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.**

I. INTRODUCTION

Some working groups are carrying out investigations in order to establish conditions to make a balance between the number of nonlinear loads connected and the highest distortion admitted by the electrical grid possible.

It is necessary to design some measurement instrumentations which, according to power and energy definitions in the nonsinusoidal stage, —updated and accepted by most important international organizations like CIGRE, IEC, IEEE or CENELEC—, capable of applying new prices in which a balanced sinusoidal consumption and a unit power factor is benefited, and reactive power consumption —like we now have—, injected harmonic distortion and unbalanced consumption are penalized.

Some Working Groups are designing new methods to establish how much harmonic current demanded by one costumer is due to its nonlinear loads and how much comes from Point of Common Coupling (PCC). *Electricité de France* y *Reseau de Transport Electrique* [1] present some methods which, as their own developers recognized, are not very effective.

In this paper a new methodology is developed which, using sampling instruments, separates exported currents by nonlinear loads and imported ones from PCC [2].

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_{cc}/S_i between short circuit power at PCC, and power demanded by a costumer, it 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.

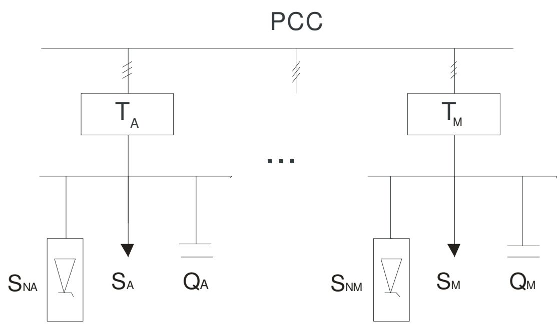


Figure 1.Circuit proposal for distortion discrimination study.

T_M instrumentation determines frequential components of voltage and current, corresponding to costumer M; referring to the fundamental components, it calculates $\bar{V}_1 = V_1$ and $\bar{I}_1 = I_1\angle\varphi_1$. If connected capacitor's reactive power it is known on each measurement, $\bar{I}_{C1} = Q_1 / V_1\angle 90°$ it is known too.

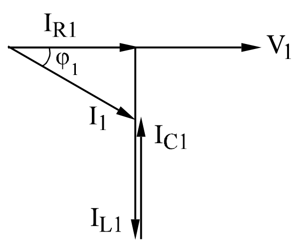


Figure 2. Phasorial diagram referred to M costumer's fundamental components.

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:

$$\bar{I}_1 = \bar{I}_{R1} + \bar{I}_{L1} + \bar{I}_{C1} \quad (1)$$

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[1] 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.

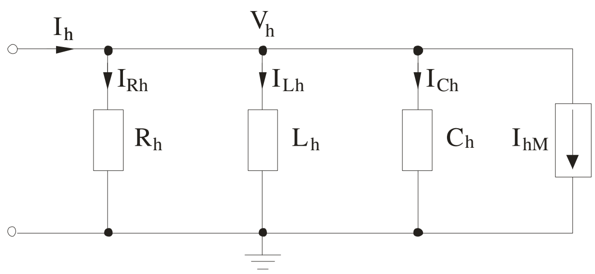


Figure 3. Consumer M´s equivalent circuit for h^{th} *harmonics*..

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, $THDi=0$ will be assigned to the costumer.

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

$$\bar{I}_h = \bar{I}_{Rh} + \bar{I}_{Lh} + \bar{I}_{Ch} + \bar{I}_{hM} = \bar{I}_{Th} + \bar{I}_{hM} \quad (2)$$

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

$$\bar{I}_{Th} = \bar{I}_{Rh} + \bar{I}_{Lh} + \bar{I}_{Ch} \quad (3)$$

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

$$\bar{V}_h = V_h \quad , \quad \bar{I}_h = I_h \angle \varphi_h \quad (4)$$

The software instrumentation calculates the value of $\bar{I}_{Ch}$, in function of fundamental current component I_{C1}:

$$\bar{I}_{Ch} = h I_{C1} \frac{V_h}{V_1} \angle 90^o \quad (5)$$

[1] Linear loads in sinusoidal grids, will be no linear at frequencies above fundamental one. Only capacitors are linear in power systems frequencies, $f<3kHz$.

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

$$\bar{I}_{Rh} = I_{R1} \frac{V_h}{V_1} \angle 0^o \quad (6)$$

$$\bar{I}_{Lh} = \frac{1}{h} I_{L1} \frac{V_h}{V_1} \angle -90^o \quad (7)$$

Generally, it will satisfy:

$$\bar{I}_{Rh} = \frac{V_h}{\bar{R}_h} \quad (8) , \qquad \bar{I}_{Lh} = \frac{V_h}{\bar{X}_h} \quad (9)$$

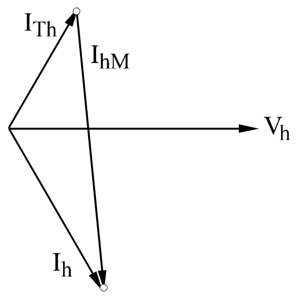


Figure 4. Phasorial diagram corresponding to costumer M's h^{th} harmonic.

From figure 4's diagram, $\bar{I}_{hM}$ value is defined by:

$$\bar{I}_{hM} = \bar{I}_h - \bar{I}_{Th} \quad (10)$$

Figure 5 shows that, in function of the relative phase difference between phasors I_{Th} 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).

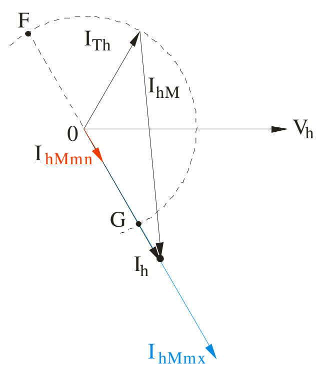


Figure 5. Current loci for phasor I_{Th} .Exported distortion.

I_{hM} is h^{th} harmonic current exported by costumer M, which generally is different than $\bar{I}_M$ value, showed by instrumentation T_M.

The whole costumer M's nonlinear load group's total demanded current, defined *adjusted harmonic current* I_{Hc} is given by the expression:

$$I_{Hc}^2 = \sum_{h \neq 1} I_{hM}^2 \tag{11}$$

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

$$I_{ec} = \sqrt{I_{e1}^2 + I_{Hc}^2} \tag{12}$$

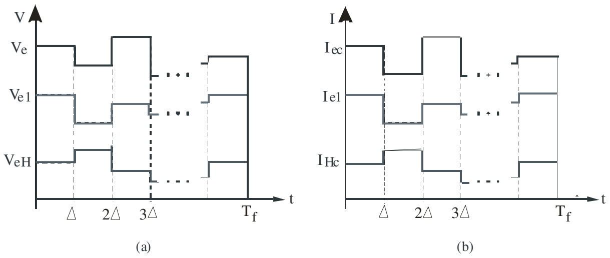


Figure 6. Magnitude averages of costumer (a) Voltages. (b) Currents.

Instrumentation T_M should make an average every Δ time units, of voltages V_e, V_{e1}, V_{eH}, and of the currents I_{ec}, I_{e1}, 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_{eNc}, *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–:

$$S_{ec} = 3V_e\ I_{ec} \tag{13}$$

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.

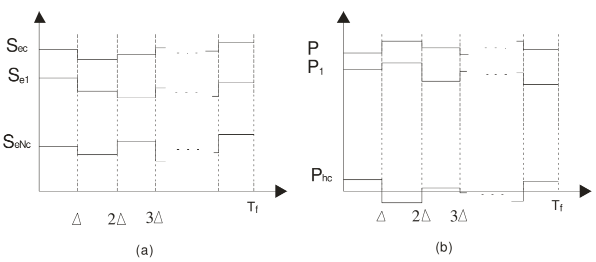


Figure 7. Magnitude averages of costumer (a) Apparent powers. (b) Active powers.

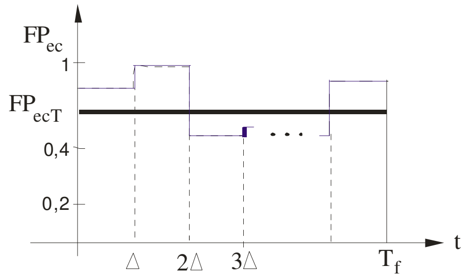


Figure 8. Costumer's M adjusted equivalent power factor.

Adjusted equivalent power factor FP_{ec}, is given by:

$$FP_{ec} = \frac{P}{S_{ec}} \tag{14}$$

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

$$FP_{ecT} = \frac{\sum_{\Delta}^{m\Delta} FP_{ec}}{m} \tag{15}$$

where $m\Delta = T_f$. *Adjusted equivalent power factor* includes all costumers' consumption definitions: single-phase loads unbalances, exported harmonics and uncompensated reactive power.

III. NEW INVOICE CRITERION

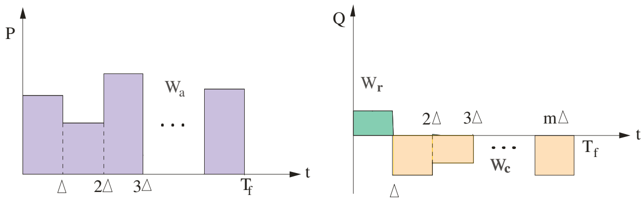
In the electrical rating at the Spanish legislation, is defined *Kr (%)* as *reactive power complement*, as a function of *cos φ*, and has the expression:

$$\cos\varphi = \frac{W_a}{\sqrt{W_a^2 + W_r^2}} \tag{16}$$

where *Wa* y *Wr* are active and reactive consumed energies, respectively, during invoice time. Validity of *cos φ*, 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 φ* is substituted by *FPec, adjusted equivalent power factor.*

Figure 9 represents, schematically, active and *classic reactive* energy consumption during invoice time T_f , according to current regulation. It is important to notice that, at *cos φ* expression, only positive or inductive power is considerate – that during T_f gives reactive energy W_r value to invoice it –. But capacity energy W_c it is not taken in account.

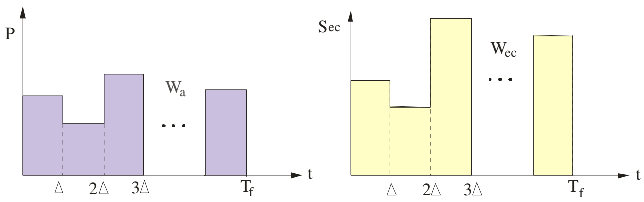


(a) (b)

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*:

$$FP_{ec} = \frac{W_a}{W_{ec}} \quad (17)$$



(a) (b)

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

IV. MEASUREMENTS. RESULTS ANALISYS.

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 costumer, 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 costumer. This facility is composed by work stations and different kinds of informatic devices, feed by UPSs.

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.

MAGNITUD	CASE A.1	CASE A.2	CASE B	CASE C.1	CASE C.2
$THDv_e(\%)$	1,77	1,94	8,8	1,95	1,76
$THDi_e(\%)$	8,52	15,89	195	23,48	9,40
$V_1^-/V_1^+(\%)$	0,90	1,09	1,10	0,34	0,42
$I_1^-/I_1^+(\%)$	92,29	47,19	10,95	15,38	27,52
$I_1^0/I_1^+(\%)$	91,90	56,29	8,31	0	0
$S_e(kVA)$	15,79	18,05	12,16	47.511	25.244
$S_{e1}(kVA)$	15,73	17,83	5,53	46.245	25.129
$S_{eN}(kVA)$	1,37	2,85	10,83	10.895	2.407
$S_1^+(kVA)$	7,13	11,56	5,39	45.703	24.226
$S_{d1}(kVA)$	14,02	13,57	1,20	7.059	6.676
$P(kW)$	7	11,41	5,40	45.140	6.411
$P_H(W)$	1	-3	127	-38.000	-3.000
$P_1(kW)$	7	11,41	5,27	45.178	6.414
$P_1^+(kW)$	7,12	11,51	5,27	45.189	6.408
$Q_1(kVar)$	0,29	1,04	-1,13	6.818	-23.391
$N(kVar)$	14,15	13,99	10,90	14.821	24.416
$\cos\varphi$	1	1	0,98(c)	0,99(i)	0,26(c)

At table II, some powers of table I are indicated referred to a basis power $S_{e,base}$=*100 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 $I_1^-/I_1^+/I_1^0$ and harmonic distortion of current *THDi* with defined powers. There is a correlation between relations of current's symmetric components and powers S_{d1}/S_{e1}, and in the same way, *THDi* values and relation S_{eN}/S_{e1} are similar. However $\cos\varphi$ and *FPe* present generally, a great dispersion.

Table II. Magnitudes related to $S_{e,base}=100$

MAGNITUD	CASE A.1	CASE A.2	CASE B	CASE C.1	CASE C.2
S_{e1}	99,62	98,74	45,44	97,34	99,54
S_{eN}	8,71	15,81	89,08	22,93	9,53
S_{d1}	88,81	75,16	9,88	14,86	26,45
P	44,35	63,21	44,40	95,01	25,40
N	89,63	77,49	89,60	31,19	96,72
FP_e	0,44	0,63	0,44	0,95	0,25

At table IV, lines' power losses magnitudes are shown, referred to studied cases, as well as committed error, *ε (%)* when approximation $FPei^2$ is made. Error maximum value is *2,95%* at case A.1. At table IV is shown, too, P_{Li}/P_{Lmn} relation value, which in other words, means line power losses increase, in relation with minimum losses.

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

MAGNITUD	CASE A.1	CASE A.2	CASE B	CASE C.1	CASE C.2
$I_1^-/I_1^+(\%)$	92	47	11	15	27
$I_1^0/I_1^+(\%)$	92	56	8	0	0
$S_{d1}/S_{e1}(\%)$	89	75	22	15	27
$THDi_e$	9	16	195	23	9
$S_{eN}/S_{e1}(\%)$	9	16	196	23	10
$\cos\varphi$	1	1	0,98(c)	0,99(i)	0,26(c)
FP_e	0,44	0,63	0,44	0,95	0,25

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 $P_1^+=6.4MW$. As P_{Lmn} a value of *4,7%* of P_1^+ 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:

$$W_{Lmn} = P_{Lmn} H_{C2} = 1.314 MWh/\,year \qquad (18)$$

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

$$\Delta W_{LC2} = 14{,}52 W_{Lmn} = 19.079 MWh/\,year \qquad (19)$$

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.

MAGNITUD	CASE A.1	CASE A.2	CASE B	CASE C.1	CASE C.2
P_{Lmn}/P_{Li}	0,203	0,400	0,191	0,905	0,064
FP_{ei}^2	0,197	0,399	0,194	0,903	0,064
$\varepsilon(\%)$	2,95	0,25	-1,57	0,22	0
$\Delta P_{Li}/P_{Lmn}$	3,93	1,50	4,24	0,11	14,52

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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