EFFECTS OF SERVICE QUALITY IN LOW VOLTAGE URBAN DISTRIBUTION SYSTEMS

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***Abstract* - This paper presents the bases for establishing the cost effect, on the major components in low voltage urban distribution systems (UDS/LV), from harmonic distortion levels that are common today, due to the large number of non-linear loads (NLL) connected. Based on the contamination levels originated by these NLL and the typical home and industrial loads currently connected, an unbalanced UDS/LV is simulated, in order to establish the conclusions that can be drawn from the study and the aspects to be analyzed in greater depth in subsequent studies.**

I. INTRODUCTION

The current development of electrical equipment for home, commercial and industrial use has taken place hand in hand with the development and evolution of solid state technologies applied to Power Electronics, which has allowed for more efficient processes and an important reduction in the cost and size of the equipment used. This has given place to a widespread use of above mentioned equipment in multiple applications, such as industrial processes, public street lighting, in medicine, communications and home applications. This equipment acts as a non-linear load (NLL) that introduce harmonic contamination that is sent through the low voltage urban distribution system (UDS/LV), affecting the shape of the voltage wave at the common connection point (CCP) with the medium voltage level. Harmonic contamination al the UDS has effects for the distribution company and for the client [1],[2],[3],[4]. This study focuses on the distribution company due to its importance in terms of the number of units of equipment involved and the magnitude of the economic effects produced. Taking into account the increasing importance of service quality, this study intends to identify these NLL's and to show the characteristic levels of their harmonics components as sources of contaminants, as well as to provide background information regarding its effects and a methodology for its quantification on a UDS/LV.

II. EFFECTS ON THE UDS/LV

Harmonic contamination causes the distribution company's operational costs to increase, as a result of the greater losses, the premature replacement of equipment, fines applied, the investments to mitigate these effects and others [4],[5],[6]. The effects on the main components of the UDS/LV are estimated below, under the assumption that these may be classified as direct and indirect.

II. A. Losses in transformers

The direct effects correspond to the increase in losses and the reduction of the transformer's capacity, while the loss in its useful life is considered an indirect effect. The analysis considers the following variables [5],[6],[7],[8]:

La	Additional losses in the transformer
Ltn	Overall nominal load losses = Ljn + Lecn.
Ljn	Joule nominal losses.
Lecn	Eddy current. nominal losses
w	Fundamental angular frequency.
h	Harmonic component order.
i_h	Order h, current component
ΔC La	Increased cost due to additional losses in the transformer, in US$ per year.
Ce	Energy cost, in US$/kWh.
Cp	Power cost, in US$/kW/year.
Fll	Load factor for losses.
DI	Current distortion

II.A.1) Increase in losses. This is produced in the windings and in the metallic body. The latter related to dispersion flux, which in transformers with a power of less than 100 MVA are insignificant and therefore not taken into account in this study. Only the increase in losses caused by the Joule and by Eddy current effects are considered, that is:

$$La = Ljn \cdot \sum_{h=2} i_h^2 + Lecn \cdot \sum_{h=2} i_h^2 h^2 \qquad (1)$$

For the distribution company, additional losses mean an increase in costs related to commercial electric power development. The first is related to the MWh bought each year and the second to the cost of the infrastructure required to reach a specific point of the UDS with a specific level of power. To evaluate this increase in costs, the following expression is used:

$$\Delta C,La = La \times (Cp + 8760 \times Ce \times Fll) \qquad (2)$$

The graph on Figure 1 shows the cost for losses in a 25 MVA transformer as a function of the harmonic distortion, when applying a weight factor on the harmonics without altering the fundamental component.

II.A.2) Reduction in the capacity. In order to maintain the level of losses at the design values for nominal load, in the presence of harmonics it is necessary to reduce the effective current circulating through it, which is given in equation (3). Figure 2. shows the increase in costs in a 25 MVA transformer due to current distortion.

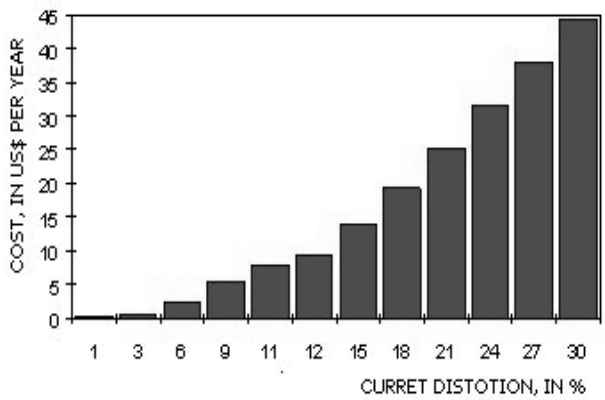

Fig. 1. Cost of increase in losses in a 25 MVA transformer as a function of the DI.

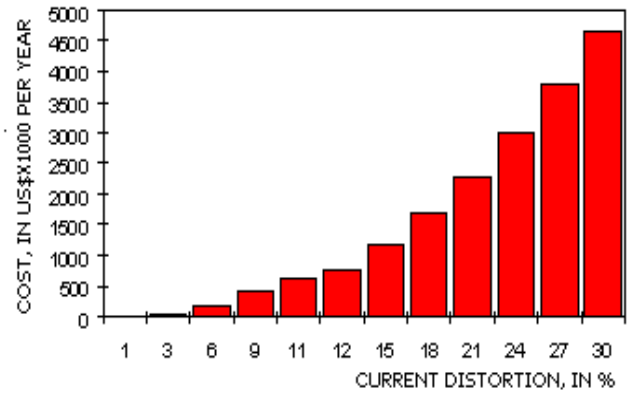

Fig. 2. Cost of a reduction in the capacity of a 25 MVA transformer as a function of the DI.

$$I_{ef,máx} = \sqrt{\frac{Ltn}{1+\left(\frac{\sum_{h=1}(f_h \cdot h)^2}{\sum_{h=1} f_h^{\,2}}\right)\cdot Lecn}} \qquad (3)$$

The reduction in the transformer capacity implies that investments in equipment renewal must be brought forward several periods, determined by the reduction in the power of the transformer and the rate of increase in consumption. Therefore if at nominal capacity the replacement is carried out at period t_1, and if, at reduced capacity (S_h) it is carried out at t_2, the present value by reason of advanced investment (ΔCa,inv) is given by expression (4), where I is the investment for equipment renewal and i is the discount rate per year.

$$\Delta Ca, inv = \frac{I}{(1+i)^{t2}} - \frac{I}{(1+i)^{t1}} \qquad (4)$$

II.A.3) Indirect effects. These are related to the loss in the useful life of the equipment as a result of its exposure to higher temperatures caused by the presence of harmonics and the consequent premature impairment of its insulation. Assuming conditions of constant demand during the entire period, it is possible to estimate the degree of incidence that the presence of harmonics has on the useful life of the transformer, when formula 5 is applied [7],[8]:

$$L(hrs) = 10^{\left(\frac{b}{\theta P + 273} - a\right)} \qquad (5)$$

with

$$\theta_P \cong \theta_{CO} \cdot L_W + \theta_{OA} \cdot L_T + \theta_A \qquad (6)$$

θ_P windings temperature at the hottest point, in °C.

θ_{CO} copper temperature with respect to oil, under nominal conditions in °C.

θ_{OA} oil temperature over ambient, under nominal conditions in °C.

θ_A ambient temperature in °C.

L_W Winding losses with harmonic contents, as °/1 of the nominal copper losses.

L_T Total losses with harmonic contents, as °/1 of total nominal losses.

a and b Constants dependent on the characteristics of the design.

II.B. Losses in conductors [5],[6].

II.B.1) *Direct effects.* These are determined by the increase in the conductor losses (Lac) in the presence of harmonics and in the subsequent increase in the conductor resistance due to the Skin and the proximity effects, which are given by :

$$Lac = \sum_{n=2}^{\infty} I_h^2 \cdot R_h \qquad (7)$$

If it is assumed that the conductor resistance remains constant with respect to frequency, the conductor's additional losses in the presence of harmonics can be expressed as a percentage of losses in sinusoidal conditions, as can be seen in equation (8) and Figure 3.

$$\%Lac = \frac{\sum_{h=2} I_h^{\,2}}{I_1^{\,2}} \times 100 = \left(DI^2\right) \times 100 \qquad (8)$$

If it is assumed that typical losses in feeders are around 1.8% of their power, it can be obtained a formula relating feeder power, distortion and the cost per year of the increases in loss, generating the graph shown in Figure 4.

II.B.2. Indirect effects. These correspond to the premature replacement of the conductor which has reached the limit of its thermal capacity due to the presence of harmonic components and the consequent increase in the effective current, this is:

$$I_{ef} = \sqrt{I_1^{\,2} + \sum_{h=2} I_h^{\,2}} \qquad (9)$$

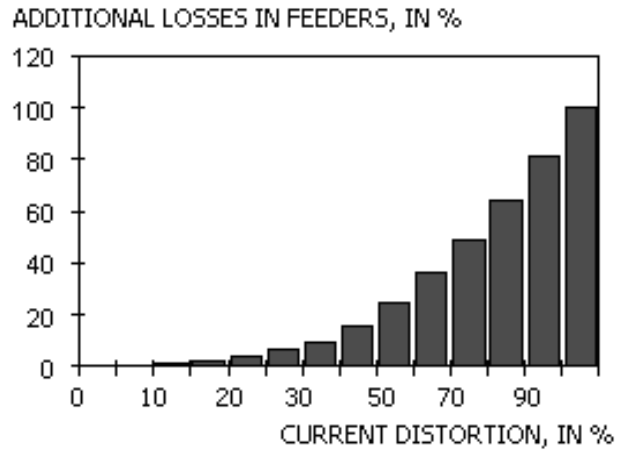

Fig. 3. Approximate increase of additional losses in feeder caused by distortion.

II.C. Losses in capacitors [5],[6].

New variables to be used are:

La,Cer	Additional losses in the capacitor.
tan δ	Loss factor in the capacitor.
V_h	Amplitud of the order h voltage component
C	Capacitor capacitance.
ΔC La,Cer	Increase in costs for additional losses, in US$ per year.

3A. Direct effects. These are determined by the voltage harmonic components and by the loss factor tan δ, as indicated in formula (10).

$$\mathrm{La,Cer} = \frac{1}{2} \cdot \sum_{h=2} \tan\delta_h \cdot V_h^2 \cdot h \cdot \omega \cdot C \qquad (10)$$

The increase in costs caused by the additional losses in the capacitor will be given by equation (11)

$$\Delta C\mathrm{La,Cer} = \mathrm{La,Cer} \cdot (Cp + 8760 \cdot Ce \cdot Flp) \qquad (11)$$

Considering the voltage harmonic component levels obtained by field measurements and applying weighting factors to these components to obtain different levels of distortion, a relation is obtained between the latter and the

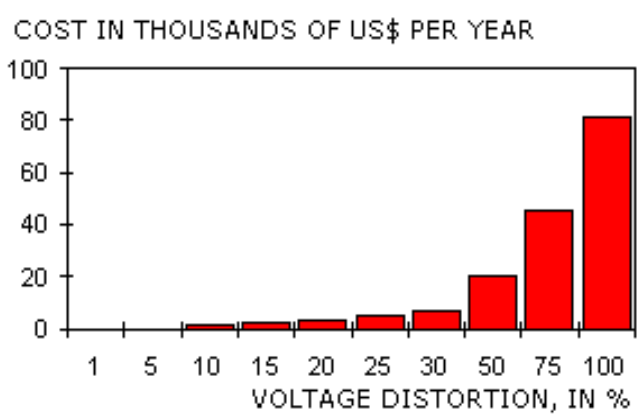

Fig. 5 Annual cost due to an increased in losses for a 4.8 MVAR capacitor bank

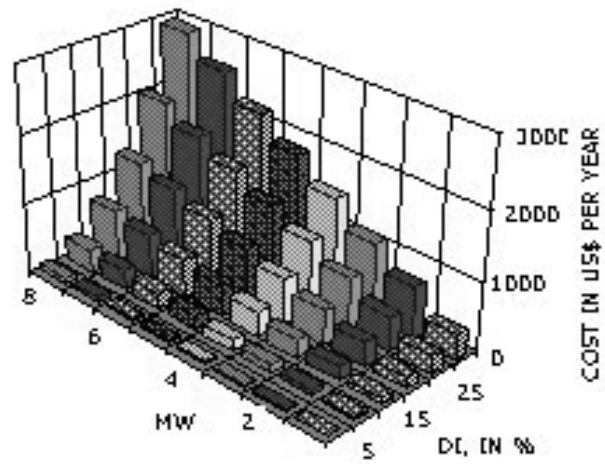

Fig. 4. Cost of additional losses in feeders as a function of power and distortion levels.

costs of increases in losses. This can be seen in Figure 5 for the case of a 4.8 KVAR capacitor bank.

II.C.2) Indirect effects. These involve a reduction in the useful life and the consequent premature replacement of capacitors due to causes attributable to harmonic contents in the UDS. These losses of units are produced by dielectric overstress and overheating generated by overvoltage and current overload. The risk of a loss of the reactive compensation equipment appears when the levels recommended by IEEE Std.18-1992, establishing operation limits for effective current and voltage are exceeded by 1.8 and 1.1 times their nominal values, respectively.

The incremental cost of a replacement in the year *t* of the faulted units (*ΔC f,Cer),* assuming an annual rate of failure of *λ*, with an investment per unit of *I* , is:

$$\Delta \mathrm{Cf,Cer} = \frac{I \cdot \lambda}{(1+i)^t} \qquad (12)$$

As there are no statistics that identify equipment failures attributable to the presence of harmonic components, it is difficult to estimate a failure rate that would permit to assess this effect and to determine the number of units that must be replaced each year. However,

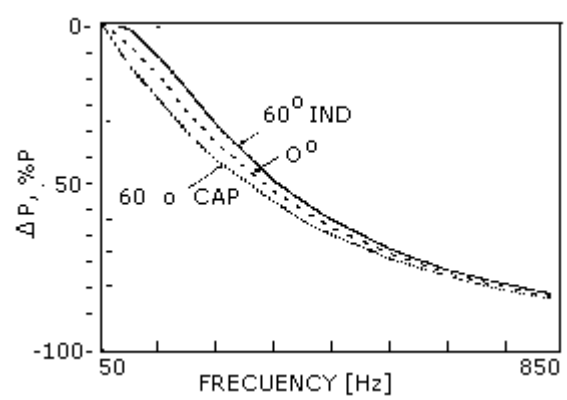

Fig. 6. Frequency characteristic of an inductive energy meter, in a single-phase test at 120 V and 5 A.

these rates of failure, should show a decreasing trend in time, in the case that the new replacement units,. the presence of harmonics is taken into accoun when determining its dimensions

II.D. Measurement instruments.

The induction meter is the measuring device most widely used by power companies and by industries, because of its low cost and ease of operation. However, as it is shown in figure 6, its frequency response and the consequent recording precision of the harmonic energy is very poor, recording the active and reactive power components and the power factor below their actual value, with the consequent cost of uncharged fines [9]. Nonetheless, the error introduced by the harmonic contents as a whole in the measurement of energy depends on the magnitude and phase of the power harmonic components with respect to the fundamental component, thus resulting in a compensation of the error.

II.E. Protection equipment.

The presence of distortion in the system could eventually cause the undesired operation of protection equipment [10] This would produce the disconnection of the feeder or part of it, leaving all or part of connected clients without service. The cost involved corresponds to unsold energy during the interruption of the service and applied fines. Equation 12 permits the quantification of this cost related to harmonic contamination.

$$\Delta Cinterrup = TI \times TMI \times PDM \times BEV \quad (13)$$

where TI is the rate of interruptions per year, TMI is the average interruption time per year, PDM is the average power in kW demanded by clients affected by the interruptions and BEV is the benefit per unit of energy sold in US$/kWh.

III. ASSESSMENT OF THE EFFECTS ON A SDU/BT.

The SDU/BT goes from the distribution transformer (D/T) to the final user. On the average there are 93 D/T per feeder with 52 connected users (17 by phase). It is unbalanced, its loads with random and dispersed behavior with respect to the characteristics of the elements that compound it. Its modeling for harmonic analysis requires measurement, computer simulation and analysis of results, considering a minimum number of nodes which would permit a certain level of certainty in forecasting. The above implies the need for software, instruments and specialized professionals to carry out these activities with the consequent high costs for the distribution company [11]..

At present the distribution company does not have adequate amount of harmonics measurements in the UDS/BT or the proper computer tools to permit its simulation. The above restrictions make it necessary to perform modeling by using a program with a limited number of nodes, together with a methodology for the characterization of loads. This means that the study will be focused on the visualization of the generic trend of the effects of harmonic contamination on the SDU/BT.

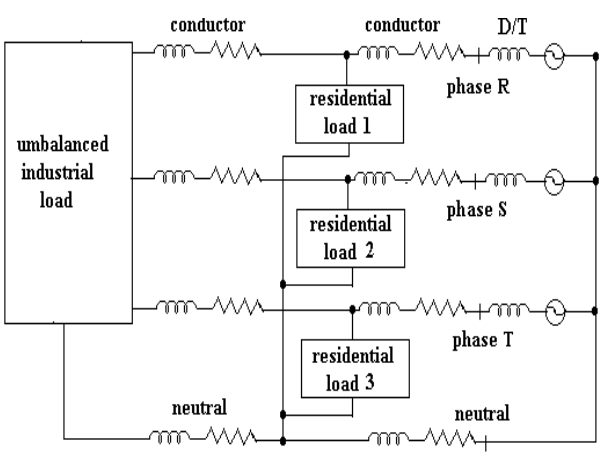

Fig. lll 7. Simulated topology for analysis

III. A. Topology considered for the analysis

Given the existent restrictions, a modeling by phase, with a limited number of bars, concentrated loads with typical consumption, with a typical NLL behavior and the worst conditions with respect to current phases has been considered in Figure 7. According to experience the typical consumption for each case were set up as well as the unbalanced effect resulting from lack of coincidence in consumption as shown in Table 1 and considering the following equipment:

A) electronic appliance, B) incandescent lamp,
C) computer station, D) microwave oven,
E) discharge lamp, F) fluorescent lamp,
G) single-phase inverter, H) three-phase motor.

TABLE 1
TYPICAL LOADS CONSIDERED

Residential 1	Residential 2	Residential 3	Industrial
10 type A 25 type B 02 type C 01 type D	20 type A 30 type B 03 type D	05 type A 20 type B 05 type E	03 type G 200 type F 50 type B 03 type H

TABLE 2
FUNDAMENTAL CURRENT COMPONENT

	Phase A	Phase B	Phase C	Neutral
Magnitude (A)	61	68	55	10

TABLE 3
HARMONIC CURRENT COMPONENTS

h	Phase A	Phase B	Phase C	Neutral
3	4.1	3.8	3.6	11.6
5	2.8	2.3	3.6	1.0
7	1.7	1.4	2.3	0.6
9	0.7	0.6	0.7	1.8

TABLE 4
HARMONIC CURRENT, DISTORTION AND ADDITIONAL LOSSES.

	Phase A	Phase B	Phase C	Neutral
I harmonic	5,31	4,70	5,62	11,75
%DI	8,76	6,91	10,21	120,78
% La	0,79	0,48	1,04	145,87

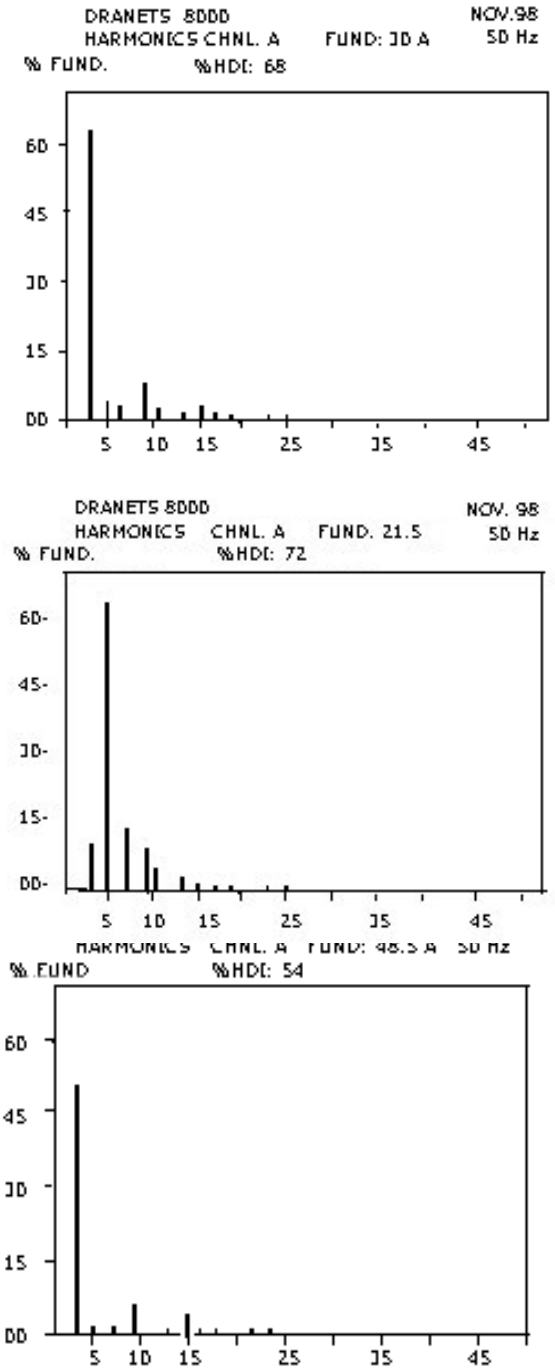

Fig. 8. Typical currents harmonic spectrum for commercial building, street lighting, neutral in a S/S of the UDS/LV.

III.A.1) Simulation findings. Through the simulation of the fundamental component models and harmonic component models the harmonic phase current and the neutral are determined in such a way as to obtain the distortion levels and the losses in the conductors shown on Tables 2, 3, 4.
It is observed that:

- The imbalance for the fundamental current shown in Table 2 is typical of these operating conditions and coincides with the usual design procedures of the neutral conductor.
- The presence of harmonic components at the entrance of the D/T presented in Table 3, produces the distortion (%DI) and the additional losses (%La) shown in Table 4, where it can be observed that the harmonic current flowing through the neutral is approximately 2,25 times the harmonic current of the phases.
- The losses in conductors (disregarding the Skin effect) resulting from the presence of harmonics a percentage of fundamental losses, shown on the last line of Table 4, confirm the high impact exerted by harmonic contamination in the increase of losses in the neutral.

Figure 8 shows the current spectrum found in two typical loads and in the neutral conductor in a S/S of the UDS/LV. These results are in accordance with those obtained in the computer simulation. However, it is necessary to carry out deeper studies to obtain precise information about the level of contamination at UDS/LV and its effects on the medium voltage level, besides of its economical effects on the distribution company.

IV. CONTROL OF HARMONIC DISTORTION

The harmonic currents from the NLD's can flow into any part of the UDS/LV to which it is connected, as determinated by the impedances of its various branches at the harmonic frequencies. The resulting harmonic voltage distortion at tha CCP with the medium voltage level wil be a function of the total inyected harmonic current and the system impedance at each of the harmonic frequencies. The harmonic current flow can be limited by several well known techniques and by means of the standars that fix responasabilities to the clients and the utility company, each one having a cost for both parts [12],[13].

Therefore, in the corresponding standard, a reasonable aproach is to limit the harmonic currents to the size of the individual customer. Conversely, it is necessary to limit the harmonic distortion of the system voltage supplied by the utility. The limits established in 1998 by the chilean standard are shown in the following tables 5 and 6 [15].

TABLE 5
ODD CURRENT HARMONICS IN [%] OF I_1,
FOR DS AT 220 V THROUGH 69 KV.

I_{CC}/I_1	h<11	11<h<17	17<h<23	23<h<35	h<35	DI
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20< 50	7.0	3.5	2.5	1.0	0.5	8.0
50< 100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

i) I_{CC} is the short-circuit current available al the PCC and I_1 is the máximun fundamental load current.

ii) Even harmonics are limited to 25% of above values

iii) For voltages > 69 KV, current harmonics are limited to 50% of above listed values.

TABLE 6.
ODD VOLTAGE HARMONICS LIMITS

h	V < 110 KV	V > 110 KV
3, 5	6.0	2.0
7, 9	5.0	2.0
11, 15	3.5	1.5
13, 21	3.0	1.5
17, $3 \times h > 21$	2.0	1.0
19	1.5	1.0
23	1.5	0.7
25	1.5	0.7
> 25	$0.2 + 1.3 \times 25/h$	$0.2 + 0.5 \times 25/h$

However the limits shown in table 5 do not take into account the large number of NLL's that are connected to the UDS/LV without any restriction, thus affecting the voltage distortion al the CCP with the medium voltage level system. It seems reasonable to consider additional limitations to the low voltage and power equipment that enter the country, as was done in the European Common Market by the application of the Standard ECC-1000-3-3 [14]

V.CONCLUSIONS

- In some S/S of the UDS/LV can be found higher DI level than that established by the national standard .
- The current flowing through the neutral conductor can be higher than the one flowing through the D/T phase, the third harmonic being of relevance. To minimize losses of energy and useful life, the design must consider a neutral conductor with a section at least equal to that of the phase conductor.
- Induction meters introduce an important error in the measurement of the power factor and consequently a cost for uncharged fines. For this reason it is necessary to evaluate their replacement for solid state meters.
- Transformers represent significant direct and indirect costs, therefore the overload produced by contamination should be considered when designing the replacement of units. In particular the harmonic triples that flow through delta windings.
- The luminous discharge lamps of public lighting have a relevant order 5 harmonic, of negative sequence, thus generating torque in an opposite to that of the fundamental, with a consequent error in measurement.
- There are several high cost technical solutions to attenuate the currents harmonics flowing through the UDS/LV. However, the best solution is to limit the harmonic current introduced by the low input voltage and power equipment that enter the country.

VI. ACKNOWLEDGEMENT

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