power is compensated on the primary side.

When filters are installed on the primary side of the furnace transformer, then the random phenomena in the arc, along with their effect on the furnace transformer, cause that design of a filter has to be based on statistical properties of the arc furnace whole assembly. Also, the effectiveness of the filter can be evaluated only in statistical terms. There is no space for a deterministic analysis of the filter performance.

However, even if the arc ignition is a random phenomenon, then after it is ignited, the arc can be regarded over a single period T, or over a few of them, as a deterministic process. When a filter is connected directly to the furnace terminals, then deterministic analysis of the filter performance becomes possible. Such a deterministic approach was adopted in this paper. A statistical approach to studies on the filter effectiveness, when for some interval of time the furnace operates in a balanced mode, with a very low level of harmonics, and next for some time with a unidirectional arc, with a very high level of harmonics, would not probably provide credible results.

This paper presents results of modeling-based studies, on the effectiveness of filters installed at the secondary side of the arc furnace transformer, in three basic states of the furnace operation, namely, in state s0, s1 or s2, and in s3, as illustrated in Fig. 2. Other states are also possible, but they are ignored in this study.

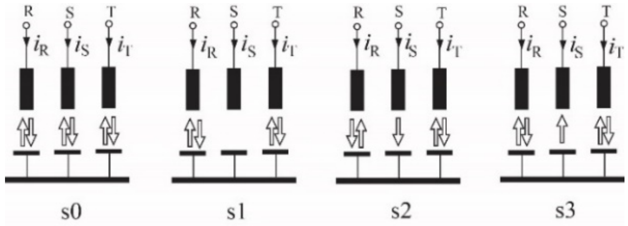

Fig. 2. States of an arc furnace operation.

The state of the furnace in the uneasy mode of operation changes randomly with the charge displacement in the melting process.

An electric arc is not equivalent to a short-circuit. There are a number of different models of arcs [2], but its selection has a secondary importance from the point of view of this paper. Therefore, a relatively simple model is selected here. It is namely assumed that the voltage on the arc has a constant value U_0 = 300V. It means that the MODEL 4 of the arc, discussed in [2], was adopted for the arc furnace analysis. The adopted model of the arc is shown in Fig. 3.

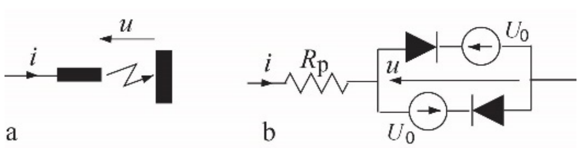

Fig. 3. A circuit (b) that approximates the arc (a).

The symbol R_p in this model represents the arc plasma resistance. It depends on the plasma parameters, such as the temperature, pressure and the arc geometry. It can be assumed, however, that in a time interval compared with the supply voltage period T, these parameters do not change, so that the plasma resistance R_p is constant.

II. A REFERENCE ARC FURNACE

Studies in this paper are carried out with the idea that the drawn conclusions would be applicable to ultra-high-power ac arc furnaces, which can have presently the power ratings at the level of 750 MVA. At such a power, available transformers do not have rated power much higher than the furnace rated power. Hence, the transformer reactance X_s, as compared to the furnace line reactance ωL, is relatively high. Consequently, compensation of the furnace reactive current by the RHF can strongly affect the furnace supply voltage.

Studies in this paper are based on modeling, so that specific data are needed for that. It was assumed for these studies that the transformer short-circuit power is only four times higher than the furnace power. The furnace supply voltage rms value can be in a range of 400 V to 1300 V. It was assumed for modeling in this paper that the transformer secondary voltage rms value equal to E = 700 V and the reactance-to-resistance ratio X_s/R_s = 5.

Computer modeling of ultra-high-power furnaces, due to currents at a level of hundred thousand amperes, would be very inconvenient. Therefore, analysis and modeling in this paper are performed for a low power furnace, regarded as reference furnace, which keeps proportions of ultra-high-power furnaces and transformer parameters.

A total line resistance, which includes the resistance of the supply line, inductor, plasma resistance R_p and the resistance of the melted steel, is denoted by R.

Assuming that the line resistance R = 0.25Ω, then from modeling results that the furnace operates at the power factor λ = 0.7 when the line reactance is X =1.0 Ω. Results of modeling are shown in Fig. 4.

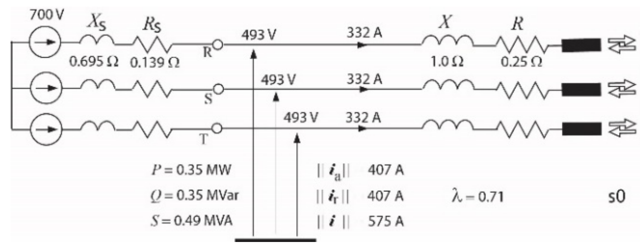

Fig. 4. The results of modeling of a furnace which operates at the power factor λ = 0.71 in state s0.

Symbols $||\boldsymbol{i}_a||$, $||\boldsymbol{i}_r||$ and $||\boldsymbol{i}||$ in Fig. 4 stand for the three-phase rms value of the active, reactive and the total three-phase load currents, defined in the frame of the Currents Physical Components (CPC)–based power theory in [5].

As long as the supply voltage rms value, assumed to be E = 700V, and the ratio of the transformer and the furnace powers 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 $a = S$[MVA]/0.49 MVA. For the arc furnace of the power rating S = 750 MVA, this scaling coefficient is equal to a = 1531. At a different supply voltage rms value than assumed E= 700V, the scaling coefficient $a = S/0.49 \times 700/E$ provides only an approximate value of the furnace currents because the arc is nonlinear, however.

The waveforms of voltages and current in line R at a balanced mode of operation, i.e., in the state s0, are shown in Fig. 5.

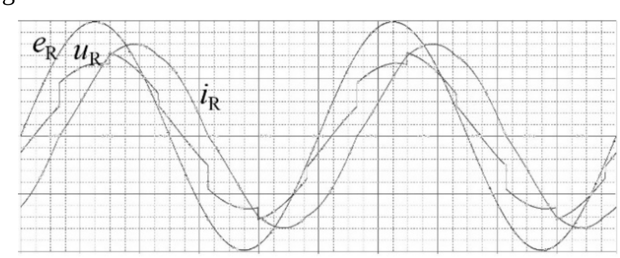

Fig. 5. Waveforms of voltages and the current in line R at furnace balanced operation, i.e., in the state s0.

Distortion of the furnace current in this state of operation is very low, of the order of only 2%. It means, that filters are not needed in this state of operation. They have to be installed only because harmonics occur in the supply current in other states of the furnace operation. In this state of operation s0, the filter can compensate the reactive current, however.

When the arc in one line, for example in line S, is not ignited, i.e., the furnace operates in the state s1. The arcs in this state are connected in series and are supplied with the line-to-line voltage e_{RT}. The voltages and current waveforms in such a state are shown in Fig. 6.

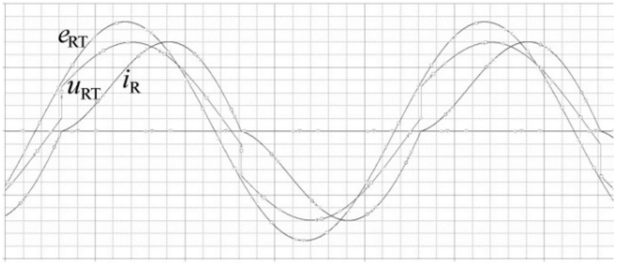

Fig. 6. The waveforms of line-to-line voltages and line R current in the state s1.

Distortion of the furnace current in this state increases because two arcs operate in series, while the voltage on them increases only by a root of two, so that the arc nonlinearity affects the current waveform to a higher degree. Nonetheless, the current distortion is still relatively low, at a level of 7%. There is also a substantial decline in the power factor. The furnace unbalanced current is responsible for that.

When an arc is ignited only in one direction, in particular when it is in the state s2, the waveforms of voltages and currents change as shown in Fig. 7.

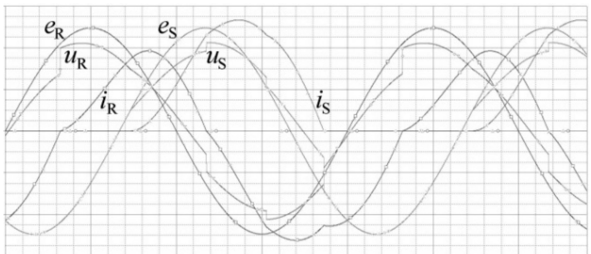

Fig. 7. The waveforms of the voltage and currents in lines R and S in the state s2.

Unidirectional arc causes a dramatic increase in the current distortion, up to the level of 40%. The even order harmonics, including the zero order (a dc component), are the dominating harmonics of the furnace current.

III. Harmonics Generated By Arc Furnace

Ac arc furnaces of ultra-high power are sources of the current and voltage distortion to such degree that other sources of this distortion could be ignored, therefore, it is assumed in studies presented in this paper that the furnace under consideration is supplied with sinusoidal and symmetrical voltage.

Assuming that same possible asymmetries between individual arcs are ignored and an asymmetry at the current flow direction, the harmonic spectra of the furnace current in specific states of the furnace are relatively well predictable.

Only harmonics of the odd order n can be generated in the furnace in the state s0. However, because of the furnace symmetry, any harmonic of the zero symmetrical sequence, i.e., $n = 3k$ cannot occur in the supply lines.

The furnace symmetry disappears in the state s1 and harmonics of the zero symmetrical sequence, in particular, the third order harmonic, can occur in the furnace current.

In states s2 and s3, i.e., at unidirectional arcs, harmonics of all orders, including the zero sequence harmonic, i.e., a dc component, occur in the current.

The vector of a furnace line current can be presented [5] as a sum of harmonics and presented in the form

$$\boldsymbol{i} = \begin{bmatrix} i_R \\ i_S \\ i_T \end{bmatrix} = \sum_{n=0}^{\infty} \boldsymbol{i}_n \approx \begin{bmatrix} I_{R0} \\ I_{S0} \\ I_{T0} \end{bmatrix} + \sqrt{2}\mathrm{Re}\sum_{n\in N} \begin{bmatrix} \boldsymbol{I}_{Rn} \\ \boldsymbol{I}_{Sn} \\ \boldsymbol{I}_{Tn} \end{bmatrix} e^{jn\omega_1 t} \tag{1}$$

Symbol N denotes the set of the current harmonics order n, including the fundamental, $n = 1$. The furnace current can be decomposed next into the vector of the fundamental harmonic $\boldsymbol{i}_1$ and a harmonic current $\boldsymbol{i}_h$, namely

$$\boldsymbol{i} = \boldsymbol{i}_1 + \boldsymbol{i}_h . \tag{2}$$

The current distortion is specified as s

$$\delta_i = \frac{||\boldsymbol{i}_h||}{||\boldsymbol{i}_1||} \tag{3}$$

where a vector in double bars ||.|| denotes a three-phase rms value of that vector, defined in [5] as

$$||\boldsymbol{x}|| = \sqrt{||x_R||^2 + ||x_S||^2 + ||x_T||^2} . \tag{4}$$

The results of modeling of the arc furnace under consideration in the states s0, s1 and s2 are compiled in Table1.

--	--	s0	s1	s2
$\|\|\boldsymbol{u}\|\|$	V	854	1070	958
$\|\|\boldsymbol{i}\|\|$	A	575	370	525
P	kW	350	229	302
λ	-	0.71	0.58	0.61
δ_i	-	2.2	7.5	40.7
$\|\|\boldsymbol{i}_0\|\|$	A	-	-	168
$\|\|\boldsymbol{i}_1\|\|$	A	574	368	460
$\|\|\boldsymbol{i}_2\|\|$	A	-	-	77.8
$\|\|\boldsymbol{i}_3\|\|$	A	-	25.0	17.3
$\|\|\boldsymbol{i}_4\|\|$	A	-	-	17.4
$\|\|\boldsymbol{i}_5\|\|$	A	11.1	9.0	8.3
$\|\|\boldsymbol{i}_6\|\|$	A	-	-	7.5
$\|\|\boldsymbol{i}_7\|\|$	A	5.6	4.6	5.0

Table 1. Results of a furnace modeling in states s0, s1, and s2.

It should be noticed that a dc current which occurs at unidirectional arcs, i.e., in states s2 and s3, cannot be transformed to the primary side of the transformer, but it saturates its core. This, in turn, can cause additional distortion of the transformer primary side current.

IV. Resonant Harmonic Filters

For most of the time in one cycle of a steel production, the arc furnace operates in the state s0. The line reactance is commonly selected by the furnace operator to keep the power factor at the level of 0.7, meaning, the reactive power Q is kept on a level of the active power P of the furnace. Due to the arc nonlinearity, the line reactance X has to be a few times higher than the furnace resistance R. The reference furnace at its supply conditions, as assumed in this paper, and R = 0.25 Ω, has $Q = P$ when X = 1.0 Ω, i.e., the line reactance is four times higher than the furnace resistance.

Arc furnaces in a balanced state (s0) do not cause substantial distortion of the supply current. The 3rd order harmonic, as the zero sequence harmonic, cannot occur in symmetrical line currents, so that the 5th order harmonic is the lowest order harmonic of the supply current. The 3rd order harmonic occurs in the supply current in the state s1 because of the current asymmetry. A dramatic increase in the furnace current distortion occurs at unidirectional arcs, i.e., in the states s2 and s3, mainly due to the dc component and harmonics of the even order, $n = 2, 4, 6\ldots$

A presence of a unidirectional arc, meaning 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, mainly the second order harmonic. Such order current harmonics should not occur either in state s0 nor in state s1. Switching compensators, known as active power filters, built of power transistors, due to their limited switching power, cannot be probably used presently for reducing current harmonics of ultra-high-power arc furnaces. Resonant harmonics filters are needed for that. Such a filter has to be connected permanently, for the whole cycle of the steel production. There are no technical means for switching the filter ON/OFF, depending on the furnace state.

A general structure of a filter, per phase, is shown in Fig. 8.

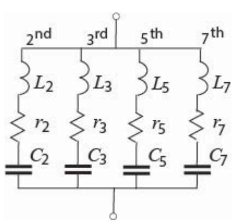

Fig. 8. A resonant harmonic filter structure

They can be configured in Δ or in Y structure. The selected structure has an effect on the filter parameters, on the attenuation of the zero sequence harmonics and on the possibility of capacitor grounding. Since these are not the issues for studies in this paper, it was assumed for modeling, that the filter is configured in Δ.

The subject of this paper is not a method of design of RHFs for arc furnaces, but studies on their effectiveness in harmonic reduction. Therefore, the effectiveness of single-branch filters, tuned separately to only two, the most dominating harmonics, the 2nd and the 3rd order, will be investigated. The effectiveness of a two-branch filter tuned to the 2nd and the 3rd order harmonics will be studied as well.

Since it was assumed in this study that the distribution voltage harmonics are negligible as compared to those generated by the arc furnace, there is no need for de-tuning the filter branches from harmonic frequencies, $n\omega_1$, $n = 2, 3, 5$, as it was discussed in [4, 5]. Thus, branches should be tuned to the frequencies

$$\frac{1}{\sqrt{L_n C_n}} = n\,\omega_1, \qquad n = 2, 3, 5. \tag{5}$$

It will be also assumed that according to a suggestion in [1] each branch of the filter should compensate the same amount of the reactive power of the fundamental harmonic Q_1, thus in a case of a K-branches filter, a single branch compensates the reactive power $Q_1/(3K)$. Thus, a branch tuned to the n^{th} order harmonic with susceptance for the fundamental frequency B_{1n}

$$B_{1n}U_1^2 = \frac{\omega_1 C_n}{1-\omega_1^2 L_n C_n}U_1^2 = \frac{1}{3K}Q_1 \tag{6}$$

Equations (5) and (6) results in the filter parameters

$$C_n = \frac{1}{3K}\Big(1-\frac{1}{n^2}\Big)\frac{Q_1}{\omega_1 U_1^2} \tag{7}$$

$$L_n = \frac{1}{n^2\omega_1^2 C_n}. \tag{8}$$

The resistance R_n in Fig. 8 stands for the inductor's equivalent resistance. It is specified by the inductor's quality factor q, defined as

$$q = \frac{\omega_1 L_n}{R_n}. \tag{9}$$

It was assumed for the filter modeling that $q = 50$.

An RHF at the fundamental frequency is equivalent to a capacitance. This capacitance compensates the fundamental harmonic of the reactive current of the furnace, thus it improves its power factor.

The arc furnace operates for most of the time in the state s0, with the power factor maintained for arcs stability, at the level of 0.7. Parameters of the filter can be selected such that the power factor in the state s0 is improved to almost unity value. In fact, in the state s0, the filter operates only as the compensator of the reactive current because the furnace does not generate current harmonics at such a level that should be reduced by a filter.

The most crucial of the RHF branches are those branches tuned to the dominating harmonics in the furnace current, namely, to the 2nd and to the 3rd order harmonics. The whole filter should have branches tuned to the 5th and to the 7ht order harmonic, but their presence does not contribute to the problem studied in this paper.

An individual RHF tuned to the 2nd order harmonic, connected permanently, independently on the state of the furnace, affects the furnace supply as shown in Table 2.

--	--	**s0**	**s1**	**s2**
$\|\boldsymbol{u}\|$	V	1083	1639	1244
$\|\boldsymbol{i}\|$	A	518	930	671
P	kW	560	316	540
Q_1	kvar	0	– 964	– 232
λ	-	0.999	0.21	0.65
δ_1	%	0	0	77
$\|\boldsymbol{i}_0\|$	A	0	0	411
$\|\boldsymbol{i}_1\|$	A	518	930	529
$\|\boldsymbol{i}_2\|$	A	0	0	1.6
$\|\boldsymbol{i}_3\|$	A	0	0	10.2
$\|\boldsymbol{i}_4\|$	A	0	0	4.8
$\|\boldsymbol{i}_5\|$	A	0	0	4.6
$\|\boldsymbol{i}_6\|$	A	0	0	4.2
$\|\boldsymbol{i}_7\|$	A	0	0	3.6

Table 2. Results of modeling a reference arc furnace with RHF tuned to the 2nd order harmonic

The filter reduces in the state s0 the supply current three-phase rms value $\|\boldsymbol{i}\|$, and consequently, it increases the voltage on the furnace terminals and the active power i.e., it contributes an increase in the energy delivery to the furnace, thus to a reduction of the melting time. No harmonics are observed in the supply current. When an arc is not ignited, i.e., the furnace state changes to s1, not only the second order, but all harmonics are reduced. It is because the filter along with the transformer inductance creates a low-pass filter. However, a dramatic increase of the current rms value is observed. It is because of the over-compensation of the furnace. Its power factor λ declines to a very low value.

The effects a filter tuned to the 3rd order harmonics are shown in Table 3.

--	--	**s0**	**s1**	**s2**
$\|\boldsymbol{u}\|$	V	1085	1162	1237
$\|\boldsymbol{i}\|$	A	517	933	677
P	kW	561	229	541
Q_1	kvar	0	– 977	– 213s
λ	-	0.999	0.21	0.65
δ_i	%	0.6	0	82
$\|\boldsymbol{i}_0\|$	A	0	0	414
$\|\boldsymbol{i}_1\|$	A	516	933	524
$\|\boldsymbol{i}_2\|$	A	0	0	115
$\|\boldsymbol{i}_3\|$	A	0	0	0
$\|\boldsymbol{i}_4\|$	A	0	0	3.7
$\|\boldsymbol{i}_5\|$	A	2.7	0	1.5
$\|\boldsymbol{i}_6\|$	A	0	0	2.0
$\|\boldsymbol{i}_7\|$	A	1.7	0	1.7

Table 3. Results of modeling a reference arc furnace with RHF tuned to the 3rd order harmonic

The effects of two filters tuned to the 2nd and the 3rd order harmonics are shown in Table 4.

--	--	**s0**	**s1**	**s2**
$\|\boldsymbol{u}\|$	V	1091	1664	1228
$\|\boldsymbol{i}\|$	A	518	941	666
P	kW	564	294	536
Q_1	kvar	0	– 988	– 988
λ	-	0.999	0.19	0.65
δ_i	%	0.86	0.4	78
$\|\boldsymbol{i}_0\|$	A	0	0	412
$\|\boldsymbol{i}_1\|$	A	518	934	527
$\|\boldsymbol{i}_2\|$	A	0	0.5	2.4
$\|\boldsymbol{i}_3\|$	A	0	0.4	0.1
$\|\boldsymbol{i}_4\|$	A	0	0	5.3
$\|\boldsymbol{i}_5\|$	A	3.7	3.0	2.8
$\|\boldsymbol{i}_6\|$	A	0	0	2.7
$\|\boldsymbol{i}_7\|$	A	2.2	1.8	2.5

Table 4. Results of modeling a reference arc furnace with two RHF tuned to the 2nd and the 3rd order harmonics

It is worth to observe, that filters reduce also harmonics of the order above the tuning frequencies, i.e., the 2nd and the 3rd order. It is because the filter, with the transformer inductance, creates a low-pass filter.

The results compiled in Table 4 show that the problem overcompensation of the furnace in states s1 and s2 by the filter remains unchanged, however.

The reader should be aware as well that results of modeling as compiled above apply to the steady state of the furnace. Each change of the furnace state causes transients. They are beyond the scope of the research in this paper, however. An example of the transient in the line R when the furnace, with filters tuned to the 2nd and the 3rd order harmonics, is switched to the state s0, is shown in Fig. 9.

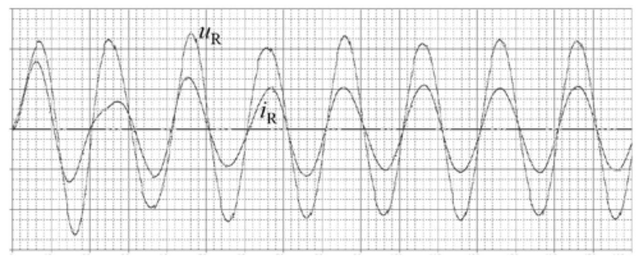

Fig. 9. The voltages and current in line R when the furnace is switched to state s0.

For parameters assumed in this paper, transients are observed over approximately five periods T.

V. CONCLUSIONS

Resonant harmonic filters connected directly on the terminals of the arc furnace, cause overcompensation of the furnace in states s1 and s2. At ultra-high-power of a furnace, when the furnace transformer has a relatively low power, i.e., a high inductive reactance, overcompensation causes a substantial increase of the voltage at the furnace terminals. Moreover, a dramatic increase of a dc component in the state s2, as shown in Tables 2, 3 and 4, can occur. Therefore, as long as over-compensation by RHFs is not handled by a sort of adaptive compensation, benefits of using such filters seem to be very problematic.

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