Simulation Result about Harmonics Filtering for Improving the Functioning Regime of the UHP EAF

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Abstract: - This paper present the results obtained by simulation for the functioning regime improvement of an UHP Electric Arc Furnace. Because the nonlinearity of the electric arc the EAF functioning regime are perturbed from three causes: the current harmonics, the reactive power and the unbalanced load. In this paper there are study the possibilities of harmonics filtering and compensate the reactive power. The study was made using the results of some measurements made on an EAF and using an electric arc model for simulation. The simulations are performed in PSCAD EMTDC simulation program, a program dedicated to the power system.

Key-Words: - PSCAD-EMTDC simulation program, electric arc modeling, harmonics mitigation, filtering, reactive power compensation

1 Introduction

The electric arc is a nonlinear element. For study the behavior of the systems containing an electric arc it must use techniques to model the nonlinearity of the electric arc. Because the electric arc's nonlinearity, this is a massive generator of harmonic currents and reactive power in electrical power system. The EAF are also a reactive power source because the electric arc is also a reactive load. The electric arc furnace is also and unbalance load. For improving the functioning regime of the electric arc furnace it can be used harmonic filters and a reactive power compensation installation. The effect of these installations was analyzed using simulation program PSCAD/EMTDC [15]. PSCAD (Power System Computer Aided Design) is a multi-purpose graphical user interface capable of supporting a variety of power system simulation programs. This release supports only EMTDC (Electro-Magnetic Transients in DC Systems).

For simulation it was use an electric arc model, depending on the nonlinearity of the electric arc. The modeling approach adopted in the paper is graphical, as opposed to mathematical models embedded in code using a high-level computer language. The well-developed graphic facilities available in an industry standard power system package, namely PSCAD-EMTDC, are used to conduct all aspects of model implementation and to carry out extensive simulation studies.

2 The Electric Arc Model

In [1], [3], [4], [11], [12], [13] and [14] was present some models for the electric arc. From these models in this paper was choose the model based on the empirical relation between the arc current, arc voltage and arc length. This model are considered by the authors the most appropriate model for describe the electric arc behavior. This model, given in [3], [4], [11] and in [12], considers the characteristic current-voltage described by relation

$$U_A = U_{th} + \frac{C}{D + I_A}. \quad (1)$$

In this relation U_A and I_A are the arc voltage and arc current, and U_d are the threshold voltage. The C and D constants determine the difference between the current increasing part and current decreasing part of the current–voltage characteristic (C_a, D_a irrespective C_b, D_b). The typical values ([3], [4], [11], [12]) are: $U_d = 200\ V$, $C_a = 190000\ W$, $C_b = 39000\ W$, $D_a = D_b = 5000\ A$. Because the real values of the model parameters depend on the voltage arc variations, the dynamic arc voltage–current characteristic must be an arc length function, given by relation ([3], [4]):

$$U_A = k \cdot U_{A0}(I_A). \quad (2)$$

In (2) U_{A0} represent the value of the arc voltage for a reference arc length l_0 and k is the ratio between the threshold voltage value for arc length l, $U_{th}(l)$ and the threshold voltage value for arc length $l_0, U_{th}(l_0)$.

The dynamic model for electric arc presumes that the relation between the threshold voltage value and the arc length can be expressed by:

$$U_{th} = A + Bl \, . \tag{3}$$

In (3) A is a constant equal with the sum of cathode and anodic threshold voltages ($A \cong 40V$) and B represent the threshold voltage on the unit length, having usual values of $10V/cm$ ([3], [4], [11]). The dependency of k by the electric arc length is:

$$k(l) = \frac{A + B \cdot l}{A + B \cdot l_0} \, . \tag{4}$$

Using this model, the correction of the electric arc power can be done within loose limits by modifying the threshold voltage, which corresponds in practice to the modification of the distance between the electrodes and the metal bath.

The simulation of the EAF installation was performed by using the dedicated simulation program PSCAD – EMTDC. This program is dedicated to the power systems simulation ([15]). PSCAD (Power Systems CAD) is a powerful and flexible graphical user interface to the EMTDC solution engine. PSCAD enables the user to schematically construct a circuit, run a simulation, analyze the results, and manage the data in a completely integrated, graphical environment.

The PSCAD electrical scheme of the EAF is show in figure 1. The parameters of the electrical installation of the EAF were determined based on the real installation on an industrial plant ([2]). The relation (5) and (6) show the values of the short network's parameters.

The total resistances, on each phase are:

$$\begin{aligned} R_{r1} &= 0{,}6908 \, m\Omega, \\ R_{r2} &= 0{,}3640 \, m\Omega, \\ R_{r3} &= 0{,}0372 \, m\Omega, \end{aligned} \tag{5}$$

And the total inductivities:

$$\begin{aligned} L_{r1} &= L_{r3} = 9{,}5422 \, \mu H, \\ L_{r2} &= 8{,}9416 \, \mu H. \end{aligned} \tag{6}$$

Because the impedances of medium voltage supplying line are small compared with the ones from the low voltage line, these were included in the EAF's transformer parameters. The values of the main parameters of the EAF's transformer are 73 MVA; 30KV/0,6k; Δ/Y.

Following the measurements made on the EAF's real installation, was observed that its operation is featured by the presence of an unbalanced 3-phase regime regardless the technological step, both on the low voltage supply line and the medium voltage one ([1], [2]).

3. The results for the reactive power compensation and harmonics filters design

Based on the model present in the previous section, it was design a simulation scheme for the entire electrical installation of the EAF. The simulation scheme is show in figure 1 and contained the model implementation for the three phases for the electric arc. The simulations are validating by some experimental measurement made on the electrical installation of an UHP EAF on an industrial plant in Romania. It results also from the simulation and from experimental measurement that the functioning regime are unbalanced, affected by the reactive power and by the current harmonics. The values for characterize this functioning regime are show in table 1 and they are result from [2]. To determine the values of the elements of the harmonic filters and reactive power compensation installation the authors used the measurement results realized to the real installation on the 100 tones electric arc furnace. The measurements where realized during the whole charge duration. It was measured periodic the currents and voltages from the 30 KV bus on 250 ms at 10 seconds intervals. From these values it can be determined using FFT transform the variation of the distortion powers and harmonic currents on the charge duration. In fig. 2 are show the way of connecting the harmonics filters and the power compensation installation.

The computing of the values of the elements was made using a method based on the record of the active and reactive power on the supplying line [6]. After the FFT analyze it result that the most important harmonics was the 5, 7, 11 and 13 orders. From the maximum values of the harmonic currents was computed the values of the element of each harmonic filter. Knowing the maximum value of the reactive power among the whole charge and the reactive power of the harmonic filters it can be determined the variable reactive power needed to be compensated. From the condition that the voltage variation to be less then 0.4% result that the number of steps of the fixed reactive power compensation installation is 14. Under these circumstances, the reactive power, which can be compensated, can be divided in two parts: fixed reactive power:

$$Q_{const} = 25.8 \, MVAR \tag{7}$$

composed by fixed reactive power installed in condenser battery of

$$Q_{fixed\ battery} = 13.27 MVAR \, , \tag{8}$$

the rest being the reactive power installed in harmonic filters.

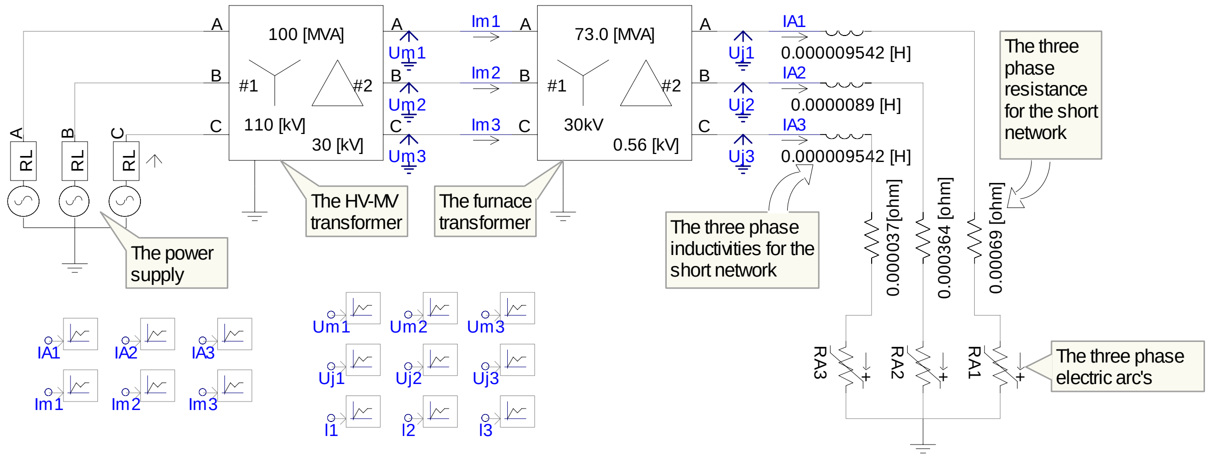

Fig. 1. The simulation circuit for the electrical installation of the EAF

Table 1

	The powers				The power factor, k_p	Thdi (%)	Thdu (%)
	S *(MVA)*	P *(MW)*	Q *(MVAR)*	D *(MVAD)*			
Measure values	72,25	48,63	52,43	10,29	0,546	16,83	7,3
Simulating values	73,51	47,36	55,97	5,35	0,644	8,44	3,17

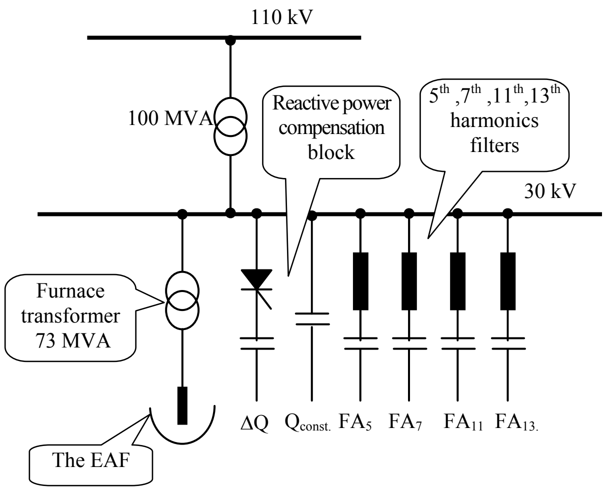

Fig. 2. The reactive power compensation and harmonics filters installation

Variable reactive power

$$Q_{var} = 58.4 MVAR, \quad (9)$$

this consists in 14 equal steps, the reactive power of one step being

$$\Delta Q_{step} = 4.17 MVAR. \quad (10)$$

For determine the values of the filters capacitors it is necessary to know the values of the kth order harmonics currents, because, following the recommendation ([7], [8], [9]) a capacitor with a certain nominal voltage U_{n50}, corresponding to the fundamental with the frequency of 50 Hz and a certain nominal current I_{n50} can functioning in a long time distorted regime characterized by $U_{ef} = 1{,}1 \cdot U_{n50}$ and $I_{ef} = 1{,}3 \cdot I_{n50}$, which mean a overloading by 43%. For this reason it is important to determine the nominal value for the *k* – harmonic. Taking into account of the measurements on the 30kV supplying line feed, the nominal currents for the filters design are $I_n^5 = 100A$ $I_n^7 = 50A$ $I_n^{11} = 25A$ and $I_n^{13} = 25A$. The values for the nominal currents are greater than the recorded values by measure because, in practice, it was observed some cases of filters deterioration which was rigorous dimension based on the load harmonics generator [6]. This fact is based on the harmonics circulation of provenance on the far distorted loads [10].

Using a method present in [6] and [1] it was design the harmonics filters for the 5th, 7th, 11th, and 13th harmonics. The results are show in table 2. The sum of powers absorbed by the filters is:

$$Q_F = Q_F^5 + Q_F^7 + Q_F^{11} + Q_F^{13} = 12{,}53 MVAR. \quad (11)$$

In fig 3 are show the PSCAD EMTDC simulation scheme for the EAF with the harmonics filters, the reactive power compensation and the load balancing component. In this scheme the user can simulate the unbalancing load by selecting different length for the electric arc.

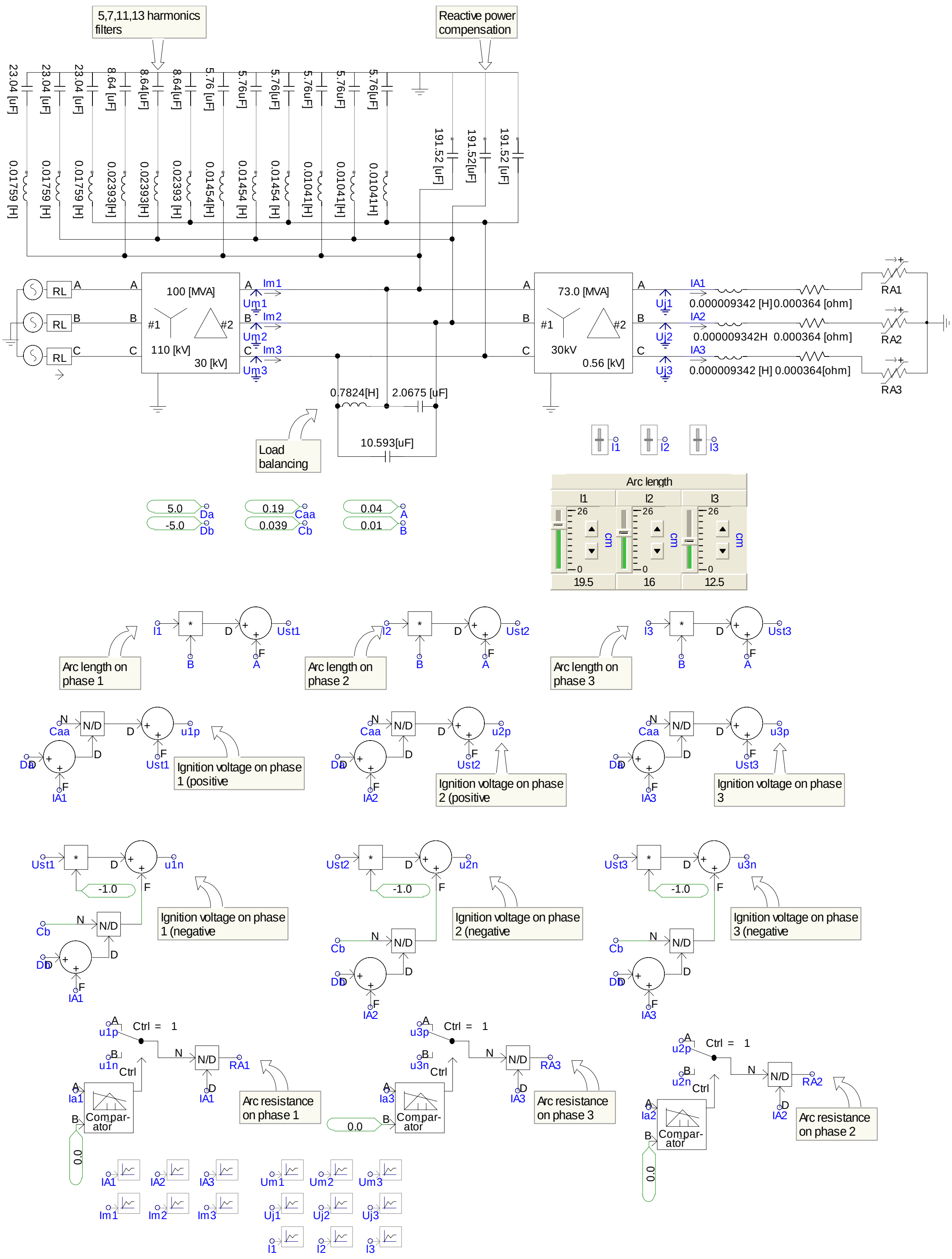

Fig. 3. The PSCAD EMTDC simulation scheme for the electrical installation of the EAF

4. The simulation results

Because the capacity value necessary to achieve such a battery is 14,4 μF, in order to simulate the introduction of a number of n steps, the value of the selected capacity in the fix capacitor battery's diagram is given by the relation (12).

$$C = 47{,}52 + n \cdot 14{,}4 \quad (\mu\text{F}) \tag{12}$$

The values for powers, power factors and distortions obtained for each of the *14* steps were written in table 2 for the primary furnace transformer. Analyzing these results, we notice that:

- The effect of using the reactive power compensation installation is negligible on the secondary furnace transformer. One can observe that the reactive power keeps high values, regardless the compensation step, fact which reflects also in keeping of a small value, even decreasing, of the power factor.
- Since the deforming power keeps high values regardless the compensation step, it results that on the secondary voltage transformer the harmonic filters don't have a significant effect.
- On the primary voltage transformer is found that the reactive power compensation installation allows, depending on the compensation step, to offer an adjustment of the reactive power within +30,57 MVAR ÷ -25,93 MVAR. This makes that, for a certain step, the reactive power value to be the closest to zero. One can observe that the variation of the reactive power between two subsequent steps is of $\Delta Q_{step,\,\text{simulate}} = 4{,}04\,\text{MVAR}$, lower than the designed one, $\Delta Q_{step} = 4{,}17\,\text{MVAR}$, given by the relation (10) due to the fact that the selected value for capacity on one phase of a compensation step is lower than the one resulted by calculation.
- The reactive power's value compensated by the fix batteries (difference between the reactive power values from the first two lines of table 2) is $Q_{const,simulat} = 25{,}4\,\text{MVAR}$, closed to the one resulted by designing $Q_{const} = 25{,}8\,\text{MVAR}$, given by the relation (7).
- The value of the total compensated reactive power (difference between the reactive power values from the first and last line of table 2) is $Q_{comp,simulate} = 81{,}9\,\text{MVAR}$, and the one resulted by designing $Q_{comp} = 82{,}4\,\text{MVAR}$, given by the sum of the relations (7) and (9).
- Since the deforming power is relatively small, one can observe that, practically, in the moment when the reactive power is null, the active power is approximately equal with the apparent one, fact which leads to obtaining of some maximum values of the power factor (fig. 4).
- From the total harmonic distortions' viewpoint, one can observe that their maximum value is obtained for power factor values close to 1. Also, the obtained values are framed in the range of the measured values on the medium voltage supply line.

Table 2

Comp. step	S (MVA)	P (MW)	Q (MVAR)	D (MVAD)	Kp	ρ	σ	Thdi (%)	Thdu (%)
Without comp	73,51	47,36	55,97	5,35	0,64	1,18	0,073	4,44	3,17
Q_I	56,74	47,58	30,57	4,63	0,83	0,64	0,082	3,77	2,34
1.	54,67	47,57	26,53	4,64	0,87	0,55	0,085	3,94	2,16
2.	52,91	47,65	22,55	4,61	0,90	0,47	0,087	4,12	2,06
3.	51,46	47,75	18,61	4,61	0,92	0,39	0,090	4,21	1,94
4.	50,08	47,71	14,53	4,59	0,95	0,30	0,092	4,36	1,83
5.	49,17	47,80	10,55	4,61	0,97	0,22	0,094	4,45	1,67
6.	48,49	47,83	6,51	4,58	0,98	0,13	0,095	4,48	1,58
7.	48,16	47,87	2,53	4,61	0,99	0,05	0,096	4,51	1,52
8.	48,17	47,92	-1,55	4,62	0,99	-0,03	0,096	4,56	1,48
9.	48,47	47,92	-5,61	4,61	0,98	-0,11	0,096	4,54	1,54
10.	49,18	48,00	-9,65	4,65	0,97	-0,20	0,095	4,49	1,67
11.	50,18	48,06	-13,7	4,68	0,95	-0,28	0,094	4,37	1,71
12.	51,45	48,06	-17,7	4,71	0,93	-0,36	0,092	4,26	1,79
13.	53,00	48,05	-21,8	4,72	0,90	-0,45	0,089	4,14	1,85
14.	54,85	48,10	-25,9	4,70	0,87	-0,53	0,086	4,03	1,92

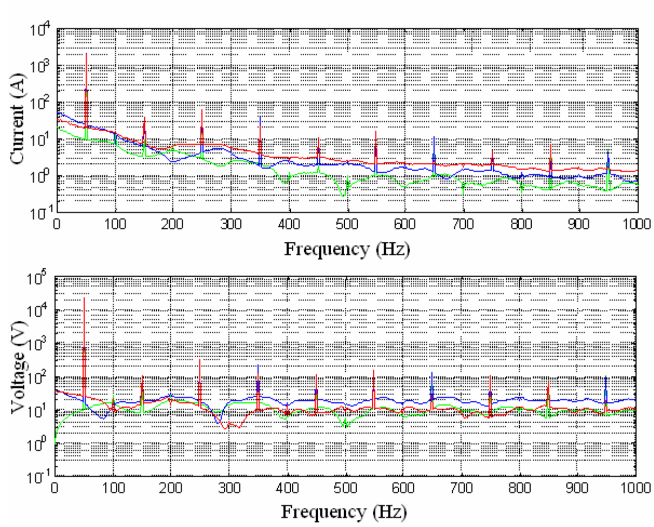

Fig. 4. The signal spectrum obtain by simulation without filters and reactive power compensation

4 Conclusion

From all previously presented, resulted that the simulations concerning the operation of the reactive power's compensation installation confirm the expecting conclusions, that the installation allowing obtaining a power factor very close to 1. Analysis of the effects of using filters on the harmonics 5, 7, 11 and 13 can be made comparing the current and voltage harmonics' spectral characteristics on the voltage supplying line, obtained for the electric installation's operation without filters (fig. 4) and the ones obtained when the filters are used on the optimal compensation step, the 8th from table 2, presented in fig. 5. One can observe that, in case of using harmonic filters, the harmonics' amplitude for which were placed the filters is greatly reduced, against the situation when these were not used.

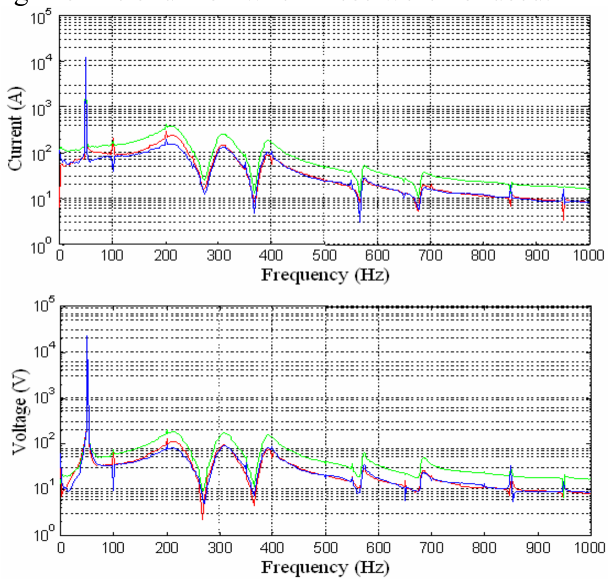

Fig. 5. The signal spectrum obtain by simulation after currents filtering and reactive power compensation

However, as expected, the deforming power can not be cancelled because, in the current's and voltage's specters, besides the harmonic of rank 5, 7, 11 and 13 for which were designed and placed the filters, there are on one side also other harmonics of which effect was not cancelled but also a series of inter-harmonics which, together, contribute at generating of a deforming power, but of a much reduced value.

In conclusion, it was proven by simulation that the values obtained for the parameters of the reactive power's compensation installation, as well as of filters' for the harmonics of rank 5, 7, 11 and 13 allow a significant improvement of qualitative use indicators of the electric power at the electric arc furnace, both from power factor's viewpoint, of powers in deforming regime, as well as of the current's and voltage's total and partially balanced harmonic distortion.

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