# STATISTICAL ANALYSIS OF MEASUREMENTS TO DEFINE THE MINIMUM FEATURES OF HARMONICS RECORDING EQUIPMENTS IN DISTRIBUTION SYSTEMS

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***Abstract* - This work puts forward results of the statistic analysis of voltage harmonic measurements achieved in different Low Voltage networks of the argentine electric system. The analysis involves individual harmonics from the 2nd to the 40th order as well as the total distortion voltage values, the THDv. Different alternatives are evaluated to reduce features of normalized meters, with the aim of decreasing costs allowing the use of a bigger amount of equipments in the control of power quality supply implemented in the argentine distribution systems.**

***Key Words* - Measurement equipments, Power Quality Supply, Statistics, Voltage harmonics.**

## I. INTRODUCTION

Most of the Distribution Systems in Argentina have been suffering outstanding changes since several years ago due to the privatization of the Electricity Supply Distribution Service [1], [2], [3]. Consequently, nowadays some regulations related to control of the quality service provided by the private companies are applied. The compliance of such regulations is controlled by regulatory authorities. Such regulations, aiming at controlling the technical product quality that the supplying companies should assure to the users, involves the voltage level control, and the harmonic perturbations and flicker [4].

The herein work shows a part of a research project development [5] whose objective is aimed at solving tangible problems of the technical product quality control, specifically those related to the harmonic distortion of the voltage wave. Other results obtained in the frame of this project and related to the harmonic distortion selection and measurements are shown in [6].

An electric product is specified as appropriate according to the quality of the voltage wave, considering mainly, two basic aspects: the voltage level and the disturbances harmonics and flicker. Quality control analysis carried out nowadays makes evident the deficiency of the present regulations in relation with the little amount of measurement points or verification ones of quality, noticing the lacks in the following particulars:

- The number of measurements allows controlling only power quality supplied to a reduced number of users at each period of measurement. The rotation foreseen of the measurement points allows controlling the power quality supply to all users, but it is affected by errors due to the requirements of the demand and the natural evolution of the network and its loads. As example, one Argentinean organism of control states 24 measurements per year of harmonics, thus more than 100 years are required to cover all Medium Voltage /Low Voltage (MV/LV) stations.
- Compensations are only applicable to those users which it is detected a deficient supply during the period of measurement and the following ones, until the company solves the problem. Nowadays, there are no practical methodologies to extend measurements results to users who are not directly verified.
- Measurements done on MV/LV station may be inappropriate to determine those distortion levels affecting different type of users fed from the same station, due to different voltage drops produced by harmonic currents.

Under this working context, it is valid the formulation of new control methodologies and procedures, more appropriate to overcome the mentioned disadvantages.

Among the proposals of the research project it is mentioned the use of a bigger number of measurement devices with better specified performance and reasonable costs, providing an accurate indication of the power quality supply of each user.

Thus, a widen control scheme of the network will be done based on a large number of measurements with equipment of adjusted characteristics and therefore less cost, which allows a primary control of the quality supplied to most of users. Those measurements, defined considering the stochastic nature of distortioning loads will allow, after an appropriate procedure, to determine with bigger feasibility those users affected by an excessive harmonic distortion of voltage.

Results of these measurements will be not directly applicable to the calculation of penalties in the scheme in force, but they will help to locate easily those points where later on detailed measurements will be required.

The methodology used to specify the characteristics of the recording meters is based on the assessment of errors produced while discharging or modifying the involved variables in the calculation of THDv.

Sensitive parameters to changes involved in this index are:
- Number of harmonic used.
- Phases where harmonics are measured.
- Average and storage time period.

Analysis before is made on historical files of measurements from different low voltage networks and different years. These records were obtained by mean of standard equipments which calculate and store THDv value and first 40 individual harmonics, at periods of 10 minutes. These equipments comply with the technical specs in [4] and [10], nevertheless their brand names are unknown.

By means of this methodology the behavior of different measurement alternatives are evaluated. The performance on each one is also established by means on the comparison with values obtained under standard conditions and for a real electric system. The stated scheme analysis simplifies the search of the optimal relation between the reduction of characteristics and the error produced.

## II. PERFORMED ANALYSIS

In order to determine the most significant variables of the power quality supply, 316 three phase measurements of harmonics voltage were analyzed, included in all 423.479 values recorded every 10 minutes (for each phase) in LV networks. These measurements were taken from the LV side of MV/LV (13.2kV/380V) substations and were performed on different nets. These were obtained between November 2000 and December 2004 and each of them corresponds to a different point of the distribution system. The place they were taken is unknown; consequently the kinds of user or load predominant (residential, commercial, industrial) are unknown too.

From those results, reductions were established in technical features of measurement equipment. Those analysis are detailed hereinafter:

### *A. Measurements Analysis*

Three types of analysis were done over the values of individual harmonics:

- The first, of descriptive statistics, to know the maximum, minimum, medium value, the standard deviation and the feasibility of being bigger than zero of the 2nd harmonics up to the 40th.
- The second analysis has as an aim a general evaluation of each individual harmonic values respect those limits fixed by the norm taken as reference [4].
- Harmonics grouped in three different sets (odd harmonics non multiple of three, odd harmonics multiple of three and even harmonics) were analyzed and the THD index sensitivity was evaluated as a percentage, at each of these groups.

These analysis were done taking each phase separately.

### *B. Analysis of alternative calculations of THDv with less amount of harmonics*

Different calculus alternatives of Total Harmonics Distortion of voltage (THDv) were pondered, considering less harmonics in relation to those required by the reference standard (2nd up to the 40th harmonics). Lastly this aim to reduce the memory demanded and the necessary functional characteristics of the recording equipment.

In this sense, five alternatives were determined for the new calculation of the THDv.

Alternative 1: from the harmonic 2nd up to the 25th.
Alternative 2: from the harmonic 2nd up to the 19th.
Alternative 3: from the harmonic 2nd up to the 13th.
Alternative 4: from the harmonic 2nd up to 9th.
Alternative 5: only harmonics 3rd, 5th and 7th.

The criterion for the selection of the four first alternatives is based on harmonic currents orders which are injected to the network by the popular controlled rectifier (Converters CA/DC).

These converters are important loads of non-linear characteristics, which inject harmonic currents and produce distortion of the voltage wave, in the point of common coupling between the system and load (PCC).

The order of the harmonic currents can be determined theoretically by means of the following equation:

$$h = n \cdot p \pm 1 \qquad (1)$$

Where:

h - Is the harmonic currents order.
p - Is the pulse number of rectifier circuit. It is the number of non simultaneous commutations per cycle of the fundamental alternate current.
n - Is any positive integer: 1, 2, 3...

The last alternative of THDv calculation was chosen because of those harmonics were the most representative ones according to the analysis in the point II-A.

Simulations of THDv calculus using normalized measurements and the five alternatives proposed, was carried out estimating the absolute error at each case and considering only the involved harmonics. THDv new values were compared with one calculated by means of 40 components (THDv40), which has been considered as actual value. Error is derived from the following equation.

$$Absolute\,Error_{i,x} = THD_{40\,i} - THD_{x,i} \qquad (2)$$

Where:

Absolute Error i, x - Absolute error for the record i of the alternative x.
i - number of record (i = 1, 2, 3, ..., 423.479).
x - alternative.
$THD_{40}$i - THDv calculated value according to norm (from the 2nd harmonics up to the 40th) of the record i.
THDx, i - THDv calculated value according to alternative x of the record i.

### *C. Analysis of Measurement in only one phase*

The aim of this analysis was evaluating the possibility of carrying out measurements in only one phase instead of the common three ones, thus, reducing even more the functional features to be satisfied by the recording equipment.

Using the available measurements it was analyzed the meter behavior with this characteristic and its behavior was evaluated calculating the absolute errors produced when two phases are disregarded.

THDv40 and the 3rd, 5th and 7th individual harmonics were chosen for this analysis.

The adopted criterion analyzes if the election of a phase considered as representative of the three, can produce or not an important error.

The procedure extracts from the three values corresponding to each phase the maximum and minimum value for the mentioned variables and for each average period.

The calculation of absolute errors was carried out according to (3).

$$Absolute\ Error_{i,j} = V\max_{i,j} - V\min_{i,j} \quad (3)$$

Where:

Absolute Error i, j - Absolute error for the record i of the variable j.

i - Number of record (i = 1, 2, 3, ..., 423.479).

j - Variable (THDv40, 3rd , 5th and 7th harmonics)

Vmax i, j - Maximum value between the three phases for the same record i of the variable j.

Vmin i, j - Minimum value between the three phases for the same record i of the variable j.

*D. Analysis of Increase of Average Period*

The aim was to evaluate if it is feasible that the recording equipment stores and averages values at bigger periods of time than 10 (ten) minutes, as it is established by the reference standard [4].

Therefore, THDv40 values recorded by standard equipments were used and new averages were calculated every 20', 30´, 40', 50', 60', 70', 80', and 90' (minutes). This last one simulates that the measurement equipment averages and stores in these time periods.

The evaluation of these alternatives was done based on absolute errors produced by considering the calculated average respect the original values.

The average calculation uses the necessary amount of records to reach the new time of average. For ex. for a 30' period of time three consecutive records of 10' are averaged and the new THDv value is pondered with each of the three records, using the relation (4).

$$Absolute\ Error_i = \sqrt{(Average\ value_i - Real\ value_i)^2} \quad (4)$$

Where:

Absolute Errori - Module of absolute error for the record i.

Real valuei - THDv40 value for the record i.

Average valuei - THDv40 value obtained as average that corresponds to the record i (for its calculation it was used the record i).

i - record number of the measurement (i = 1, 2, 3…N).

Similarly, the same analysis was done averaging THD3,5&7 values obtained in II-B, comparing, like the previous case, with the THDv40 value assumed as actual.

*E. Error Definition Em%*

The absolute error obtained by measuring a variable indicates the magnitude of the error, while to determine if this magnitude is large or small it is necessary to compare this error to those levels that the variable takes in itself. According to those mean values that the absolute error may reach and the measured value, the error Em% is defined as it is shown in the following relation.

$$Em\ Error\,\% = \frac{Mean\ Absolute\ Error\ of\ the\ measured\ variable}{Mean\ Value\ of\ the\ variable} \cdot \% \quad (5)$$

This last error is used to verify the performance of the alternative stated and accordingly, be able to do a comparative analysis.

For the case of the THDv, the absolute error shows how much distortion is lost by discharging harmonics in the calculation. In order to determine if the lost is large or small, the Em% error should be estimated for each alternative.

Therefore, the mean values of THDv40 of the three phases are averaged and this value is assumed as representative of the magnitude. The most unfavorable Em% error is obtained by choosing the bigger absolute mean error of the three phases and applying the previous relation (5).

## III. RESULTS

*A. Measurements Analysis*

From the evaluation done over individual voltage harmonics, it is assumed that the most significant ones are the 5th, 7th and 3rd.

These ones present the biggest mean values and the highest feasibility of occurrence. The following in importance are 9th, 11th and 13th, with mean values noticeably slower and smaller feasibility. These results are shown in Table I. Similar Results of those obtained here, can be found in [6], [7], [8] and [9].

As regards the comparison of individual harmonics with limits fixed by the regulation, average values in general are low and maximum values non frequently overpass limits. Values that reach at least a feasibility of 0,01 to overpass the stated limit by the reference regulation are shown in Table II.

**TABLE I**
**Results of the statistic analysis of individual harmonics (the biggest value between phases is shown)**

| Harm. | Mean Value | Maximum Value | Standard Deviation | Variation Coefficient | Feasibility of being bigger than zero |
|---|---|---|---|---|---|
| 5 | 1,87 | 15,4 | 1,73 | 94% | 0,99 |
| 7 | 0,92 | 6,4 | 0,67 | 74% | 0,99 |
| 3 | 0,67 | 11,2 | 0,61 | 113% | 0,98 |
| 9 | 0,22 | 2,9 | 0,27 | 124% | 0,77 |
| 11 | 0,21 | 4,1 | 0,27 | 130% | 0,75 |
| 13 | 0,15 | 4,0 | 0,23 | 153% | 0,61 |

**TABLE II**
**Feasibility of individual harmonics of exceeding their limit values according to the reference standard (it is shown the biggest value between phases)**

| Harmonics | Feasibility of exceeding the limit value | Harmonics limit value according to reference standard |
|---|---|---|
| 5 | 0,0407 | 6% |
| 15 | 0,0344 | 0,3% |

The third analysis is related with the THDv of the set of Odd harmonics Non Multiple of Three (OHNM3), Odd Multiple of Three (OHM3) and those Even ones (EH). From these analysis it can be observed that odd harmonics non multiple of three are predominant and that the influence of even harmonics is practically neglected (only a 0,11%). These results are shown in Table III.

**TABLE III**
**Influence of harmonics groups to the THDv40**

| Phase | OHNM3 | OHM3 | EH | TOTAL |
|---|---|---|---|---|
| R | 84,0% | 15,9% | 0,1% | 100% |
| S | 89,0% | 10,9% | 0,1% | 100% |
| T | 84,7% | 15,2% | 0,1% | 100% |

Mean values found at each phase are shown in Table IV as well as the average of variables THDv40 and harmonics 3rd, 5th and 7th. These are later on used in the calculation of Em% errors.

**TABLE IV**
**Mean value of variables THDv40, and harmonics 3rd, 5th and 7th**

| Variable | Phase R Mean Value | Phase S Mean Value | Phase T Mean Value | Average value between the three phases |
|---|---|---|---|---|
| THDv40 | 2,36 | 2,28 | 2,3 | 2,31 |
| 3rd harmonic | 0,67 | 0,46 | 0,64 | 0,59 |
| 5th harmonic | 1,87 | 1,85 | 1,80 | 1,84 |
| 7th harmonic | 0,9 | 0,89 | 0,92 | 0,90 |

*B. Analysis of THDv calculation alternatives with less amount of harmonics*

This analysis was carried out taken each phase separately, being defined a set of absolute errors for each phase, and from where average errors done for each alternative are obtained. The biggest of these errors is presented in Table V.

**TABLE V**
**Biggest values between phases of the absolute mean error and the Em% error**

| Alternative | Biggest absolute mean error between phases | Mean Value of THDv40 (from table IV) | Em% Error |
|---|---|---|---|
| THD25 | 0,000 | 2,31 | 0,00% |
| THD19 | 0,001 | | 0,04% |
| THD13 | 0,006 | | 0,26% |
| THD9 | 0,037 | | 1,60% |
| THD3,5&7 | 0,059 | | 2,55% |

After analyzing specifically the set of errors obtained with the alternative THD3,5&7 it was observed that in a 99% of the records the absolute error produced is less than 0,5. The histogram of errors up to such a range is shown in fig. 1.

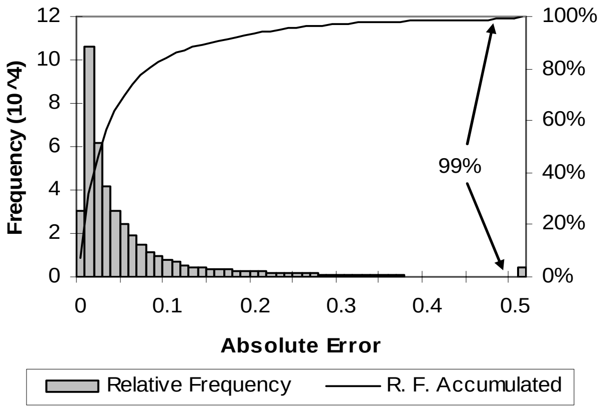


Fig. 1. Relative frequency accumulated and histogram of absolute errors of Phase R of the alternative THD3,5&7. The 99% of the absolute errors are less than 0,5. The behavior in other phases is similar to this one.

*C. Analysis of measuring in only one phase*

Mean values of errors calculated according (3) are shown in Table VI.

**TABLE VI**
**Mean absolute error and Em% error**

| Variable | Mean absolute Error | Mean Value of the variable (of table IV) | Em% Error |
|---|---|---|---|
| THDv40 | 0,33 | 2,31 | 14,29 % |
| 3rd harm. | 0,46 | 0,59 | 77,97 % |
| 5th harm. | 0,29 | 1,84 | 15,76 % |
| 7th harm. | 0,17 | 0,90 | 18,89 % |

It is observed that Em% errors for the four variables analyzed while measuring in only one phase are of importance compared with those found in the analysis of the different alternatives of THDv calculation.

The analysis for the 3rd harmonic shows that the mean value overpass the 70%, thus, it is assumed that the magnitude at this frequency is quite different between the measured phases.

*D. Analysis of increase of the average interval*

This analysis was done taking each phase separately, leaving defined a set of absolute errors for each phase, and from which are obtained average errors done for averaging interval. The biggest of these errors is shown in table VII.

**TABLE VII**
**Biggest values between phases of the mean absolute error and Em% error**

| Averaging | Biggest absolute mean error between phases THDv40 | Mean value of the THDv40 (of table IV) | Em% Error |
|---|---|---|---|
| 20 min. | 0,03 | 2,31 | 1,30% |
| 30 min. | 0,05 | | 2,16% |
| 40 min. | 0,06 | | 2,60% |
| 50 min. | 0,07 | | 3,03% |
| 60 min. | 0,08 | | 3,46% |
| 70 min. | 0,09 | | 3,90% |
| 80 min. | 0,09 | | 3,90% |
| 90 min. | 0,10 | | 4,33% |

Those cases in which appeared the biggest errors were analyzed. In all cases it was observed that the maximum error is produced when there is a quick variation of the original THDv, either increasing or decreasing one.

The averaged value changes with a delay or advance that do not allow to follow those situations where there are unexpected changes in the original THDv. These effects are the result of the averaging procedure used and its consequence intensifies as the averaging interval increases.

Results from the increase of storage interval in the calculation of THDv based in harmonics 3rd, 5th and 7th are included in Table VIII.

**TABLE VIII**
**Errors due to increase the average interval with THD3,5&7 alternative**

| Averaging | Biggest absolute mean error between phases alternative THD3,5&7 | Mean value THDv40 between phases (of table IV) | Em% Error THD3,5&7 |
|---|---|---|---|
| 20 min. | 0,08 | 2,31 | 3.46 |
| 30 min. | 0,09 | | 3.90 |
| 40 min. | 0,10 | | 4.33 |
| 50 min. | 0,10 | | 4.33 |
| 60 min. | 0,11 | | 4.76 |
| 70 min. | 0,12 | | 5.19 |
| 80 min. | 0,13 | | 5.63 |
| 90 min. | 0,13 | | 5.63 |

With the THD3,5&7 alternative and for an averaging time of 60 minutes it was observed that the 99% of absolute errors are less than 0,76. The histogram of errors up to such rank can be seen in Fig. 2.

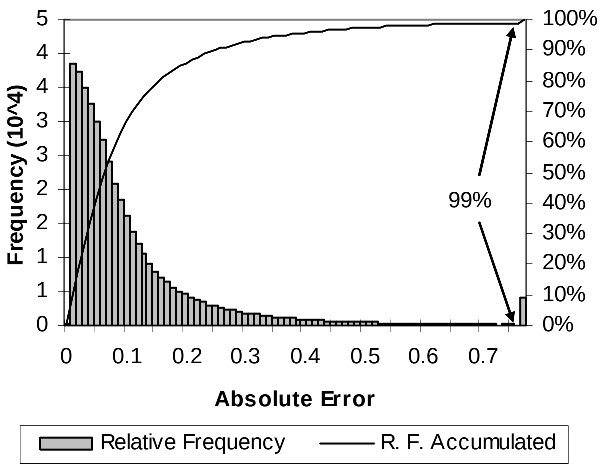


Fig. 2. Relative frequency accumulated and Histogram of the absolute errors of Phase R of the alternative THD3,5&7 averaged every 60min. The 99% absolute errors is less than 0,76. The behavior in the other phases is similar to this one.

## IV. CONCLUSIONS OVER RESULTS

### *A. Analysis of Alternatives of THDv calculation with less amount of harmonics*

Although alternative THD3,5&7 results the most unfavorable respect the amount of harmonics that participate in the calculation, it was observed that the mean absolute error is of small value, and 99% of the times it is less than 0,5.

In relative terms, its mean value do not overpass the 3% respect the mean value of the THDv40. In a detailed analysis of absolute errors for this alternative, but estimated for each measurement point, it can be observed that only for the 7,6% of these the maximum absolute error overpass the value of 0,5. An analysis of the absolute mean errors over these files showed in addition, that these situations appeared for short periods of time obtaining less mean amount. Only in three of the previous points the absolute mean error is higher than 0,5 and they can be treated as special cases since they present a higher harmonic 11th than the rest measuring points analyzed.

Briefly, the analysis suggests that the alternative 5, based in harmonics 3rd, 5th and 7th (THD3,5&7) presents in all evaluated cases an acceptable performance, thus it can be inferred that for the rest of alternatives the situation is more favorable.

This analysis allows to conclude that it is valid the use of only the 3rd, 5th and 7th harmonics to calculate the THDv, whenever it is accepted a reasonably low error.

### *B. Analysis of measuring in only one phase*

Mean absolute errors result small at a first sight, but later they turn to be important if they are compared with the mean representative values of each variable. Specially, the 3rd harmonic which is approximately four times bigger than the rest, being the possible cause of this difference the unbalance produced by the monophase loads.

Therefore, and due to the calculations of the error produced evaluating the third harmonics with only one phase, it is concluded, that it is not a reasonable alternative. Measurements then, should be of three phase character.

### *C. Analysis of increase of the averaging interval*

It was observed, that in general, the Em% error does not reach important values, it increases with the averaging period and does not overpass the 5% in the most unfavorable case found for intervals of 90 minutes. The most significant errors appear in situations of consecutive records with important variations of THDv (increasing or decreasing), that when they are analyzed with bigger averaging intervals have a delay in reflecting in the value of the resulting variable.

In the comparative study of the index THD3,5&7 respect the THDv40 for each one of the averaging alternatives, it was observed a logical increase of error considering less amount of harmonics and increasing the calculation interval. Nevertheless, the errors overpass the 5% only if data for bigger periods than 60 minutes are averaged.

Thus, it can be concluded that it is valid the use of averaging intervals bigger than 10 minutes established in the regulation, whenever it is accepted a reasonable low error.

## V. FINAL CONCLUSIONS

Significant results are obtained showing that it is possible to evaluate the harmonic condition at a measuring point with equipment of fewer features than the ones required, if the resultant error is reasonably low.

Specially, the alternative based on the use of third, fifth and seventh harmonics (THD3,5&7) shows an absolute mean error that does not overpass the 3% of the THDv average value.

Nevertheless, measurements that may be obtained with an equipment of few features *WOULD NOT be appropriate to calculate penalties* for distributing utilities according to the present regulation scheme. These are only required for a more appropriate control of the power quality.

As an example of a reduction in the equipment features, if 3rd, 5th and 7th harmonics are measured, storing results at intervals of 30 minutes, the necessary memory capacity would be reduced in a 96% and the frequency of sampling of the equipment would be decreased the 83%.

In this sense, if it is considered to obtain only the voltage harmonics it is necessary to count with three inputs of measurements. Records of currents may be omitted since they do not calculate the energy supplied to the client necessary only to estimate penalties. On the other hand, the reduction of costs followed by the possibility of increasing dramatically the number of measurements, would allow installing small harmonic recorders at each user where the energy can be obtained from the installed energy meter.

The mentioned reduction in the amount of samples to be acquired, not only allows having less memory capacity of calculation but also, it is in direct relation to the calculation power required and to the availability of resources to be used. The use of processor with few features opens the possibility of using simpler technologies associated to smaller costs, less energy requirements and with the enough connectivity, which provide important advantages at the moment of facing developments apt to be used in a portable form and mainly with reduced cost.

Notwithstanding the results obtained in the herein work, it is clear that the dependence of the harmonic content with the nature of the loads results in the fact that these statements need to be checked in a future. This re-evaluation aims at considering the possible new problems of the nets due to loads that inject harmonics of bigger order than those that currently are dominant.

Finally, from the experimental information and punctual aspects analyzed, it is expected that this work constitutes an important contribution in two areas of work.

The first one is directly related to the development of equipment for the measurement of harmonics, considering the basic functional principles that allow to use this equipment to know the harmonic disturbance state at a distribution system.

The second one is to contribute with the methodological formulation for the implementation of effective control of the power quality supply in distribution systems in the framework of research projects permanently developed at the Instituto de Energía Eléctrica of the Universidad Nacional de San Juan.

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