A Study on Direct Reduction of Harmonics of Ultra High Power AC Arc Furnaces in Uneasy Mode of Operation

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***Abstract*— An arc furnace (AF) transformer is exposed to harmonics generated by the furnace. To mitigate this, filters are installed usually at AF primary terminals. In this scenario, the harmful current components, namely, the furnace-generated harmonics, the unbalanced, and reactive current, contribute to the transformer energy loss. This loss can be reduced if the filter is installed at the secondary terminals of AF transformer.**

This article investigates and validates the furnace performance when the reactive current compensation and harmonic mitigation is implemented on the secondary side of AF transformer. The studies were performed using a real-time simulator OPAL-RT. Results from these studies can significantly enhance our understanding of the impact of filter installed at the furnace terminals.

Keywords*: *Harmonics mitigation, ultra-high-power furnaces, energy-loss reduction, Current's Physical Components, Filters

I. Introduction

Electric arc furnaces are devices that provide a substantial amount of steel for the manufacturing industry. These furnaces stand for high power loads, which draw very distorted, often random current, with a wide range of change of its rms value. Such furnaces contribute to the degradation of the power quality in the distribution systems [1] and create problems in the system protection [2]. Their common power is in the range of thousands of MVA, but there are also ultra-high-power (UHF) furnaces with the power ratings of several hundred MVA.

The AC arc furnaces, with the power which reaches currently the value of 750 MVA, which is comparable to one million population city and the yearly expenditures for the energy of the order of M$500, is one of the largest individual loads in electrical power systems.

Such furnaces are supplied from three-phase transformers. In common power systems, the supply transformers have power ratings several times higher than the load power. In the case of UHP arc furnaces, this cannot be satisfied. Such transformers are not available. Consequently, UHP arc furnaces are supplied from a transformer with the power ratings comparable with that of the furnace power rating. Such a transformer has relatively high short-circuit impedance.

The supply current of an ac arc furnace is composed, apart from the active current, also the reactive, unbalanced, and harmonic currents. The unbalanced current occurs due to the natural asymmetry of the furnace electrodes and arcs, as well due to arcs extinctions, especially in the uneasy mode of the furnace operation. These extinctions cause a sudden increase of harmonic distortion [3] of the furnace supply current. These currents cause the loss of energy in the furnace transformer windings, which due to its relatively high resistance, could be very high. This increases the required rating of the furnace transformers and can contribute [4] to the reduction of transformer life expectations.

Currently, the reactive current, along with the harmonic current, and sometimes also the unbalanced current, are compensated on the furnace transformer primary terminals [5, - 8, 14]. This is because currents on the primary side are lower and easier to be handled by harmonic filters and adaptive compensators. Unfortunately, such compensation does not reduce transformer energy loss. This issue can be handled if filters and compensators are installed on the transformer secondary side.

Compensation on the secondary side of AF transformer, meaning directly on the arc furnace, not only reduces the energy loss in the transformer but also it can reduce the requirements as to its power ratings, thus its cost. By reduction of the voltage drop on the transformer windings, compensation increases the voltage on the furnace, thus the effectiveness of the furnace in the melting process.

The power of arc furnaces changes in the melting process, so that the compensator should have an adaptive property. This could be particularly important in the uneasy phase of the furnace operation when some arcs can extinct and the furnace operates in a strongly unbalanced mode.

Possibility of the development of an adaptive compensator that would be capable of operating at the furnace terminals is confined by the switching capability of thyristors needed for such a compensator. Now, with the availability of thyristors which can switch current on the level of 50kA, development of such a compensator seems to be feasible, major investigations are needed for that, however.

The development of filters and an adaptive compensator installed at the furnace terminals necessitates that the electrical phenomena on the load side of the transformer are well comprehended. This paper just serves this purpose. It is devoted to studies on the electrical phenomena, directly at the furnace terminals, thus phenomena not hidden by the transformer.

These studies were carried on based on the MATLAB modeling of AC arc furnace operation states. Results of this modeling were confronted, for their verification with results obtained from a real-time simulation using OP-4510 simulator from Opal-RT Technologies. The samples of voltages and currents acquired from the simulator were stored for further analysis.

II. AC Arc Furnace

The electrical schematic of AC arc furnace is shown in Fig. 1. The transformer is configured on the secondary side in Δ to protect the primary side against the 3rd order current harmonics. The line inductors are connected in series with electrodes for the arc stabilization. The cage is covered inside with a high resistance ceramic so that the cage grounding

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does not provide the pass for arc currents. The furnace has to be regarded as a load supplied with a three-wire line.

In the first phase of the whole cycle of the furnace operation, when the scrap loaded in the cage is not yet melted and it is on move, specific arcs can be extinct or not be fired. This is considered as an uneasy mode in the furnace operation [13].

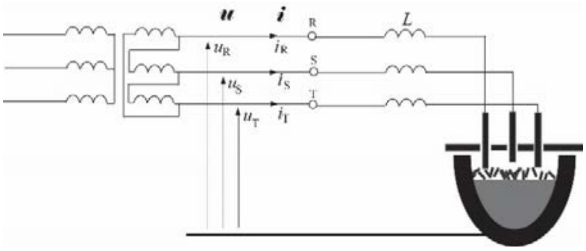


Fig. 1. An electrical schematic of an arc furnace.

Assuming for simplicity sake that the arcs in phases R and T are normally fired and the only arc that could be fired or not is in phase S, we can conclude that the furnace can be in one of four states, shown in Fig. 2.

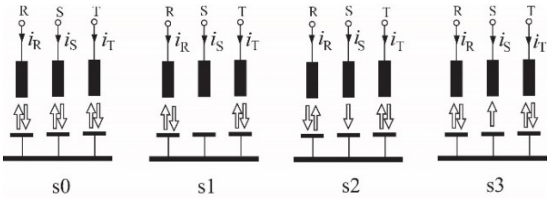


Fig. 2. Operation modes of a furnace.

These states are marked as states s0, s1, s2, and s3. In operating modes s2 and s3, we observe that the arc is unidirectional, with positive (s2) or negative (s3) current [12]. Modes s2 and s3, i.e., the states with unidirectional arc, although can occur, it is very unlikely that they can remain for a long time. It can be expected that they may occur only during a transition from s0 to s1 and in the opposite transition, i.e., from s1 to s0. Anyway, there are no reports in the subject literature that the operation of furnaces with unidirectional arcs was observed. Therefore, there are no reasons to take such an operation into account in this paper.

An electric AC arc is a nonlinear phenomenon. It is fired when the voltage u between the electrode and the melted scrap reaches a specified value U_0, depending on the length of the arc [9]. When the arc is fired, the voltage on the arc remains almost constant. The AC arc can be modeled as two diodes, as illustrated in Fig. 3, incorporating DC voltage sources in series and a resistor which represents the arc plasma resistance.

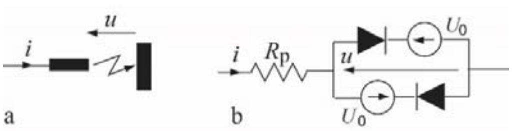


Fig. 3. AC arc schematic (a) and its equivalent model (b).

III. Reference Furnace Model

Analysis carried out in this study was aimed at UHP arc furnaces of the power ratings of 750 MVA or higher, supplied from a transformer of relatively low power ratings, almost comparable with the power ratings of the arc furnace. Such a transformer can have the windings reactance X_S of the same order as the furnace line reactance ωL. Thus, compensation with filters installed on the secondary terminals can significantly affect the voltage of arc furnace.

Analyses in this article are performed with an assumption that power ratings of AF transformer are 4 times larger than that of furnace power, with the secondary voltage E = 700 V rms and $X_s/R_s = 5$ (reactance-to-resistance ratio).

Modeling and analysis of the furnace with such a high level of the power ratings could be cumbersome, however. Therefore, it is performed in this paper on an equivalent low power arc furnace. Results obtained can be extended for UHR arc furnaces.

Resistances of arc plasma R_p, supply line, melted steel, and the inductor are collectively represented as R. With a line resistance and reactance as $R = 0.25\ \Omega$, $X = 1.0\ \Omega$. and at the power factor of $\lambda = 0.7$. Modeling results are demonstrated in Fig. 4.

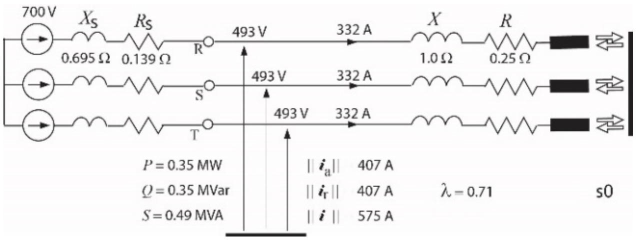
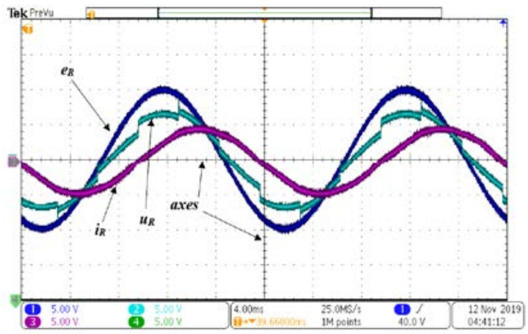
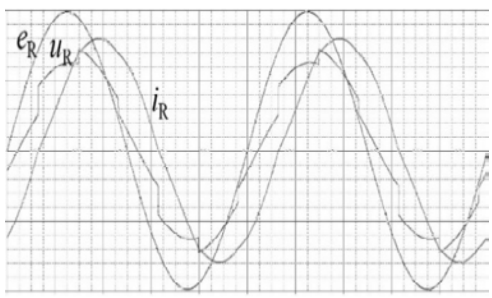


Fig. 4. An equivalent circuit of the arc furnace with the transformer and modeling results of the furnace in s0.

Symbols $||\boldsymbol{i}_a||$, $||\boldsymbol{i}_r||$ and $||\boldsymbol{i}||$ in Fig. 4 denote 3-phase active, reactive RMS currents and load currents rms respectively as defined in the Current's Physical Components (CPC) - power theory [15]. Detailed analysis and calculation of the scaling parameters for any arbitrary furnace are presented in. Current and voltage waveforms of phase R in the balanced mode (s0) of furnace operation are shown in Fig. 5.



(a)



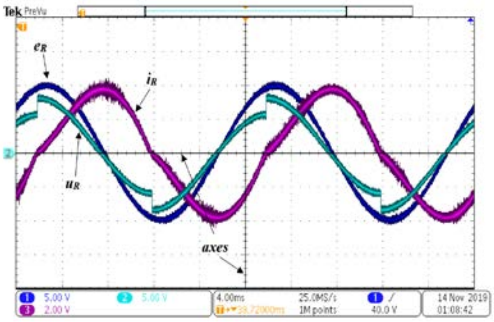
(b)

Fig. 5. Current and voltage waveforms of phase- R in state s0. (a) results from real-time simulation, (b) results from MATLAB.

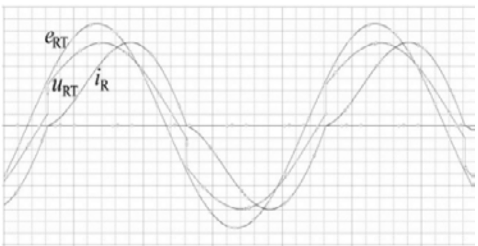
One of the goals of this paper is a comparison of the results of the arc furnace analysis obtained using a real-time simulator, with those obtained from Simulink modeling. The waveforms, shown in Fig. 5 (a) and (b), demonstrate that these results seem to be comparable. This comparison serves also as a sort of validation of the results obtained.

Current distortion in the balanced mode (s0) of furnace operation is low, of the order of 2%, which implies that the presence of a filter in such a state is not mandatory. To mitigate harmonics in the supply current in other operation modes and for compensation of the reactive current in the state s0 the filter is necessary, however.

When a furnace operates with one arc extinct, it is in the mode s1. In this mode, arcs are supplied with e_{RT} (line-to-line) voltage and in series. The voltage and current waveforms in the state s1 are shown in Fig. 6.



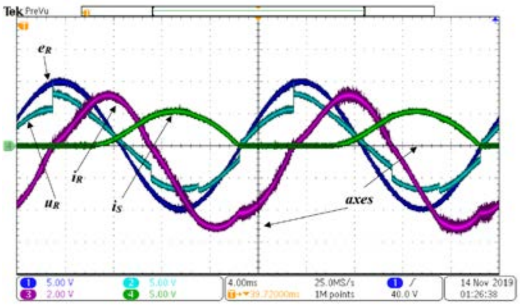
(a)



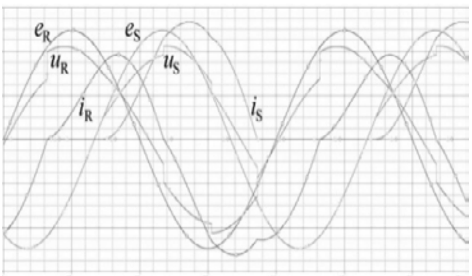
(b)

Fig. 6. Voltage and current waveforms in state s1.
(a) results from real-time simulation, (b) results from MATLAB.

In the state s2, one arc is unidirectional. The current and voltage waveforms are in this state are shown in Fig. 7.



(a)



(b)

Fig. 7. Current and voltage waveforms of phase- R in state s2.
(a) results from real-time simulation, (b) results from MATLAB.

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. This state is not likely to occur for a long time, however.

IV. AC Arc Furnace Harmonics

Ultra-high-power arc furnaces are bulk-sources of harmonic distortion. As compared to this distortion, the power system-originated distortion can be ignored. The same applies to the supply voltage asymmetry. Therefore, it was assumed in this study that AF is supplied with symmetrical sinusoidal voltage. It simplifies the analysis of harmonic spectra of furnace current in various furnace operation modes.

In the state s0, we observe only the occurrences of the odd-order harmonics. Owing to furnace symmetry, rest of the harmonic components i.e., $n = 3k$ are not observed in supply lines. Whereas, in the state s1 the furnace asymmetry causes harmonics of zero sequence and 3rd to be present in the furnace current. In s2 and s3 modes of furnace operation, there is an occurrence of unidirectional arc, resulting in the presence of all order harmonic components in the current.

Furnace current can be represented as a vector in [10]

$$\boldsymbol{i} = \begin{bmatrix} i_{\mathrm{R}} \\ i_{\mathrm{S}} \\ i_{\mathrm{T}} \end{bmatrix} = \sum_{n=0}^{\infty} \boldsymbol{i}_n \approx \begin{bmatrix} I_{\mathrm{R0}} \\ I_{\mathrm{S0}} \\ I_{\mathrm{T0}} \end{bmatrix} + \sqrt{2}\,\mathrm{Re}\sum_{n\in N} \begin{bmatrix} \boldsymbol{I}_{\mathrm{R}n} \\ \boldsymbol{I}_{\mathrm{S}n} \\ \boldsymbol{I}_{\mathrm{T}n} \end{bmatrix} e^{jn\omega_1 t} \qquad (1)$$

wherein, N represents the set of harmonic order n, with fundamental, n=1 included. The furnace current vector can be further decomposed as the sum of fundamental $\boldsymbol{i}_1$ and the harmonic current component $\boldsymbol{i}_{\mathrm{h}}$

$$\boldsymbol{i} = \boldsymbol{i}_1 + \boldsymbol{i}_{\mathrm{h}} . \qquad (2)$$

Current distortion is evaluated as

$$\delta_{\mathrm{i}} = \frac{||\boldsymbol{i}_{\mathrm{h}}||}{||\boldsymbol{i}_1||} \qquad (3)$$

Here, double bars ||.|| for a vector (1), represents a three-phase rms value of the vector. Modeling results of the furnace in various operation modes are tabulated in Table1.

$$||\boldsymbol{x}|| = \sqrt{||x_{\mathrm{R}}||^2 + ||x_{\mathrm{S}}||^2 + ||x_{\mathrm{T}}||^2} \ . \qquad (4)$$

Table 1. Modeling results of the furnace.

--	--	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

In the states s2 and s3, the DC current of the unidirectional arcs is not transformed to primary, thus, saturating the core.

Thereby increasing current distortion on the primary side.

The Table 1 shows that if the states s2 and s3 are ignored as they are not very likely to occur, that the highest value at the level of 25%, has the 3rd order harmonic in the state s1. The next ones that can be a matter of concern are harmonics of the 5th and the 7th order.

V. HARMONIC FILTERS

Conventionally, Resonant Harmonic Filters (RHF) are installed on the primary terminals of AF transformer to mitigate the current distortion [3-6]. Such filters have the capability of reducing both harmonics originated in AC furnace as well as in the transformer. Besides, the filter capacitance required is much lower when RHF operates at a high voltage. The AF transformer remains, however, exposed to reactive current and the furnace current harmonics caused by the arc nonlinearity.

Reduction in energy loss in the AF transformer can be achieved by reduction of harmonics, the reactive, and unbalanced currents To limit the exposure to harmonics and minimize the energy loss, the RHF should be installed on the secondary side of the transformer.

When a compensator is installed the transformer secondary terminals, it increases the furnace voltage rms value. Thus, enhancing the melting operation. Usually, a furnace operates in the balanced mode (s0) in the final and the longest interval of steel production. Hence, the line reactance is selected in such a way that furnace operates at the power factor of 0.7. To reach this value in the presence of the arc non-linearity, the line reactance has to be higher than the furnace resistance.

In the balanced mode s0 of the furnace operation, owing to the assumed in this study symmetric nature of arcs, the 3rd, and the 0th order harmonics cannot appear in the supply current. Hence, distortion is substantially low as we have only the 5th order harmonic. When furnace operates in the state s1, the presence of the 3rd order harmonic is observed. This is caused by the current asymmetry. A drastic increase in the distortions occurs in the modes s2 and s3 due to the presence of the 0th order (a dc-component) and other even-order harmonics.

Due to limitations of the available on the market power transistors' switching capability, switching compensators built of such transistors cannot be used for harmonic mitigation in UHP arc furnaces. RHFs needed for that It is assumed in this paper that RHFs are installed as shown in Fig 8. These filters cannot be switched OFF during the entire cycle of steel production because changes in the furnace modes are too fast while transients in filters at such changes cannot be avoided.

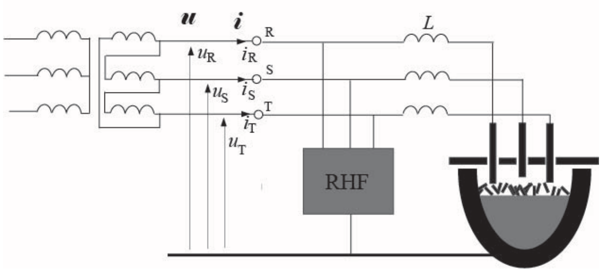


Fig. 8. A diagram of an arc furnace with a RHF.

The filter parameters depend on its structure, meaning Δ or Y configuration. The selection of the structure also affects the grounding possibility, as well as the possibility of reduc-tion of the zero-sequence harmonics, mainly the zero and the 3rd order harmonics. It assumed for these studies that filters are configured in Y. An individual branch of the filter, usually tuned to the frequency of the 3rd, 5th, and the 7th order harmo-nics, has the structure shown in Fig. 9.

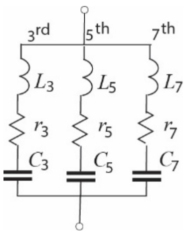


Fig. 9. A branch of a RHF structure.

Ultra-high-power arc furnaces are usually supplied from dedicated generators therefore, the supply voltage is sinusoiddal with high accuracy. This improves the performance of RHFs, since its branches do not have to be de-tuned from the harmonic frequencies, to avid a short-circuit for the supply system originated voltage harmonics. This substantially simplifies the filter design process as compared to the method discussed in [11].

According to this, the parameters of the filter branches should satisfy the condition

$$\frac{1}{\sqrt{L_n C_n}} = n\,\omega_1, \qquad n = 3, 5, 7. \tag{5}$$

Although the term "resonant harmonic filter" suggests that the filtering of harmonics is the main function of these devices, compensation of the load reactive power is equally important and maybe, in the case of the AC arc furnaces, even more important. Current harmonics have a substantially lower impact upon the power factor than the reactive current of the furnace. In an attempt of the power factor improvement, first, the reactive current has to be reduced. Current harmonics reduction can be regarded as a sort of a by-product at the reduction of the reactive current.

In the presence of the supply voltage harmonics, there are different strategies [1] as to the amount of the reactive power compensated by branches tuned to particular harmonic frequencies. This problem is irrelevant in the absence of the supply voltage harmonics and we can assume, after [1], that each branch compensates the same amount of the reactive power of the fundamental harmonic Q_1. Thus, if the filter is tuned to K frequencies, its parameters have to satisfy the condition

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

where B_{1n} is the branch susceptance at the fundamental frequency. Conditions (5) and (6) are used for calculating the filter parameters

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

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

If the inductors of the filter have equivalent resistance R_n, then their quality factors for the fundamental frequency are

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

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

AC arc furnace conventionally operates at a power factor of 0.7, maintaining arcs stability for long time intervals. Thus, filter parameters are designed in such a way that the unity power factor is attained in mode s0. Hence, the RHF operates almost only as a reactive compensator, since the furnace generated harmonics in this state, as shown in Table 1, have very low value.

Due to the random distribution of the steel load inside of the furnace cage, especially in the uneasy phase of the furnace operation, and random properties of electric arc, the RHF operates in a random environment, where the states s0, s1, s2. s3 change randomly. Consequently, the performance of RHFs can be specified only in statistical terms. This makes impossible to evaluate the effect of the filter parameters on its performance. This is possible only when the filter operates at deterministic conditions. Therefore, to enable such a study, we will assume that when the arc furnace operates in a fixed state, i.e., in one of the states s0, s1, s2, s3, then in intervals of a few periods *T* long, the voltages and currents do not change randomly, but in a deterministic way.

Even thous the RHFs should reduce more than one harmonic in the supply current, the most crucial is the reduction of the 3rd order harmonic. This study will demonstrate the arc furnace performance in a situation when just only one filter, tuned to the 3rd order harmonic and designed for improving the power factor in the basic state, namely the state s0, is exposed to the situation where the furnace goes over the states s1 and the state s2.

The diagram of the voltage and current at terminal R, for the furnace in the state s0, provided by the OP-4510 simulator, is shown in Fig. 10. It demonstrates that the current i_R is in-phase with the voltage u_R. The performance of the system with this only filter are compiled in Table 2. It improves the power factor to almost unity value but reduces, as compared to Table 1, even the 5th and the 7th order harmonics.

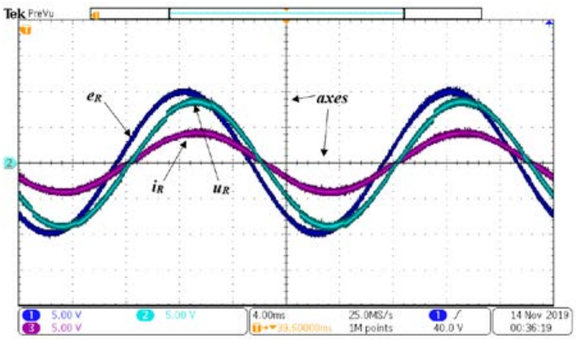


Fig. 10. Voltage and current waveforms on terminal R in state s0 with the filter of tuned to 3rd order.

Unfortunately, when the state of the furnace changes from s0 to the state s1, meaning one arc extinct, in the presence of the filter there is a sort of a disaster. The power factor declines dramatically. This is because the reactive power Q_1 in state s1 is much lower than in the state s0. Thus, the filter designed to compensate the reactive power Q_1 in the major state, s0, causes the furnace over-compensation. It means that the AF transformer is loaded with a capacitive current. This transformer, because of relatively low power ratings as compared to the furnace power, has a high impedance, so that, at a capacitive current, the voltage on the furnace, as can be seen in Table 2, increases, and the reactive power Q_1 increases even more.

The voltage and current waveforms at terminal R, provided by the OP-4510 simulator, of the furnace with a filter of the 3rd order harmonic in the state s1, are shown in Fig. 11. These diagrams explain clearly why the power factor is so low.

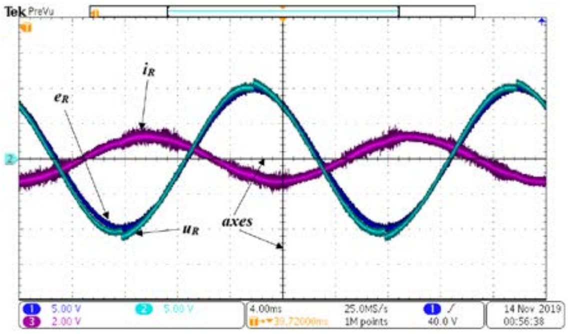


Fig. 11. Waveforms of voltages and current in the state s1 of the furnace with the filter of the 3rd order harmonic.

As it is shown in Table 2, the filter of the 3rd order harmonic reduces effectively also the 5th and the 7th order harmonic, but this does not balance, of course, the power factor degradation and dramatic increase of the supply current.

When the arc furnace is in state s2, meaning with unidirectional arc, the over-compensation is not as strong as in the state s1, but a dramatic distortion of the supply current occurs. Harmonics of the order higher than three are reduced by the filter but of the lower order, meaning the 2nd and the zero-order are enhanced.

Table 2. Results of 3rd order harmonic filter installation

--	--	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	– 213
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

The effects of three-branch filters, tuned to the 3rd, 5th and the 7th order harmonics, on the furnace performance were investigated in this research as well. Apart from some differences in numbers, the main picture of the problem is comparable with that, when the filter is tuned to only the 3rd order harmonic, however. The problem of over-compensation in states other than s0 cannot be avoided and this has devastating effects on the power factor value.

These studies demonstrate that reduction of harmonic distortion along with compensation of the reactive power of UHP arc furnaces by filters/compensators, installed on the secondary side of the AF transformer, and with fixed parameters does not seem to be possible. Filters/compensators with adaptive properties are rather needed for that. Simple switching could not be sufficient for that because of transients which occur when a filter or its parameters are switched ON-OFF, or even the state of the furnace changes.

Fig. 12 shows transients in the voltage and current waveforms at terminal R when the furnace with a filter tuned to the

3rd order harmonic returns to the state s0. Four periods are approximately needed to reach a steady-state of the system.

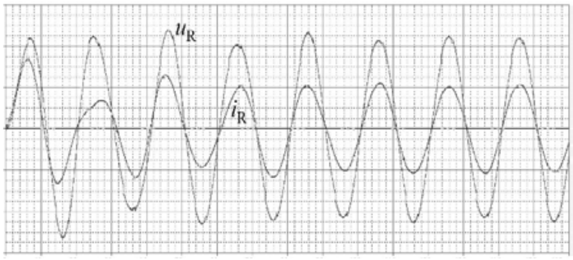


Fig. 12. A transient state in the supply line R.

VI. CONCLUSION

The study shows that a resonant harmonic filter installed on the secondary side of the AF transformer and designed for the improvement of the power factor in the main state of the furnace, s0, causes over-compensation in other states of the furnace and degradation of the power factor.

To avoid it, a filter/compensator installed on the secondary side of the furnace transformer should have adaptive properties. It is very unlikely, that compensation can be achieved with a compensator with fixed parameters.

Due to the level of the compensated currents, only an adaptive reactive compensator can be used for that. When the major harmful components of the arc furnace current are compensated by such a reactive compensator, a switching compensator [16] would probably have the power sufficient for mitigating the current harmonics originated by the arcs.

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