Simulation Results Regarding High Power Loads Balancing

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Abstract: - It is very well known that electric arc furnace as a three-phase load represent one of the most important generator of harmonic currents, reactive power and unbalanced conditions in electrical power systems. This paper work aims to achieve a study concerning the unbalanced regime and to propose a method for load balancing. It is well know that the electric arc is a nonlinear element. Thus, for modeling his behavior, it was use a model which parameters like of a real electric arc. For simulation it was use the PSCAD-EMTDC program dedicated to power systems. It was also performed a study for modeling the three phase electric arc furnace installation. For comparative studies it was made measurements in secondary furnace transformer.

Key-Words: - simulation, modeling, unbalanced load, electric arc

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, the electric arc furnace is a source of harmonic currents and reactive power in electrical power system. 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 [1], [5] reactive power compensation installation [2] and load balancing. 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.

2 Measurements made on the electric arc furnace installation
The measurements were made at a 3-phase power supply installation of a 3-phase EAF of 100t, to which were not connected the filters for the current harmonics, neither the load balancing device nor neither reactive power compensation. It’s been used a computer system with a data acquisition board. The system allows the simultaneous acquisition of 3 currents and 3 voltages, for the low or medium voltage lines of the transformer which supplies the furnace. The data acquisition on the 6 channels was made using acquisition frequency of 5 KHz [5]. The wave forms of the currents and voltages on the low voltage supply line, are presented in fig. 1, and as it can be observe, in the melting phase is found a strong distortion of these. Also, one can notice that the load is strongly unbalanced. In the phase of the electric arc’s stable burning, that appears towards the final of the heat’s making, is found that the distortions that appear in the current’s and voltage’s wave forms are more mitigated, as results from fig. 2, in which are presented the wave forms obtained in the stable burning phase. In this phase, the amplitudes of the three phase currents remain different showing that the load impedance remains unbalanced.

The spectral characteristics of the current and voltage were achieved by using a Matlab program by processing the data acquired by using the Fourier rapid transform [5]. Thus, were obtained the spectral characteristics presented in [5]. Analyze these waveforms it is found that in the melting phase one can observe the presence of harmonics of 3rd, 5rd, 7rd order, but also the components of other frequencies than the harmonics’ (inter-harmonics) [5]. It is found also the presence of unbalanced functioning regime.

For characterize the unbalanced regime we use the negative nonsimetry factors for current and voltage (%):
\[
k_U^- = \frac{U^-}{U^+} \cdot 100 \tag{1}
\]
\[
k_I^- = \frac{I^-}{I^+} \cdot 100 \tag{2}
\]
The zero nonsimetry factors for current and voltage(%):
\[
k_U^0 = \frac{U^0}{U^+} \cdot 100 \tag{3}
\]
\[
k_I^0 = \frac{I^0}{I^+} \cdot 100 \tag{4}
\]
where \(U^-\) and \(I^-\) are the inverse sequences components, \(U^+\) and \(I^+\) are the direct sequences components and \(U^0\) and \(I^0\) are the homopolar components of voltage and current.

Based on the equations (1) and (2) have been calculated the negative non-symmetry factors of the current and voltage and were represented in fig. 3. It is found that the minimum value of the current’s negative non-symmetry factor is of 5%, value which exceeds that minimum permitted limit of 2% [11], [12], [13] and [14]. As regards the voltage’s negative non-symmetry factor, it is found that in the melting phase and at the beginning of the stable burning phase is over 2%, but towards the end of the heat’s making is situated around 2%, sometimes over this value.

Fig. 1. The waveform for voltage and current during the melting stage for 0.25 s

Fig. 2. The waveform for voltage and current during the stable burning stage for 0.25 s

Fig. 3. The variation of non-simetry factors of the current, respectively the voltage, on the entire heat’s duration
It is found that the minimum value of the current’s negative non-symmetry factor is of 5%, value which exceeds that minimum permitted limit of 2% [11]–[14]. As regards the voltage’s negative non-symmetry factor, it is found that in the melting phase and at the beginning of the stable burning phase is over 2%, but towards the end of the heat’s making is situated around 2%, sometimes over this value.

3. Modeling the electric arc furnace

For performed an improvement of the functioning regime of the EAF the authors have analyzed and implement the main models of electric arc from the reference literature [6]–[10]. From the studies models, it was select a model, consider the most appropriate [3], [4]. All simulations were carried out using the simulation program PSCAD-EMTDC. This model, use by the authors also in [1], [2] and [5], considers the characteristic current-voltage described by relation

\[ U_A = U_A(I_A), \quad U_A = U_d + \frac{C}{D+I_A} \]  

(5)

\[ U_d \] and \[ I_d \] are the voltage and current of the electric arc, \[ U_d \] is the drop voltage towards which the voltage tends as the current increases. Constants \( C \) and \( D \) determine the difference between the sectors of the characteristic where the current increases or decreases (\( C_a \) and \( D_a \), respectively \( C_b \) and \( D_b \)). The value of the ignition voltage is obtained for \( I_d=0 \) and is given by relation

\[ U_{ig} = U_d + \frac{C}{D} \]  

(6)

The typical values [3], [4], for the model’s parameters are \( U_d=200 \) V, \( C_a = 190000 \) W, \( C_b = 39000 \) W, \( D_a = D_b = 5000 \) A.

4. Simulation of the electric arc furnace based on the presented model

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 [5]; 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. The electrical installation of the analyzed EAF are:

- the total resistances, on each phase
  \[ R_{11} = 0.6908 \text{ m}\Omega, \quad R_{12} = 0.3640 \text{ m}\Omega, \quad R_{13} = 0.0372 \text{ m}\Omega, \]  
  (7)

- as well as of the total inductivities
  \[ L_{11} = L_{13} = 9.5422 \mu\text{H}, \quad L_{12} = 8.9416 \mu\text{H}. \]  
  (8)

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; \( \Delta/\Upsilon \). Transformer’s parameters LV - MV was identified based on the catalog data from the Medium Voltage Transformer Station: 100MVA; 110kV/30kV; \( \Delta/\Upsilon \). 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. The electrical circuit used for simulation are show in figure 4.

Fig. 4. The simulation circuit for the electrical installation of the EAF
5. Design of load balancing system
Compensation is non-symmetrical and is possible by means of a circuit in Δ connection, which contains only susceptances, connected in parallel with the mains, in the section where the balancing is desired.

A first method for determining the compensator’s elements that should allow the achievement of the load’s balancing function is based on solving of equations

\[ L = L_A + L_S \]  \hspace{1cm} (9)

In this case in which the compensator does not consume reactive power.

As was presented in [IJMIC], at achievement of the reactive power’s compensation, due to the steps where the compensator’s capacity in Y can vary, not always can be achieved the total cancellation of the direct sequence current’s reactive component. On the other side, in [11] was shown that it can be determined a compensator in configuration which, besides the balancing function, can compensate totally the reactive power (\( \cos \varphi = 1 \)).

In this situation, the compensator can be considered as being achieved from two compensators, one which should fulfill only the balancing function and the second one the cancelling function of the direct sequence current’s reactive component.

Based on these observations where calculated the values of the balancing installation’s elements, using a second method. This method consists in the calculation of the balancing installation’s elements using the currents’ and voltages’ values obtained after the best compensation of the reactive power, the balancing installation being in this case a compensator in Δ configuration that can compensate totally the reactive power difference.

The advantages of the method proposed by the authors consist in:
- reactive power compensator assembly – balancing installation which has the same performances as a reactive power total compensator together with a balancing installation which does not consume reactive power;
- the load balancing installation, even if it consumes reactive power, its value is so small that the tyristors from the structure will not be overloaded, in conditions when can be achieved also a continuous adjustment of the compensator’s reactive power.

The calculation of the balancing installation starts from determination of the currents’ and voltages’ values in case of the best reactive power compensation, using the optimal value of the a compensation capacity \( C_{\text{optim}} = 201.7 \mu F \) [5]. These values were obtained based on the data resulted following simulation, being given by the relations

\[ I_R^S = 516.93 \text{ - } j \, 852.41 \text{ A} \]
\[ I_S^S = 952.32 \text{ + } j \, 167.66 \text{ A} \]  \hspace{1cm} (10)
\[ I_T^S = 435.39 \text{ + } j \, 684.74 \text{ A} \]
\[ U_R^S = 7624.4 \text{ - } j \, 15547 \text{ V} \]
\[ U_S^S = -17260 \text{ + } j \, 1163.9 \text{ V} \]  \hspace{1cm} (11)
\[ U_T^S = 9635.6 \text{ + } j \, 14381 \text{ V} \]

Based on which can be calculated the load’s admittances in Y connection

\[ Y_R^S = G_R - jB_R = 0.057343 + j \, 0.005128 = 0.057572 \cdot e^{j5.1102^\circ} \]
\[ Y_S^S = G_S - jB_S = 0.055577 - j \, 0.005966 = 0.055896 \cdot e^{-j6.1270^\circ} \]
\[ Y_T^S = G_T - jB_T = 0.046861 + j \, 0.001123 = 0.046875 \cdot e^{j-3.728^\circ} \]

is found the presence of an unbalance regarding the modules of the three admittances, while their phases are very small, shows that it was achieved a correct compensation. Based on the load admittances’ values in Y connection, can be determined the load admittances’ values in Δ connection according to the relations provided in [11]

\[ G_{RS}^S = \frac{1}{6} \left( G_R + G_S + \frac{1}{\sqrt{3}}(B_S - B_R) \right) = 0.01988773 \]
\[ B_{RS}^S = \frac{1}{6} \left( B_R + B_S + \frac{1}{\sqrt{3}}(G_S - G_R) \right) = 0.00030963 \]  \hspace{1cm} (13)
\[ G_{TR}^S = \frac{1}{3} \left( G_R + \frac{1}{\sqrt{3}}(B_R - B_S) \right) = 0.01697944 \]
\[ B_{TR}^S = \frac{1}{3} \left( B_R + \frac{1}{\sqrt{3}}(G_S - G_R) \right) = -0.00204928 \]
\[ G_{ST}^S = \frac{1}{3} \left( G_S + \frac{1}{\sqrt{3}}(B_S - B_R) \right) = 0.01639071 \]
\[ B_{ST}^S = \frac{1}{3} \left( B_S + \frac{1}{\sqrt{3}}(G_R - G_S) \right) = 0.000164883 \]

Dimensioning of the compensator in Δ connection is made based on the cancelling conditions of the reverse sequence current, according to the relation (9) and cancelling the reactive power absorbed from the mains. This leads to the equations system

\[- G_{RS} + 2G_{ST} - G_{TR} + \sqrt{3}(B_{TR} - B_{RS}) = 0 \]
\[ \sqrt{3}(G_{TR} - G_{RS}) + B_{RS} - 2B_{ST} + B_{TR} = 0 \]  \hspace{1cm} (14)
\[ G_{RS} - G_{TR} - \sqrt{3}(B_{RS} + B_{TR}) = 0 \]

system where have been used the notations
where the exponent $^s$ defines the load’s elements, and the exponent $^\Delta$ defines the compensator’s elements. Solving the equations system (14), considering as unknown the compensator’s susceptances, are obtained the values

$$
B_{RS}^s = -B_{RS}^s + \sqrt{3} \left( G_{ST}^s - G_{TR}^s \right) = -0,0006495
$$

$$
B_{ST}^s = -B_{ST}^s + \sqrt{3} \left( G_{TR}^s - G_{RS}^s \right) = -0,0033279
$$

$$
B_{TR}^s = -B_{TR}^s + \sqrt{3} \left( G_{RS}^s - G_{ST}^s \right) = 0,0040683
$$

In this case the compensator in $^\Delta$ connection has as elements

$$
C_{RS} = 2,0675 \ \mu \Phi \quad C_{ST} = 10,5931 \ \mu \Phi
$$

$$
L_{TR} = 0,7824 \ \text{H}
$$

With these values, following the performed simulations, were obtained the results presented in table 1. Analyzing the obtained results is found that the reverse sequence current’s value is very small, fact which demonstrates that it was achieved a good load balancing. Regarding the currents on the three phases it was also found a very good symmetry on the fundamental of the currents of the three phases. The asymmetry factor is much mitigated compared with the situation when was not action for power quality improvement.

As in case of reactive power’s compensation, it was a matter of finding some values of the balancing installation for which should be obtained a value as smaller of the current’s reverse sequence component.

Following an iterative process, was found that the optimal values of the balancing installation are

$$
C_{RS,\text{optim}} = 2,10 \ \mu \Phi
$$

$$
C_{ST,\text{optim}} = 10,60 \ \mu \Phi
$$

$$
L_{TR,\text{optim}} = 0,79 \ \text{H}
$$

for which was obtained an effective value of the reverse sequence current of $I^s = 0,8752 \text{A}$, smaller than the one presented in table 1.

### 4 Conclusion

Following the simulation performed in the present paper and in [2], [5], it resulted a series of values which allow the obtaining of some comparative conclusions regarding the obtained effects concerning the improvement of the electric power’s quality in the addressed node. Using only reactive power compensation, the power factor is close to 1 but the load remain unbalanced (the asymmetry coefficient for current, $\text{kni}$ are increase). Using only load balancing, the asymmetry coefficient for current, $\text{kni}$ are more reduce, but current distortion and power factor have same values. Using only current harmonics filters the total harmonic distortion are reduce but power factor are not improved and the asymmetry coefficient for current have actually higher value. In generally the power quality in point of common coupling is much improved only in case of use all elements (reactive power compensation, load balancing and harmonics filtering)

### Table 1. Simulation results using load balancing system

<table>
<thead>
<tr>
<th></th>
<th>The fundamental</th>
<th>5th harmonic</th>
<th>7th harmonic</th>
<th>11th harmonic</th>
<th>13th harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_R$</td>
<td>-567,81-j1300,14</td>
<td>-17,94+j46,50</td>
<td>6,93+j26,98</td>
<td>-9,60-j3,30</td>
<td>-8,21+j2,37</td>
</tr>
<tr>
<td>$I_R$</td>
<td>1418,72</td>
<td>49,84</td>
<td>27,86</td>
<td>10,15</td>
<td>8,55</td>
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<tr>
<td>$I_S$</td>
<td>-844,92-j1143,65</td>
<td>-27,99-j16,50</td>
<td>6,61-j25,54</td>
<td>0,37-j2,89</td>
<td>7,21-j1,92</td>
</tr>
<tr>
<td>$I_S$</td>
<td>1421,91</td>
<td>32,49</td>
<td>26,38</td>
<td>2,92</td>
<td>7,46</td>
</tr>
<tr>
<td>$I_T$</td>
<td>1412,73+156,49</td>
<td>45,93-j30,01</td>
<td>-13,54-j1,44</td>
<td>9,23+j6,19</td>
<td>1,00-j0,45</td>
</tr>
<tr>
<td>$I_T$</td>
<td>1421,37</td>
<td>54,86</td>
<td>13,62</td>
<td>11,11</td>
<td>1,10</td>
</tr>
<tr>
<td>$I^+$</td>
<td>-568,51-j1301,39</td>
<td>-12,81+j1,80</td>
<td>10,41+j19,33</td>
<td>-2,11-j4,22</td>
<td>-3,68+j2,95</td>
</tr>
<tr>
<td>$I^+$</td>
<td>1420,71</td>
<td>12,93</td>
<td>21,95</td>
<td>4,72</td>
<td>4,71</td>
</tr>
<tr>
<td>$I^-$</td>
<td>1,15+j1,43</td>
<td>-5,22+j44,54</td>
<td>-3,53+j7,67</td>
<td>-7,44+j0,85</td>
<td>-4,56+j0,65</td>
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<tr>
<td>$I^-$</td>
<td>1,83</td>
<td>44,85</td>
<td>8,44</td>
<td>7,49</td>
<td>4,60</td>
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<td>$k_{in}$[%]</td>
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<td>346,75</td>
<td>38,45</td>
<td>158,66</td>
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<tr>
<td>$k_{in}$[%]</td>
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<td>371,23</td>
<td>39,34</td>
<td>193,33</td>
<td>96,09</td>
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