METHODOLOGY FOR HARMONIC DISTORTION LEVEL DETERMINATION

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Abstract—In order to make an equitable application of bonuses or extra charges due to harmonic distortion, it is necessary to separate between harmonics exported by nonlinear loads used by costumers, and imported ones due to distortion at Point of Common Coupling (PCC) property of the electric utility.

On this paper, a new methodology is presented to assign each costumer his own distortion. Same sampling instrumentation applied in charging electrical bills—with new software—registers total exported harmonic current, making possible determination of corrected non-sinusoidal apparent power and equivalent power factor during an invoicing period.

Some effects of nonlinear loads on grids are determined and analyzed, and experiments done on compact fluorescent lamps are shown and described.

Keywords—Adjusted Equivalent Power Factor, Adjusted Equivalent Apparent Power, Exported Harmonic Current, Sampling Instrumentation, Nonlinear load.

II. METHODOLOGY PROPOSAL

In this paragraph the newly developed methodology, capable of assigning to each costumer his produced distortion, is presented. First of all, the following hypothesis it is made: ratio \( S_{sc}/S_i \) between short circuit power at PCC, and power demanded by a costumer, is enough big to have any influence in applied voltage and its distortion; if ratio value it is above 100, hypothesis it is guarantied: error committed it is negligible. Figure 1 represents PCC, to which companies A, B, ⋯ M, are connected, and measurement instrumentations \( T_A, T_B, ⋯ T_M \), samples applied voltage and samples demanded current by each costumer.

\[ \frac{S_{sc}}{S_i} > 100 \]

Figure 1. Circuit proposal for distortion discrimination study.

\( T_M \) instrumentation determines frequential components of voltage and current, corresponding to costumer M; referring to the fundamental components, it calculates \( \bar{V}_i = V_i \) and \( \bar{I}_i = I_i \angle \varphi \). If connected capacitor’s reactive power it is known on each measurement, \( \bar{I}_{C1} = Q_i/V_i \angle 90^\circ \) it is known too.

\[ \bar{V}_i = V_i \]

\[ \bar{I}_i = I_i \angle \varphi \]

\[ \bar{I}_{C1} = Q_i/V_i \angle 90^\circ \]

Figure 2. Phasorial diagram referred to M costumer’s fundamental components.

According to figure 2, \( I_{R1} \) and \( I_{L1} \), could be calculated as active and reactive components of the linear load \( S_M \)'s consumed current and nonsinusoidal fundamental
component \( S_{NM} \). Then, all terms in the following expression are known:

\[
I_1 = I_{R1} + I_{L1} + I_{C1}
\]

(1)

Figure 3 represents the equivalent circuit of consumer M for \( h^{th} \) harmonic, where \( R_h \) and \( L_h \) are resistor and inductor corresponding to the load for the frequency \( h_f \) and \( C_h = C_1 \) the capacitor. For each case, the best load model should be chosen in order to adjust linear and nonlinear loads consumption of costumer M, in which are included models mentioned in [3], [4]. \( I_{hM} \) is nonlinear load’s total \( h^{th} \) harmonic injection.

If the costumer had only linear loads, \( I_{hM}=0 \) would be verified for each \( h \) value. In this particular case \( I_h \), linear load consumed current value, will be caused only by grid distortion; so, for this kind of consumption, talking about harmonic quality, \( THD_i=0 \) will be assigned to the costumer.

Generally, there will be nonlinear loads, that means that \( I_{hM} \neq 0 \). According to figure 3:

\[
I_h = I_{Rh} + I_{Lh} + I_{Ch} + I_{hM} = I_{Th} + I_{hM}
\]

(2)

where \( I_{Th} \) is imported current due to voltage distortion at PCC:

\[
I_{Th} = I_{Rh} + I_{Lh} + I_{Ch}
\]

(3)

For \( h^{th} \) harmonic, \( T_M \) instrumentation shows these values:

\[
\overline{V_h} = V_h \quad \overline{I_h} = I_h \angle \phi_h
\]

(4)

The software instrumentation calculates the value of \( I_{Ch} \), in function of fundamental current component \( I_C \):

\[
I_{Ch} = h I_C \angle 90^\circ
\]

(5)

Depending on the selected load model, \( \overline{I_{Rh}} \) and \( \overline{I_{Lh}} \) values will have different formulations; in a first approximation, where \( R_h=R_1 \) and \( L_h=L_1 \), we can verify:

\[
\overline{I_{Rh}} = \frac{V_h}{V_1} \angle 0^\circ
\]

(6)

\[
\overline{I_{Lh}} = \frac{I_h}{I_{L1}} \frac{V_h}{V_1} \angle -90^\circ
\]

(7)

Generally, it will satisfy:

\[
\overline{I_{Rh}} = \frac{V_h}{R_h} , \quad \overline{I_{Lh}} = \frac{V_h}{X_h}
\]

(8)

(9)

From figure 4’s diagram, \( I_{hM} \) value is defined by:

\[
I_{hM} = I_h - I_{Th}
\]

(10)

Figure 5 shows that, in function of the relative phase difference between phasors \( I_h \) and \( I_{Mh} \), infinity \( I_h \) values could be obtained, from a minimum \( I_{hMmn} \) –when phasors are in opposite ways(F)– to a maximum \( I_{hMmx} \) when they have the same phase (G).

\[
I_{hM} = I_h - I_{Th}
\]

(10)

\[
I_{hM} = I_h - I_{Th}
\]

(10)

\[
I_{hM} = I_h - I_{Th}
\]

(10)

\[
I_{hM} = I_h - I_{Th}
\]
The whole costumer M’s nonlinear load group’s total demanded current, defined adjusted harmonic current $I_{Hc}$ is given by the expression:

$$I_{Hc}^2 = \sum_{h \neq 1} I_{HM}^2$$  \hspace{2cm} (11)

So, the adjusted equivalent current $I_{ec}$ will be:

$$I_{ec} = \sqrt{I_{Ic}^2 + I_{Hc}^2}$$  \hspace{2cm} (12)

Instrumentation $T_M$ should make an average every $\Delta$ time units, of voltages $V_e$, $V_{el}$, $V_{eh}$, and of the currents $I_{ec}$, $I_{el}$, $I_{eh}$ of figure 6. Software implemented in the instrumentations calculates, in function of mentioned values, active and apparent power defined by IEEE workgroup [5]. Figure 7(a) represents apparent power values measured by instrumentation’s software, included ones proposed in this paper. They can be defined as: $S_{Ne}$, adjusted nonsinusoidal apparent power – that includes only exported distortion by nonlinear loads – and $S_{ec}$, adjusted equivalent apparent power – that is the one really demanded by costumer–:

$$S_{ec} = 3V_e I_{ec}$$  \hspace{2cm} (13)

In figure 7(b) some active powers are represented. It is added to this group $P_{hc}$, adjusted harmonic power, which is the one exported by nonlinear loads.

$cos \varphi = \frac{W_a}{\sqrt{W_a^2 + W_r^2}}$  \hspace{2cm} (16)

where $W_a$ and $W_r$ are active and reactive consumed energies, respectively, during invoice time. Validity of $cos \varphi$, as electric performance indicator, is limited to sinusoidal grids, either single phase or equilibrated three phase. So, the more deviated consumption from these regimens the more error committed when $Kr$ is applied.

Based on studies and results obtained, a new coefficient is proposed: $K_L$, line losses complement, in which $cos \varphi$ is substituted by $FP_{ec}$, adjusted equivalent power factor.

III. NEW INVOICE CRITERION

In the electrical rating at the Spanish legislation, is defined $Kr$ (%) as reactive power complement, as a function of $cos \varphi$, and has the expression:

$$FP_{ec} = \frac{P}{S_{ec}}$$  \hspace{2cm} (14)

for each interval $\Delta$, and it is represented in figure 8. Its average $FP_{ecT}$ for the whole invoice time will be:

$$FP_{ecT} = \frac{\sum_{\Delta} FP_{ec}}{m}$$  \hspace{2cm} (15)

where $m \Delta = T_f$. Adjusted equivalent power factor includes all costumers’ consumption definitions: single-phase loads unbalances, exported harmonics and uncompensated reactive power.
energy \( W \) value to invoice it –. But capacity energy \( W_c \) it is not taken in account.

Figure 9. Active and reactive energies, according to current legislation.

Figure 10 shows proposed invoice method; active energy is evaluated at the same way, although reactive one is not registered, but adjusted equivalent apparent \( S_{ec} \). This one, integrated for all invoice period, allows to obtain \( W_{ec} \) value and adjusted equivalent power factor:

\[
FP_{ec} = \frac{W_a}{W_{ec}}
\]

(17)

Figure 10. Apparent and active energies, according to proposed invoice model.

IV. MEASUREMENTS. RESULTS ANALYSIS

Following are included measurements made at different three phase facilities, using MEPERT instrumentation, designed by Cantabria University’s Department of Electric and Energetic Technology. From all measurements made during the last years, most appropriate ones, in order to show different consumption situations for different kinds of industries, were selected. At table I are shown measured magnitudes at analyzed industries.

Case A is a low tension three-phase source at a little customer, which has 16.5 kW contracted. This facility has a high percentage of linear loads. The rest are computers and lighting composed by mercury vapour and fluorescent lamps. Measurements were made with two different topologies: A.1, which is equivalent to a medium load situation, and A.2, which is the full load situation, when all loads are connected.

Case B is low tension consumption of the calculation centre of a big customer. This facility is composed by work stations and different kinds of informatic devices, feed by UPS’s.

Case C is a 220 kV supply of an iron and steel company. C.1 and C.2 are measurements at different time zones at utility’s power substation. The first one is equivalent to a full load situation, and the second one, to a low work, with oven out, but without disconnecting passive filters.

Table I. Measurements made with MEPERT instrumentation.

<table>
<thead>
<tr>
<th>MAGNITUDE</th>
<th>CASE A.1</th>
<th>CASE A.2</th>
<th>CASE B</th>
<th>CASE C.1</th>
<th>CASE C.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>THDv (%)</td>
<td>1.77</td>
<td>1.94</td>
<td>8.8</td>
<td>1.95</td>
<td>1.76</td>
</tr>
<tr>
<td>THDi (%)</td>
<td>8.52</td>
<td>15.89</td>
<td>195</td>
<td>23.48</td>
<td>9.40</td>
</tr>
<tr>
<td>( V_i^-/V^+ ) (%)</td>
<td>0.90</td>
<td>1.09</td>
<td>1.10</td>
<td>0.34</td>
<td>0.42</td>
</tr>
<tr>
<td>( I_i^-/I^+ ) (%)</td>
<td>92.29</td>
<td>47.19</td>
<td>10.95</td>
<td>15.38</td>
<td>27.52</td>
</tr>
<tr>
<td>( I_0^-/I^+ ) (%)</td>
<td>91.90</td>
<td>56.29</td>
<td>8.31</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( S_e ) (kVA)</td>
<td>15.79</td>
<td>18.05</td>
<td>12.16</td>
<td>47.511</td>
<td>25.244</td>
</tr>
<tr>
<td>( S_{dc} ) (kVA)</td>
<td>15.73</td>
<td>17.83</td>
<td>5.53</td>
<td>46.245</td>
<td>25.129</td>
</tr>
<tr>
<td>( S_{dc} ) (kVA)</td>
<td>1.37</td>
<td>2.85</td>
<td>10.83</td>
<td>10.895</td>
<td>2.407</td>
</tr>
<tr>
<td>( S_{dc} ) (kVA)</td>
<td>7.13</td>
<td>11.56</td>
<td>5.39</td>
<td>45.703</td>
<td>24.226</td>
</tr>
<tr>
<td>( S_{dc} ) (kVA)</td>
<td>14.02</td>
<td>13.57</td>
<td>1.20</td>
<td>7.059</td>
<td>6.676</td>
</tr>
<tr>
<td>( P ) (kW)</td>
<td>7</td>
<td>11.41</td>
<td>5.40</td>
<td>45.140</td>
<td>6.411</td>
</tr>
<tr>
<td>( P ) (kW)</td>
<td>1</td>
<td>-3</td>
<td>127</td>
<td>-38.000</td>
<td>-3.000</td>
</tr>
<tr>
<td>( P ) (kW)</td>
<td>7</td>
<td>11.41</td>
<td>5.27</td>
<td>45.178</td>
<td>6.414</td>
</tr>
<tr>
<td>( P ) (kW)</td>
<td>7</td>
<td>11.51</td>
<td>5.27</td>
<td>45.189</td>
<td>6.408</td>
</tr>
<tr>
<td>( Q ) (kVar)</td>
<td>0.29</td>
<td>1.04</td>
<td>-1.13</td>
<td>6.818</td>
<td>-23.391</td>
</tr>
<tr>
<td>( N ) (kVar)</td>
<td>14.15</td>
<td>13.99</td>
<td>10.90</td>
<td>14.821</td>
<td>24.416</td>
</tr>
<tr>
<td>( \cos \phi )</td>
<td>1</td>
<td>1</td>
<td>0.98(c)</td>
<td>0.99(i)</td>
<td>0.26(c)</td>
</tr>
</tbody>
</table>

At table II, some powers of table I are indicated referred to a basis power \( S_{base} = 100 \text{ kVA} \). This way it is possible to compare all cases. Then, for case A.1, more than 99% is fundamental component power, and unbalanced and non active power are almost 90%. These values confirm that consumption has not distortion, but a high unbalance, being low power factor value originated by a high current unbalance. On the other side, for case B, non active and nonsinusoidal powers are about 90%, and unbalance one is less than 10%. That means that power factor value, less than 0.5, is due to high harmonic distortion at the load. Both cases C.1 and C.2, show moderate values of unbalance and nonsinusoidal powers, but for C.2, non active power is above 96%, that means a high reactive power consumption, and an unacceptable power factor of 0.25.
Table III makes a relation of classical symmetric components $I_1/I_1^*$ and harmonic distortion of current $THDi$ with defined powers. There is a correlation between relations of current’s symmetric components and powers $S_{el}/S_{el}$, and in the same way, $THDi$ values and relation $S_{el}/S_{el}$ are similar. However $\cos \phi$ and $FP_e$ present generally, a great dispersion.

Table III. Relation between classical magnitudes and IEEE Std. 1459.

<table>
<thead>
<tr>
<th>MAGNITUDE</th>
<th>CASE A.1</th>
<th>CASE A.2</th>
<th>CASE B</th>
<th>CASE C.1</th>
<th>CASE C.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_1/I_1^*$ (%)</td>
<td>92</td>
<td>47</td>
<td>11</td>
<td>15</td>
<td>27</td>
</tr>
<tr>
<td>$I_0/I_0^*$ (%)</td>
<td>92</td>
<td>56</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$S_{el}/S_{el}$ (%)</td>
<td>89</td>
<td>75</td>
<td>22</td>
<td>15</td>
<td>27</td>
</tr>
<tr>
<td>$THDi_e$</td>
<td>9</td>
<td>16</td>
<td>195</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td>$S_{el}/S_{el}$ (%)</td>
<td>9</td>
<td>16</td>
<td>196</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>$\cos \phi$</td>
<td>1</td>
<td>1</td>
<td>0,98(c)</td>
<td>0,99(g)</td>
<td>0,26(c)</td>
</tr>
<tr>
<td>$FP_e$</td>
<td>0,44</td>
<td>0,63</td>
<td>0,44</td>
<td>0,95</td>
<td>0,25</td>
</tr>
</tbody>
</table>

In order to evaluate economic impact, annual additional cost originated by costumer C to utility, is simulated, particularly in work mode 2. From table I are obtained $S_e=25.2$ MVA and $P_L^*=6.4$ MW. As $P_L^*$ a value of 4.7% of $P_L^*$ is adopted, that means 300 kW. It’s assumed that costumer has this kind of consumption about 50% of the year, $H_{C2}=4380$ hours.

Line’s minimum power losses will be:

$$W_{Lmn} = P_{Lmn}H_{C2} = 1.314$MWh/year$$

According to table IV, line’s energy losses increase in case C.2, has a value of:

$$\Delta W_{LC2} = 14,52W_{Lmn} = 19.079$MWh/year$$

If an average price of 50 €/MWh is considered, cost of line’s energy losses increase will be close to a million euros.

Table IV. Line losses related magnitudes.

<table>
<thead>
<tr>
<th>MAGNITUDE</th>
<th>CASE A.1</th>
<th>CASE A.2</th>
<th>CASE B</th>
<th>CASE C.1</th>
<th>CASE C.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{Lmn}/P_{Li}$</td>
<td>0,203</td>
<td>0,400</td>
<td>0,191</td>
<td>0,905</td>
<td>0,064</td>
</tr>
<tr>
<td>$FP_e^2$</td>
<td>0,197</td>
<td>0,399</td>
<td>0,194</td>
<td>0,903</td>
<td>0,064</td>
</tr>
<tr>
<td>$\varepsilon(%)$</td>
<td>2,95</td>
<td>0,25</td>
<td>-1,57</td>
<td>0,22</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta P_{Li}/P_{Lmn}$</td>
<td>3,93</td>
<td>1,50</td>
<td>4,24</td>
<td>0,11</td>
<td>14,52</td>
</tr>
</tbody>
</table>

The problem could be generalized to all electronic device whose electric source has deficient characteristics, both distortion and low power factor. Since some years ago, resistor emulative sources have been developed which, with a light higher cost than conventional ones, incorporate optimal electric performance characteristics, like low distortion and high power factor. High performance equipment with this kind of source, could be defined as total efficient, and is the one which should have a subvention because origins truth energy spare.

V. CONCLUSIONS

From the different power factors defined in every three-phase systems, the one derived from equivalent apparent power is selected, because is the one that is measured most exactly by any sampling instruments and because it has a relation with transport losses.

Ferraris type electricity meters are obsolete. They do not allow rational electricity invoicing. On the other hand, sampling instruments allow not only an equitable invoicing; but they allow a measurement of quality too. Furthermore they could be adapted to changes in standards, only actualizing software.

A new methodology is presented, that allows a separation of true harmonic demand of any user as a previous condition of an equitable invoicing of electricity. Thus, a balanced linear consumer with unit Power Factor, due to harmonic contamination at PCC,
will have an equivalent PF much lower than 1. Applying proposed methodology, it will have a Corrected Equivalent Power Factor of 1.

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