Modeling of Three Phase Electric Arc Furnaces

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Abstract. *In this paper are study the modeling of a three phase electric arc furnace installation. It is well know that the electric arc is a nonlinear element. Thus, for modeling his behavior, the authors are using a model which parameters like of a real electric arc. For simulation it was use the PSCAD EMTDC program. The simulations results are comparing with the measurements made of a 100t electric installation publish by the authors in a previous paper [15].*

Keywords: *PSCAD-EMTDC, electric arc, simulation*

1. INTRODUCTION

Electric arc furnace is a massive generator of disturbing in electrical power system. The three types of disturbing the electrical power system are: generation of the three phased harmonic currents, consuming of an important reactive power and unbalanced high power three-phase charge. In the first two directions it can be used harmonic filters and a reactive power compensation installation. The effect of these installations was analyzed using simulation program PSCAD/EMTDC [13]. 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).

To realize this study there is need to solve some problems as: what is the model of the electric arc, taking into account that electric arc have a nonlinear voltage-current characteristic; what is the electrical installation scheme of the electric arc furnace and which are the values of the electrical parameters; what are the elements of the harmonic filters and reactive power compensation installation; what is the PSCAD/EMTDC simulation scheme.

2. THE ELECTRIC ARC MODEL

The electric arc furnace is a nonlinear and unbalanced high power three-phase charge. In [1], [2], [3], [4], [5], [6], [7] are presented models of electric arc from which the authors used in their simulations the model based on formulas that relate arc radius/length, the arc voltage and the current. This model was presented in [2]. It consider that the arc voltage–current characteristic can be described by the following relationship

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

In (1) U_A, I_A is arc voltage and current, U_{th} is the threshold value to which voltage tends when current increases, C and D are constants whose values (C_a, D_a and C_b, D_b) determine the difference between the increasing and decreasing-current parts of the U-I characteristic. 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 [2][3]:

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

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:

$$U_{th} = A + Bl\,. \qquad (3)$$

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

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

In fig. 1 is present the PSCAD/EMTDC implementation of computing the ignition voltage, both positive and negative semi period and the electrical resistance of the arc.

3. MODELING THE ELECTRIC ARC FURNACE (EAF) INSTALLATION

In order to model and simulate the operation of the entire installation of the three-phase electric arc furnace, there are identified, by measurements, the electric diagram's parameters [15], [16]; then, there are determined the parameters of the arc's model in such way that, further the simulation of the operation of the EAF's electric installation, to be obtained results very close to the results following the measurements made on the low voltage and medium voltage supply lines during the electric arc's stable burning.

A. Choosing the values of the electric scheme components parameters

The electric parameters of the EAF's electric installation's diagram are:

Parameters of the low voltage supply line are determined by measurements made by a specialized institute [16]. The measurements made in order to determine the impedance of the supply circuit of the EAF's supply network from the analyzed installation [16] have taken into account the specific characteristics of the existent electric installation: the absence of the inductance need by the stability of the electric arc due to the fact that at the high-power furnaces its role is ensured by the own inductivity of the supply circuit; the absence of the reactive power compensation installation, of the

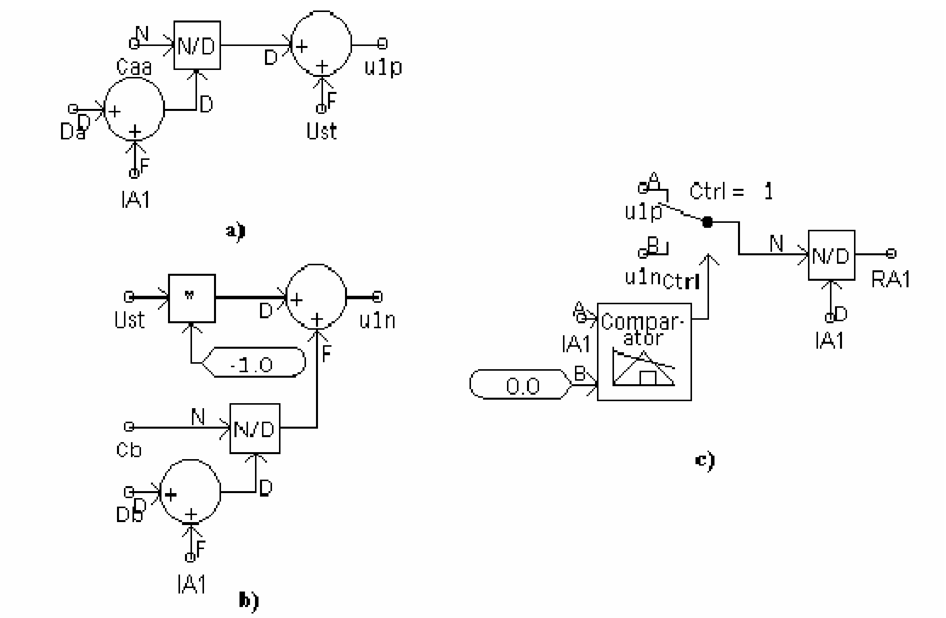

Figure 1. Computing of the: a) pozitive semiperiod ignition voltage; b) negative semiperiod ignition voltage; c) electrical arc rezistence.

harmonics filters, as well as the load balancing installation .

A first determination of the impedance of the supply network's circuit from the 30 kV station to the furnace was made by three-phase short-circuit testing with all the three electrodes introduced about 150 mm in the liquid steel bath immediately after melting. The measurements were made simultaneously in the transformer's primary and secondary.

The values of the impedance's elements of the supply network's circuit from the 30KV station up to the furnace, reduced at the transformer's secondary circuit, supposed symmetric, are

$$R = 0{,}478\, m\Omega \quad X = 3{,}349\, m\Omega , \tag{5}$$

out of which for the low voltage circuit, of the short network, supposed symmetric, is obtaining

$$R_p = 0{,}364\, m\Omega \quad X_p = \omega L_p = 2{,}935\, m\Omega . \tag{6}$$

Based on the relations (5) and (6), for the *30 kV* cables and EAF's transformer are obtaining the following values:

$$R_{C+T} = R - R_p = 0{,}114\, m\Omega \quad X_{C+T} = X - X_p = 0{,}414\, m\Omega \tag{7}$$

The second determination of the impedance of the supply network's circuit was made by 2-phase short-circuit testing, with each two electrodes in the bath and one lifted. Following the performed measurements were calculated the values of the impedances' elements reduced at the transformer's secondary circuit [17]. It's been found that, using this second trial, the obtained values are different with less than *5%* from the ones given by the relations (5) – (7). It was found that during the operation the reactance is increasing against the value determined in short circuit conditions. From this reasons, on the low voltage part was proceeded to the registration of the currents, voltages, as well as the single-phase active and reactive powers on the transformer's most often used steps, in operating conditions cu manual adjustment at minimum, normal and maximum, on the same steps. It is found that the reactance increases as the power factor increases lesser with the power step, the main causes being the modification of the short network cables' geometry, by modification of the electrodes position, and increasing of temperature due to the increase of the active power. Introducing these increased values of the reactance in the calculation of the maximum absorbed powers on the transformer's diverse steps leads towards much diminished values of the last ones. From this reason was made the third determination of the supply circuit's impedance, by technological method**.** By measurements have been determined the values that correspond to the maximum active power absorbed from the network, as well as the values that correspond by calculation for the respective step. Comparing these values with the ones determined by calculation, is found that the maximum absorbed values are getting closer, with small errors, to the values calculated with the reactance resulted from the 3-phase short circuit test. Considering that the difference is due both to the supply voltage and to the measuring devices error, increasing of the energetically characteristics of the studied furnace is made, with the admitted precision of the measuring devices, based on the reactance determined from the short-circuit test, verified with the maximum absorbed power in real operation, as well as based on the supply circuit's resistance determined from the same short-circuit testing. Conclusion arisen from this analysis is that the reactance determination for establishing the energetically characteristics to any EAF is more correctly to be calculated from the active power that is obtained by making $cos\varphi = 0{,}707$, this representing the reactance *in operation* of the installation [16]. The shortcircuit current can be determined also by construction of the circle's diagram, establishing the optimal values for the current and power from the arc. Determining by calculation of the total impedances' values on each phase of the short network can be made**,** considering the currents on the three phases as forming a symmetric 3-phase system. The total impedances' values of the short network are given by :

$$\begin{aligned}
&\underline{Z}_{r1} = R_p + \frac{\sqrt{3}}{2}\cdot\omega(M_{12} - M_{13}) + \\
&j\omega\cdot\left(L_{p1} - 0{,}5\cdot M_{12} - 0{,}5\cdot M_{13}\right) = R_{r1} + j\omega L_{r1}, \\
&\underline{Z}_{r2} = R_p + \frac{\sqrt{3}}{2}\cdot\omega(M_{23} - M_{12}) + \\
&j\omega\cdot\left(L_{p2} - 0{,}5\cdot M_{23} - 0{,}5\cdot M_{12}\right) = R_{r2} + j\omega L_{r2}, \\
&\underline{Z}_{r3} = R_p + \frac{\sqrt{3}}{2}\cdot\omega(M_{13} - M_{23}) + \\
&j\omega\cdot\left(L_{p3} - 0{,}5\cdot M_{13} - 0{,}5\cdot M_{23}\right) = R_{r3} + j\omega L_{r3}.
\end{aligned} \tag{8}$$

Calculation of the mutual inductivities between phases ***i*** and ***j*** can be made based on the relation

$$M_{ij} = \frac{\mu_0}{2\pi}\left(l\cdot\ln\frac{l + \sqrt{l^2 + d_{ij}^2}}{d_{ij}} - \sqrt{l^2 + d_{ij}^2} + d_{ij} \right) \tag{9}$$

where ***l*** represents the phase conductors' length and $\boldsymbol{d_{ij}}$ represents the distance between them. The electromagnetic unbalance of the short network is due to the zone where the short network's conductors are situated in the same plan, $M_{12} = M_{23} > M_{13}$.

In case of the EAF from the analyzed installation, the length of the section where the short network conductors are situated in the same plan is

$$l = 10\,\text{m}, \tag{10}$$

and the distance between the short network's conductors

$$\begin{aligned}
&d_{12} = d_{23} = d_1 = 1\,\text{m}, \\
&\text{d}_{13} = d_{12} + d_{23} = 2\,\text{m}.
\end{aligned} \tag{11}$$

With these values, the mutual inductivities between the phase conductors in the zone where these are in the same plan are

$$\begin{aligned}
&M_{12} = M_{23} = 4{,}1865\,\mu\text{H}, \\
&\text{M}_{13} = 2{,}9853\,\mu\text{H}.
\end{aligned} \tag{12}$$

From the relations (6), (8) and (12) are obtaining the values of the total resistances, on each phase

$$\begin{aligned}
&R_{r1} = 0{,}6908\,m\Omega, \\
&R_{r2} = 0{,}3640\,m\Omega, \\
&R_{r3} = 0{,}0372\,m\Omega,
\end{aligned} \tag{13}$$

as well as of the total inductivities

$$\begin{aligned}
&L_{r1} = L_{r3} = 9{,}5422\,\mu H, \\
&L_{r2} = 8{,}9416\,\mu H.
\end{aligned} \tag{14}$$

Because the impedances of medium voltage supply 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.

- *Transformer's parameters LV - MV* was identified based on the catalog data from the *Medium Voltage Transformer Station*: 100MVA; 110kV/30kV; Δ/Y.

High voltage supply line's parameters used in case of simulations:

- The voltage from the high voltage line is of *110 kV*,
- The high voltage supply line is considered symmetrical,
- The shortcircuit power of the high voltage line is of *1100 MVA***.**

B. Choosing the values of the model's parameters

The selection of the values of the model's parameters was made in such way that the wave shapes of the currents and voltages obtained following the simulation to correspond to the ones obtained following the measurements made on the real installation. In this purpose was analyzed the influence of each parameter which comes in the relation **(1),** finding the following:

- The constants D_a and D_b have a small influence on the values of the amplitudes of the measured values as well as of the wave shapes, finding that the values comprised between *2000 A* and *50000 A* do not modify the amplitude of the currents and voltages with more than *2%*, for the same values of the other parameters. From this reason, in the performed simulations the values of these constants were the ones mentioned in literature, $D_a = D_b = 5000\ A$ [2],[3].

- The influence of constants C_a and C_b on the ignition voltage values is small.
- In the performed simulations for these constants were taken the values from literature, $C_a = 190000\ W$, respectively $C_b = 39000\ W$. In this way, for the same value of the extinction voltage the values of the ignition voltage on the two semi-alternances are different [2],[4].
- As regards the extinction voltage value used during the simulations, was found that this influences both the wave shapes and the values of currents and voltages obtained by simulation. Was admitted $U_{th} = 200\ V$.
- Based on these conclusions, combined with a great number of simulations, resulted that the value of the extinction voltage that allow the best reproduction of the results obtained following the measurements in the reduction phase is $U_{th} = 200\ V$.

4. THE SIMULATION RESULTS OF THE REAL INSTALLATION

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 [15].

The simulation of the EAF's operation as unbalanced 3-phase load was analyzed for two cases:

- Unequalness of total impedances' values of short network phases;
- Unequalness of extinction voltages' values on the 3 phases, due to unequalness of the electric arcs' lengths on the 3 phases.

A. Simulation of the real installation's operation using unequal values of the short network impedances

Because there are sections of the short network where the cables of the 3 phases are disposed in the same plan, it appears an unbalance of the values of short network's total impedances, relations (8), (13) (14), [16]. The simulations were achieved for such values of the voltage from the transformer's secondary that should allow the obtaining of the same results as the ones obtained following the measurements made on the medium voltage line and published by authors in [15]. Using these values of the short network's total impedances, as well as the parameters of the electric arc's model previously presented, the results of simulations performed using the diagram presented in fig. 2 can be analyzed from the viewpoint of:

- *the wave shape, amplitude and non-symmetry degree of currents and voltages* from the low and medium voltage supply lines;
- *the frequency characteristics and harmonics amplitude*;
- *the powers, power factors and distortion coefficients in deformable regime.*

The comparisons of the simulation results with the ones of the measurements were made for the transformer operation's case, $S = 73\ MVA$, power which is equal with the one measured during the stable burning period after approx. 2 hours from the beginning of the heat making, [15], $S_m = 72{,}25\ MVA$. Comparing from viewpoint of currents' and voltages' forms obtained by simulations with the ones obtained by measurements on the real installation, are found the following:

- The value of the current's and voltage's amplitude from the low voltage line obtained by simulations corresponds to the one obtained by measurements made in the stable burning phase.
- On the medium voltage supply line is found that both the current's and the voltage's amplitude obtained by simulations correspond with the ones obtained by measurements made in the reduction phase [15].

Based on the results obtained by simulations, using a Matlab program, were determined the spectral characteristics and the amplitudes of the current's and voltage's wave harmonics for the low and medium voltage supply lines. Comparing the results obtained by simulations with the measured ones, can be drawn the following conclusions:

- The spectral characteristics obtained by the measurements made on the low voltage supply line in the reduction phase correspond, from the viewpoint of the harmonics present in the specter, with the ones obtained by simulation (fig. 2).
- In case of the medium voltage supply line is found the same correspondence between the spectral characteristics obtained for the signals measured in the reduction phase and the ones obtained by simulation. In voltage's case is found that, following simulations, the harmonics of which order/rank is multiple of *3* are strongly damped, fact which corresponds to the real situation.

Based on these observations, results that from the viewpoint of amplitudes, variation forms, but also from the viewpoint of the frequency characteristics and harmonics amplitude of currents and voltages, the values of the electric installation's parameters and of the chosen model's parameters allow a good reproduction of the operation of the EAF real installation. With these values of the parameters, using a Matlab program, were determined the total powers on the three phases S,P,Q,D and the power factor in

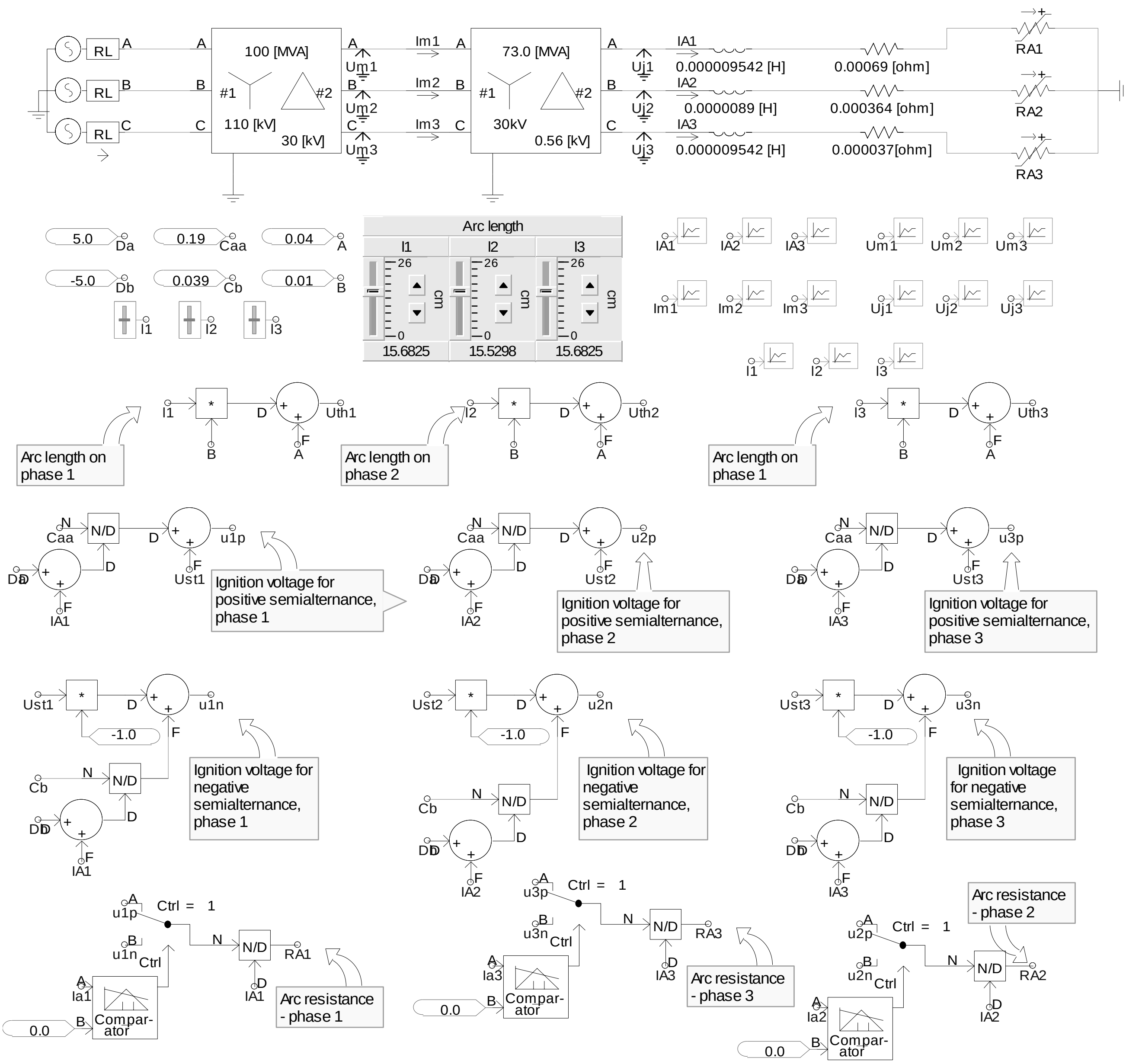

Fig. 2. The electric diagram for simulation using different values of the short network impedance.

deformable regime k_p, as well as the values of the total harmonic distortion thdi, thdu for current and voltage on the medium voltage line, presented in table 1.

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

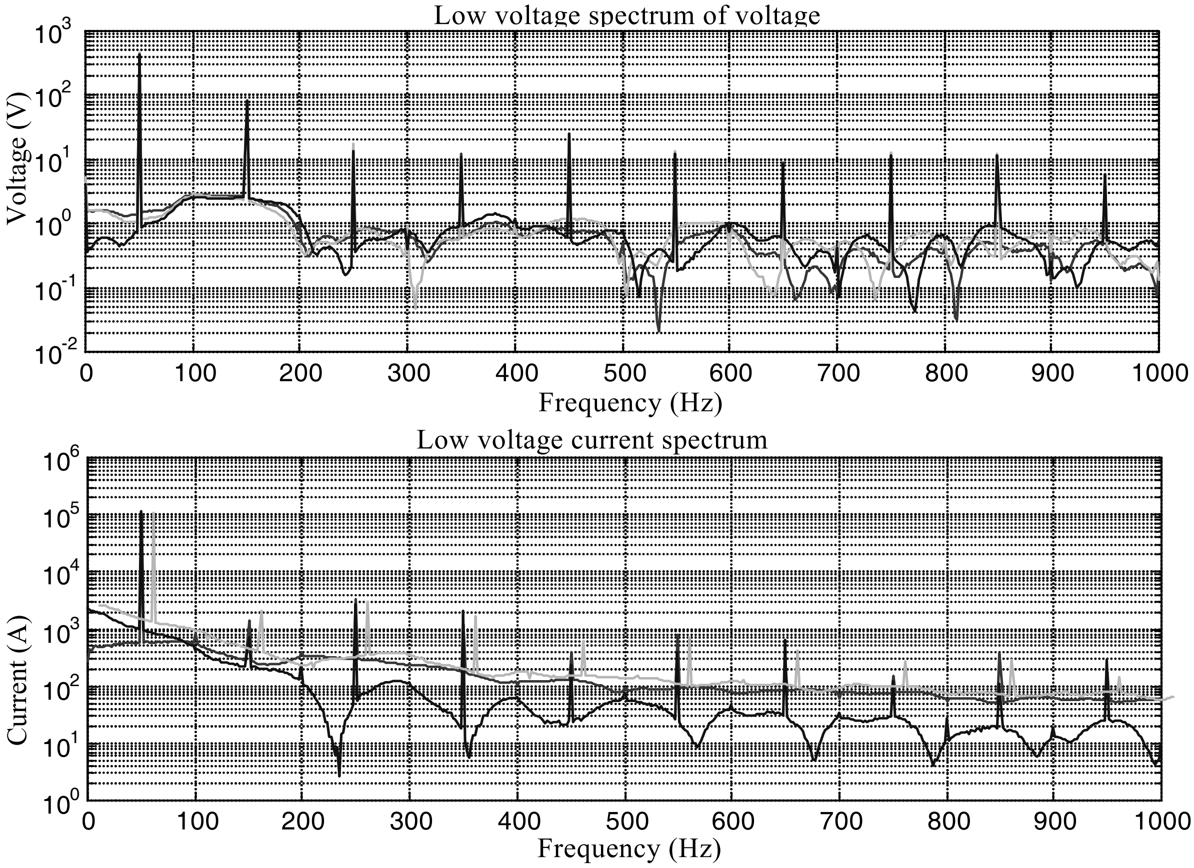

Fig. 3. Current and voltage spectrum for low voltage line feed obtained by simulation

Analyzing the values obtained by simulation compared with the measured ones on the medium voltage line, is found that there is a good correspondence.

B. Simulation of the real installation's operation using unequal values of the electric arc's length

The influence of the unequalness of the electric arc's length on the three phases is reflecting on the appearance of different values of extinction voltage on the three phases, fact which determines the appearance of a strongly unbalanced regime. If the EAF is provided with automatic installation for electrodes' position adjustment, the unbalance which appears is reduced by the modification of the electric arcs lengths on the three phases. The total cancellation of the unbalance using the automatic installation for electrodes' position adjustment is not possible due to the great feedback time, of tenth of seconds, of the electrodes' positioning system but also due to their small movement speed ($\approx 12\,\text{cm/min}$) [12]. Following the simulations, it resulted that, using equal values of the total resistances and total inductivities of the short network's conductors, given by relation **(5)**, choosing for the electric arc's length

$$l_1 = 19{,}5\,\text{cm}$$
$$l_2 = 16\,\text{cm} \quad , \qquad (15)$$
$$l_3 = 12{,}5\,\text{cm}$$

Based on relation **(3),** they lead to obtain the values of the electric arc's voltage given by the relation:

$$U_{th1} = 235\,\text{V}$$
$$U_{th2} = 200\,\text{V} \qquad (16)$$
$$U_{th3} = 165\,\text{V}$$

This results by comparing the results from table 2, where are presented the values of the direct sequence components, inverse and homopolar of the currents and voltages resulted by simulation of the unbalance between the two situations. The results were obtained using a Matlab program**.** Using the diagram from fig. 4, with the electric arc's length values given by (5)**,** there were made simulations of the installation. Following these simulations, were obtained the variation forms similar to the ones obtained following simulations, with unequal values of the short network's impedances. In conclusion, it is possible the same unbalance using different values of the total impedances of the short network's phases, or using different lengths of the electric arc on the three phases.

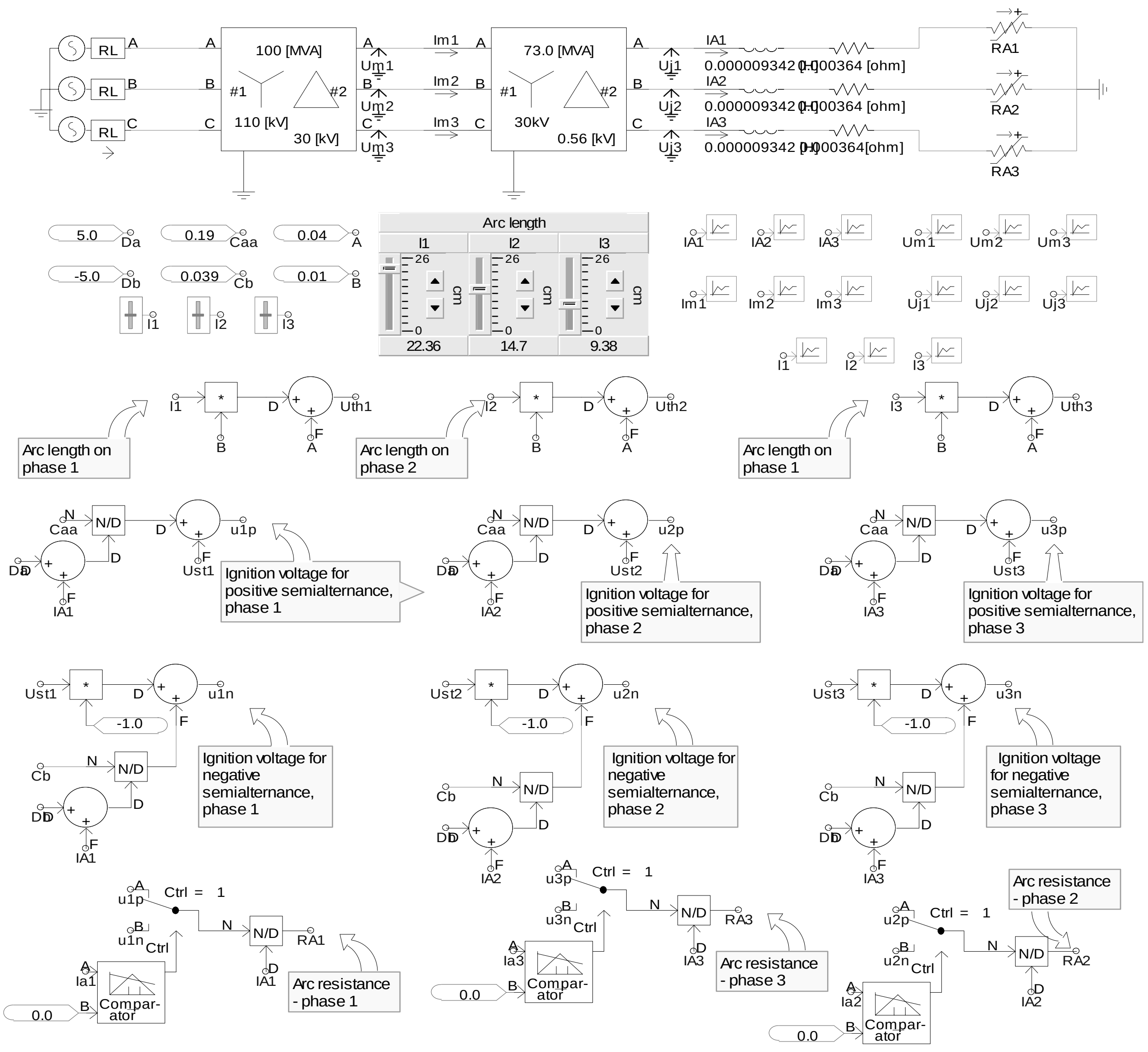

Fig. 4. The electric diagram for simulation using different values of the arc length.

	Simulation using different values of the short network impedance	Simulation using different values of the arc length
$\underline{I}_R$	-458,16-j1324,82	-219.22-1-j1292.5
I_R	1401,81	1310.99
$\underline{I}_S$	-876,95+j1248,53	-875.5+j1453.2
I_S	1525,73	1696.55
$\underline{I}_T$	1335,10+j76,29	1094.7-j160.7
I_T	1337,28	1106.44
$\underline{I}^+$	-567,17-j1300,31	-575.47-j1214.3
I^+	1418,62	1343.77
$\underline{I}^-$	109,48-j23,63	356.8-j77.09
I^-	112,00	365.03
$\underline{I}^0$	-1e-029+j7,4e-013	4.83e-013+j4.06e-13
I^0	7,41e-013	6.3e-13

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