

New Distortion and Unbalance Indices Based on Power Quality Analyzer Measurements

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Abstract—Voltage and current waveform distortion are more prevalent on power systems today related to nonlinear loads. The proliferation of loads of this kind and their interaction with the power supply system is increasing the need to use power monitoring equipment to evaluate electric power quality. Measurements show that waveform harmonics and unbalance are variable over time due to changes in load conditions and in the system configuration. Thus, the electrical engineer has a large amount of data available from each phase, acquired using commercial Analyzers. Therefore, it is necessary to find ways to characterize this group of recorded data, to allow proper evaluation of the situation. Two indices, which can be calculated with these measurements, are proposed in this work: a three-phase total demand distortion index and a total unbalance index. In addition, this paper proposes an easy way to characterize the time-varying data to simplify their representation. The exposed procedures are applied to the data registered from an electrical power system, to show the performance of the proposed methods.

Index Terms—Harmonics, index, power quality.

I. INTRODUCTION

IN RECENT years, power-quality issues have focused the attention of several researches and they have been the subject of many papers published in technical literature. The control of power quality is becoming more relevant because of the widespread use of nonlinear and time-varying single-phase or three-phase loads. They have an increasing effect on the operation and performance of distribution networks in residential, commercial, and industrial areas.

Power-quality deterioration is due to transient disturbances (voltage sags, voltage swells, impulses, etc.) and steady state disturbances (harmonic distortion, unbalance, flicker). This paper is focused on the second group, and, specifically on harmonic and unbalance phenomena.

The presence of harmonics in electrical networks causes many problems for power system engineers. Their effects on power system devices include resonance, reduced operating life of rotating machines, malfunctioning of power system protection devices, errors in power measurements, additional losses, etc.

Unbalance phenomena should also be well monitored, detected, and corrected because of the problems that they can generate. For example, a machine operating under an unbalanced supply voltage will draw a current with a degree of unbalance several times greater. As a consequence, each phase current

might have very different rms values and the machine temperature would rise dramatically. In fact, the most expensive motors and generators use appropriate protection to detect excessive unbalance.

These quality problems have entailed the need for measuring equipment to monitor the installation at the user side, [1]–[6], such as electric power quality Analyzers. This equipment has a great number of quantities available relating to the harmonic distortion for each phase. Each measurement is usually composed of the voltage and current total harmonic distortion index (THD), and the rms values of the total waveforms and the fundamental component. One problem with characterization of these data is representation of harmonic distortion when the installation has very different distortion levels in each phase. There are two choices: to consider the distortion level of each phase separately, managing three times more information, or to characterize the installation distortion using a global parameter which considers the whole three-phase system.

The first approach is more interesting for analyzing the cause of the problems in an installation. The second is more suited to characterizing the distortion level of the whole installation. This point of view is adopted in this paper. A global index allows discrimination between a distorted three-phase system and another three-phase system that is less distorted than the first or not distorted. A single-phase index allows a more detailed study, which is useful for carrying out the characterization of a small number of circuits in the installation.

In addition, taking into account that the system voltage and current waveforms change over time, the registered data suffer from some uncertainty with the different measurements. So, the data behave randomly and need to be described in statistical form, [7]–[10].

In Section II, the most suited distortion and unbalance indices for three-phase four-wire networks are defined, based on commercial Analyzer measurements. In Section III, variation in voltage and current waveforms over time is shown, as well as the utility of statistical techniques to characterize these data. Finally, in Section IV, some total demand weighted distortion and unbalance indices are introduced to evaluate the power quality from the measurements obtained with commercial Analyzers. The proposed indices have been applied to a group of data registered in an installation, at intervals of 15 min.

II. POWER QUALITY INDICES

For a three-phase four-wire system, the equivalent three-phase voltage, V_e , is defined as follows [9]:

$$V_e = \sqrt{\frac{V_{L1}^2 + V_{L2}^2 + V_{L3}^2 + V_{L4}^2}{3}} \quad (1)$$

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where V_{Lj} is the voltage rms value of each wire with respect to an artificial neutral which makes the sum of those voltages null. Usually, the fourth term in the numerator may be left out and expression (1) can be simplified to

$$V_e = \sqrt{\frac{V_{L1}^2 + V_{L2}^2 + V_{L3}^2}{3}}. \quad (2)$$

In a similar way, the equivalent three-phase current I_e may be defined as follows:

$$I_e = \sqrt{\frac{I_{L1}^2 + I_{L2}^2 + I_{L3}^2 + I_{L4}^2}{3}}. \quad (3)$$

Definitions (1) and (2) are according to the IEEE standard 1459.

Traditionally, distortion has been characterized by the total harmonic distortion indices (directly measured by the Analyzer) defined as follows:

$$VTHD_{1\phi} = \sqrt{\frac{V_{L1}^2 - V_{L11}^2}{V_{L11}^2}} \quad (4)$$

$$ITHD_{1\phi} = \sqrt{\frac{I_{L1}^2 - I_{L11}^2}{I_{L11}^2}} \quad (5)$$

where V_{L1} and I_{L1} are each phase voltage and current rms value, respectively, and V_{L11} and I_{L11} their fundamental component rms value.

Another way to analyze the harmonic content is by means of the total demand distortion index, defined as VTDD in the case of voltages

$$VTDD_{1\phi} = \sqrt{\frac{V_{L1}^2 - V_{L11}^2}{V_{L11}^2}} \quad (6)$$

and ITDD in the case of currents

$$ITDD_{1\phi} = \sqrt{\frac{I_{L1}^2 - I_{L11}^2}{I_{L11}^2}}. \quad (7)$$

These indices are similar to the usual THD index. On one hand, the THD relates the waveform harmonic part to its fundamental component. On the other hand, the TDD index relates the same harmonic part to the total rms value. In this way, problems derived from an index which would be infinite in the case of waveforms with a null fundamental component are avoided. Although the voltages present in the real world do not have this problem and so the VTHD index could be used, unification of the indices used to measure voltage and current would be advisable as in (6), (7).

Taking into account both equivalent three-phase rms values presented in (2) and (3), it is possible to characterize the three-phase system harmonic content by means of the next voltage and current three-phase total demand distortion indices

$$VTDD_{3\phi} = \sqrt{\frac{V_e^2 - V_{e1}^2}{V_e^2}} \quad (8)$$

$$ITDD_{3\phi} = \sqrt{\frac{I_e^2 - I_{e1}^2}{I_e^2}} \quad (9)$$

where V_{e1} and I_{e1} are the fundamental harmonic equivalent three-phase voltage and current, respectively.

The availability of indices like (8) and (9) has two important advantages with respect to those used up to now. Firstly, their definition is global. Thus, they present compact information about the installation, compared to the case of three single-phase indices to evaluate phase voltages, another three indices to evaluate phase currents and, possibly, a fourth index to evaluate the neutral voltage with respect to a virtual reference or neutral current. All these indices may not provide specific information for a practical focus. Secondly, when the engineer looks for only a global index, he usually takes the symmetrical components and determines positive and negative sequence distortion indices, which make analysis of the problem more difficult, cover the proposed definitions with ambiguity and do not clarify the need to include the zero-sequence components.

According to their definition, the three-phase total demand distortion indices measure the lack of conformity of the line voltage and current waveforms with respect to sinusoidal waves, because of the harmonic content; without considering possible unbalances.

It is important to point out that these new indices may be calculated in a simple way with the harmonic measurements available from a commercial device. Usually, a power quality Analyzer supplies THD values, rms values, and fundamental component rms values corresponding to each harmonic in each phase. So, the defined indices can be calculated for the measurements of each phase. For instance, the three-phase distortion indices can be calculated by means of the expressions shown at the bottom of the page.

These indices represent the rms value of $VTDD_{1\phi}$ or $ITDD_{1\phi}$, considering the neutral wire as the fourth phase in the case of currents.

To evaluate the unbalance conditions, a reference waveform may be established, [12]. In this paper a reference voltage waveform and a reference current waveform are defined in a similar way: they are sinusoidal and positive sequence waveforms

$$VTDD_{3\phi} = \frac{1}{\sqrt{3}} \sqrt{VTHD_{L1}^2 \frac{V_{L11}^2}{V_e^2} + VTHD_{L2}^2 \frac{V_{L21}^2}{V_e^2} + VTHD_{L3}^2 \frac{V_{L31}^2}{V_e^2}} \quad (10)$$

$$ITDD_{3\phi} = \frac{1}{\sqrt{3}} \sqrt{ITHD_{L1}^2 \frac{I_{L11}^2}{I_e^2} + ITHD_{L2}^2 \frac{I_{L21}^2}{I_e^2} + ITHD_{L3}^2 \frac{I_{L31}^2}{I_e^2} + ITHD_{L4}^2 \frac{I_{L41}^2}{I_e^2}} \quad (11)$$

whose rms values are the equivalent three-phase voltage and current defined in (2) and (3), respectively.

Using these references, a deviation index (DI) is defined, which measures the difference between the rms values of the actual and the reference waveforms. It is possible to calculate one DI value for each phase by means of the following expressions:

$$VDI_{1\phi} = \sqrt{\frac{|V_{Lj}^2 - V_e^2|}{V_e^2}} \cdot 100 \quad (12)$$

$$IDI_{1\phi} = \sqrt{\frac{|I_{Lj}^2 - I_e^2|}{I_e^2}} \cdot 100 \quad (13)$$

where V_{Lj} and I_{Lj} are the j phase voltage and current rms values and $||$ means the absolute value.

The DI index for one phase measures the difference between a sinusoidal positive sequence waveform whose rms value is the rms value of this phase, and the three-phase reference waveform.

The three-phase total unbalance indices (VTU and ITU) are defined as the root mean square of the DI indices as follows:

$$VTU = \frac{1}{\sqrt{3}} \sqrt{VDI_1^2 + VDI_2^2 + VDI_3^2} \quad (14)$$

$$ITU = \frac{1}{\sqrt{3}} \sqrt{IDI_1^2 + IDI_2^2 + IDI_3^2} \quad (15)$$

These indices estimate the waveforms' nonconformity with respect to the reference waveform. In their calculation, only the measurements proposed by a commercial analyzer have been taken into account.

Other indices have been used to measure the unbalance, above all, the voltage unbalance. The introduction of symmetrical components in the unbalance indices is usual. For example, the unbalance factor is very extended. It is defined as the ratio of the negative sequence voltage to the positive. This kind of index depends on the way the zero-sequence component is considered. On the other hand, there is an ambiguity in the definitions of symmetrical components. There are several definitions which differ in a normalization constant that make the transformation unitary or not.

However, the indices defined in (10), (11), (14), and (15) are not appropriated for establishing responsibility, between customer and supplier, for the lack of electric power quality.

III. HARMONIC DISTORTION AND UNBALANCE EVALUATION WITH VARIABLE WAVEFORMS

Connecting measuring equipment to register values at successive time intervals shows that the voltage and current harmonics are variable over time due to changes in load conditions and the system configuration. The study carried out in the second section is specially focused on deterministic analysis, but it does not take into account the variability of these waveforms.

Figs. 1 and 2 show the voltage and current THD variations in phase 1, respectively, from the measurements made in a low voltage installation, taken every fifteen minutes for a week. They are presented in a usual format given by the network analyzer software. The installation belongs to a University

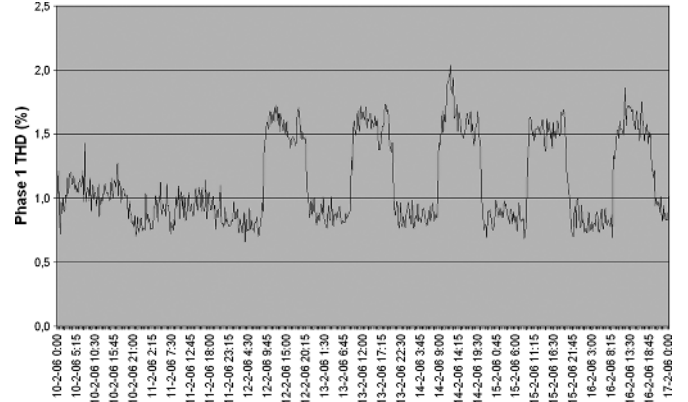


Fig. 1. Phase 1 voltage THD evolution during a week.

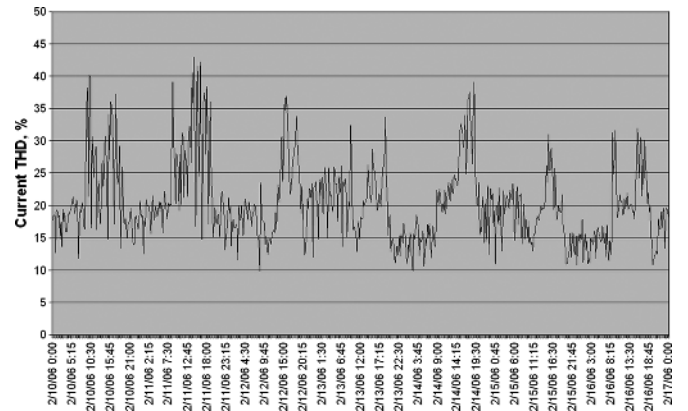


Fig. 2. Phase 1 current THD evolution during a week.

Complex composed of several buildings, some of them used as personal offices and others as classrooms.

The voltage THD has lower values during the weekend, when consumption is lower than during the rest of the week. From Monday to Friday, cyclical behavior is shown. On the contrary, the current THD is higher during the weekend than during the rest of the week. In this case, the lower consumption makes the effect of the presence of distorting loads greater.

In any case, the THD variations usually happen in a fast and random manner.

Up to now application of a deterministic study based on the worst case has been usual when proposing a security margin in system design and operation. But it frequently involves an installation being oversized and excessive costs. Consequently, the use of statistical techniques seems suited to quantifying distortion levels.

A. Statistical Characterization of the Measured Data

The industrial consumer may have a large database of an appropriate distortion index available, obtained from groups of measurements during one day, one week or one month. This random group of data requires statistical techniques to be evaluated properly.

Among the most adequate parameters, and those used by the Probabilistic Aspect Task Force which belongs to the Harmonics Working Group from IEEE [1], [2], the minimum value, the maximum value, the average value and the typical deviation

TABLE I
STATISTICAL VALUES TO EVALUATE HARMONIC DISTORTION USING THE
THREE-PHASE INDEX

| | Max | Min | Avg | Desv | CP95 |
|--------------------|-------|------|-------|------|-------|
| VTDD _{3φ} | 2.01 | 0.85 | 1.22 | 0.30 | 1.78 |
| ITDD _{3φ} | 27.00 | 9.53 | 17.74 | 2.99 | 23.38 |

TABLE II
STATISTICAL VALUES TO EVALUATE HARMONIC DISTORTION USING THE
SINGLE-PHASE INDEX

| | Max | Min | Avg | Desv | CP95 |
|---------------------|-------|------|-------|------|-------|
| 1VTDD _{1φ} | 2.03 | 0.66 | 1.12 | 0.34 | 1.67 |
| 2VTDD _{1φ} | 2.18 | 0.80 | 1.23 | 0.35 | 1.90 |
| 3VTDD _{1φ} | 2.38 | 0.87 | 1.30 | 0.27 | 1.78 |
| 1ITDD _{1φ} | 39.41 | 9.75 | 19.90 | 5.59 | 30.94 |
| 2ITDD _{1φ} | 30.82 | 8.63 | 17.82 | 4.20 | 26.16 |
| 3ITDD _{1φ} | 32.46 | 8.37 | 19.77 | 5.19 | 29.00 |
| 4ITDD _{1φ} | 0.38 | 0.00 | 0.14 | 0.06 | 0.24 |

are included. The last two values constitute a centralization and dispersion measurement, respectively, which allow a statistical distribution, i.e., a data group approximate image to be built up.

For a group of n measurements M_i , $i = 1, \dots, n$, the minimum value is represented by M_{\min} and the maximum value by M_{\max} . On the other hand, the average value, M_{avg} , and the standard deviation, σ_M , are defined as follows:

$$M_{\text{avg}} = \frac{\sum_{i=1}^n M_i}{n} \quad (16)$$

$$\sigma_M = \sqrt{\frac{\sum_{i=1}^n (M_i - M_{\text{avg}})^2}{n - 1}}. \quad (17)$$

Alternatively, calculation of the 95th percentile, CP95, can be considered in the distributions of VTDD_{3φ}, ITDD_{3φ}, VTU, ITU, introduced in (8), (9), (14), and (15). It presents the following characteristic: 95% of the measurements are lower than the 95th Percentile. It may be more relevant than the maximum value, because it is less sensitive to spurious measurements, [8]. In standards with fixed limits for the distortion values, the 95th percentile is usually related to those limits.

Table I shows the statistical results for the registered voltage and current data presented in Figs. 1 and 2, using the VTDD_{3φ} and the ITDD_{3φ} indices. In the same way, Table II presents the single phase VTDD_{1φ} and ITDD_{1φ} statistical parameters.

Tables I and II present two ways to identify the installation distortion. The first is by means of a three-phase index and the second by means of a distortion index for each phase. As can be seen, the three-phase index represents, using only one number, distortion in the three phases. The three-phase index is good for making an initial classification by distortion level, even if one phase is much more distorted than the others. On the other hand, standard deviation corresponding to the three-phase index is lower than that corresponding to the single-phase indices. Statistically, it means that the average value is more representative.

Table III also presents the statistical parameters for the VTU and ITU unbalance indices.

TABLE III
STATISTICAL VALUES TO EVALUATE UNBALANCE

| | Max | Min | Avg | Desv | CP95 |
|-----|-------|------|-------|-------|-------|
| VTU | 11.81 | 0.93 | 6.07 | 1.79 | 9.22 |
| ITU | 89.17 | 9.17 | 58.60 | 15.47 | 79.96 |

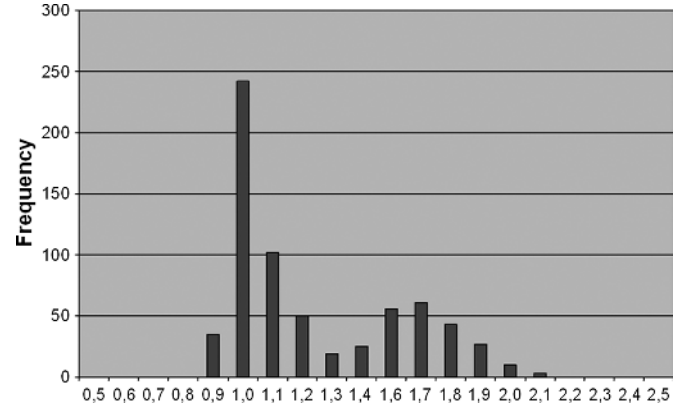


Fig. 3. VTDD_{3φ} histogram.

The indices VTDD, ITDD, VTU and ITU evaluate, respectively, the waveform distortion and unbalance. Their calculation is easy and may be performed with the measurements supplied by any commercial analyzer. The statistical parameters indicate the 95th percentile is more suitable than the maximum value because the former one is less sensitive to spurious measurements.

B. Some Considerations

If the data are distributed as a normal or Gaussian distribution, they are perfectly determined by the average and typical deviation values. The Gaussian distribution assumption is more accurate as the random level increases and, furthermore, it depends whether the signal comprises a deterministic component or not. If the waveform is completely random, the Gaussian distribution assumption is correct. But when the statistical measurements are obtained from a register that contains a relevant deterministic component, the probability distribution goes far from the Gaussian distribution.

In the same way, if the data are distributed as a Rayleigh distribution, it can also be completely determined by the statistical parameters defined above.

Due to the usual difficulty of determining the best distribution to describe a data group, a more practical method consists of the graphical representation of the absolute frequencies. This kind of graph, known as a histogram, shows the occurrence of the total data group at various intervals. When they are scaled in such a way that they cover a total unit area, the histograms represent the probability density function.

Figs. 3 and 4 show histograms of the voltage and current three-phase distortion indices corresponding to the data in Figs. 1 and 2, respectively. The histograms present the data measured in a compact way. Nevertheless, information about the moment where the particular events happened disappears.

Fig. 3 shows that the VTDD_{3φ} distribution might be assumed to be a Rayleigh distribution, being perfectly defined by the average and typical deviation values (1.22 and 0.30, respectively).

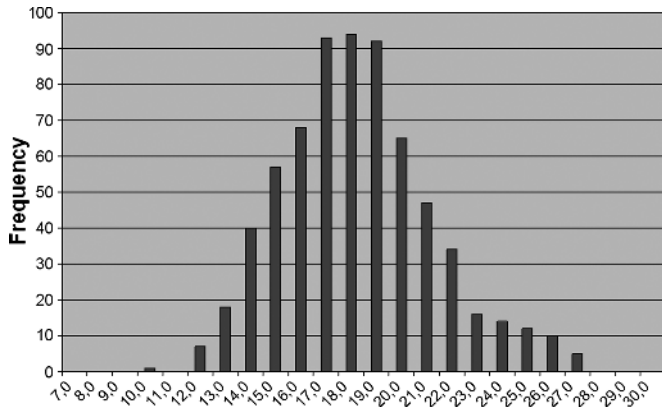
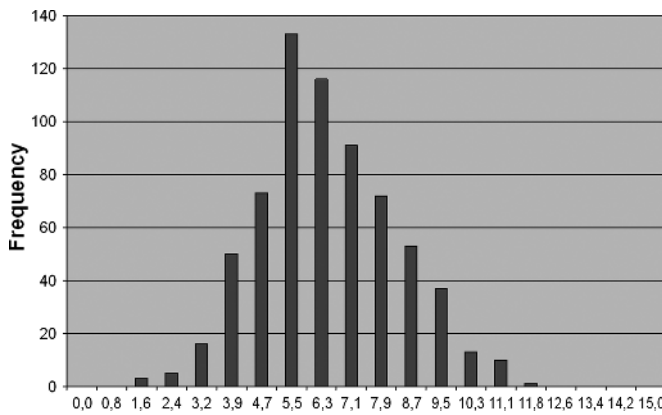
Fig. 4. ITDD_{3 ϕ} histogram.

Fig. 5. VTU histogram.

On the other hand, Fig. 4 shows that the ITDD_{3 ϕ} distribution should not be assumed to be exactly normal. However, taking into account its histogram form, the probability of finding a value around the average (17.74 A) is very similar to a Gaussian distribution although that probability is higher for low current values, and lower for high current values.

In any case, Figs. 3 and 4 show, in a simple way, the values which appear with the highest occurrence in the installation and the M_{avg} and σ_M values correspond to the data group centralization and dispersion parameters.

Taking into account the values in Table I, the relation between the maximal value and the 95th percentile may be pointed out. For the VTDD_{3 ϕ} , the first one is 2.01 and the latter one 1.78. This is slightly lower than the maximum because it is not affected by spurious values. In the case of ITDD_{3 ϕ} these values are 27.00 and 23.38, respectively.

Figs. 5 and 6 show the histograms of the VTU and the ITU indices, respectively. As can be seen, none of them can be assumed to be a Gaussian, Rayleigh or any other reference distribution. Nevertheless, although the histogram cannot be associated to a statistical model, it can be a useful data source together with the characteristic statistical parameter values such as the average and the standard deviation.

Fig. 5 shows a distribution centered and concentrated around its average value (6.07% according to Table III). The typical deviation is not too high (1.79 according to the same table), which corroborates the concentration shown by the distribution.

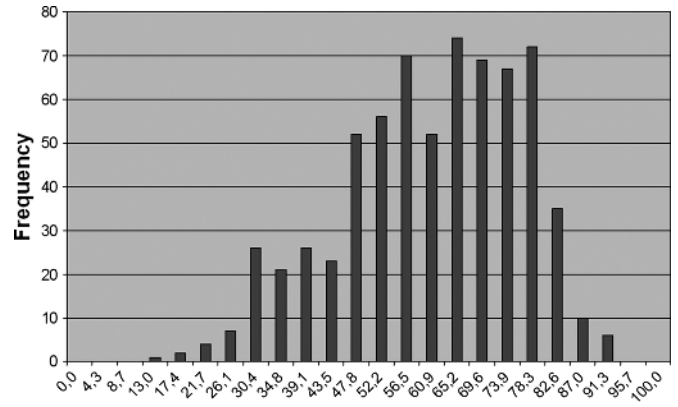


Fig. 6. ITUD histogram.

Fig. 6 shows more dispersed distribution (the typical deviation according to Table III is 15.47) centered but not concentrated around the average value (58.60%). The distribution is wider on the right than on the left.

Looking at Table III, which presents the statistical parameters relative to the TU indices, it can be seen that the 95th percentiles relative to the VTU and ITU are, respectively, 9.22 and 79.96 compared with the maximal values of 11.81 and 89.17. As in the case of demand distortion indices, the current indices are higher than the voltage indices.

IV. WEIGHTED DISTORTION AND UNBALANCE INDICES

In this paper, voltage and current demand distortion indices and voltage and current total unbalance indices have been proposed. Their calculation is based on the rms values of each phase. However, usually, the three-phase power system is not balanced. So, the power transferred by each phase differs considerably from the other phases. It affects the information supplied by the current indices in a relevant manner.

For that reason, the definition of a new distortion index which takes this new effect into account may be interesting. So, the current total demand distortion weighted index, ITDDW_{3 ϕ} , is defined, based on the weighted distortion index for each phase, ITDDW_{1 ϕ} , as will be shown bellow. The single-phase demand weighted distortion index is defined as the single-phase total demand distortion index weighted by the apparent power for each phase, as follows:

$$ITDDW_{1\phi} = \frac{ITDD_{1\phi} V A_{1\phi}}{V A_{3\phi}} \quad (18)$$

where $V A_{1\phi}$ represents single-phase apparent power and $V A_{3\phi}$ the three-phase apparent power defined as

$$V A_{3\phi} = 3 V_e I_e. \quad (19)$$

In this way, this phase contributes to the global index according to its relative importance.

Applying these new indices to expressions (10) and (11), the current three-phase total demand weighted distortion index may be defined as shown in (20), at the bottom of the page.

This index is more appropriate than (11) in those installations where the load is composed mainly of high power nonlinear

TABLE IV
STATISTICAL VALUES TO EVALUATE CURRENT WEIGHTED INDICES

| | Max | Min | Avg | Desv | CP95 |
|---------------------|-------|------|-------|------|-------|
| ITDDW _{3φ} | 15.61 | 5.50 | 10.25 | 1.73 | 13.52 |
| ITUW | 43.21 | 5.28 | 30.41 | 7.42 | 40.29 |

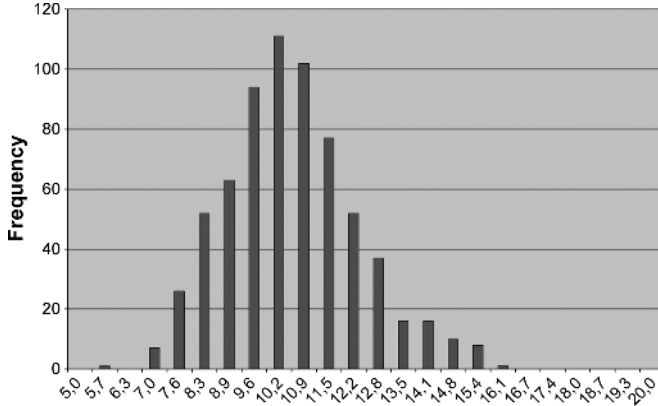


Fig. 7. ITDDW_{3φ} histogram.

single-phase loads. Actually, its effect on three-phase installation electric power quality deterioration must be higher than the effect produced by a load with lower power. The new index (20) solves this consideration, which is the opposite of the index presented in (11).

The first row of Table IV includes the values for these indices, calculated for the measured installation. The values in Table IV show the three-phase index ITDDW_{3φ}, where each phase contribution is weighted according to its apparent power rating. Its histogram is presented in Fig. 7. It must be pointed out that the distribution is quite similar to a Gaussian distribution. It is centralized around the average value (10.25% according to the first row in Table IV). The distribution dispersion is not very high (the typical deviation value is 1.73).

On the other hand, the first row of Table IV shows a 95th percentile of 13.52, compared with a higher maximal value of 15.61.

In the same way, the current total unbalance index may be weighted according to the apparent power of each phase to obtain the current weighted total unbalance index in the following way:

$$ITUW = \sqrt{IDI_1^2 \frac{VA_1}{VA_{3\phi}} + IDI_2^2 \frac{VA_2}{VA_{3\phi}} + IDI_3^2 \frac{VA_3}{VA_{3\phi}}} \quad (21)$$

Definitions equivalent to (20), shown at the bottom of the page, and (21) are possible for voltage.

The ITU statistical values are presented in the second row of Table IV and its histogram in Fig. 8. As in the case of distortion indices, these new indices are lower than those not weighted. In

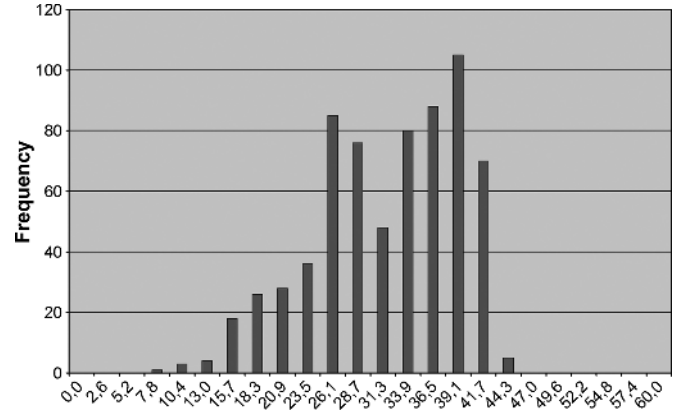


Fig. 8. ITUW histogram.

addition, the typical deviation presented by the current weighted total unbalance index (7.42) is lower than the same value corresponding to the same index without weighting.

Generally, weighted indices are lower than those not weighted, because the former do not value the power quality deterioration determining more appropriate responsibility for each phase distortion.

In fact, the dispersion presented by the weighted index histogram is similar to that in the unweighted index histogram. This histogram would not be assumed to be a Gaussian distribution.

Furthermore, the 95th percentile of the current total demand average unbalance index is 40.29, compared with a higher maximal value of 43.21%.

V. CONCLUSIONS

In this paper, possible problems in electric power quality associated with harmonic distortion and unbalance have been analyzed and evaluated. Voltage and current are variable over time due to changes in load conditions and in the system configuration. It implies random behavior of harmonic content measurements. In this paper, several distortion and unbalance indices have been proposed. In particular, a three-phase weighted total demand distortion index and a weighted total unbalance index are proposed. They can be calculated from the measurements registered by commercial analyzers.

Thus, they are global indices which characterize installation distortion and unbalance, respectively, with a single value. It provides, among other things, three main advantages. Firstly, the number of indices that the engineer must manage is reduced from three phase indices (plus that corresponding to the neutral phase) to just one index. So, the relevant information can be concentrated, avoiding nonrelevant and dispersed information. Secondly, the use of the symmetrical components which can present ambiguity in its definition and difficulty in its calculation is not necessary. And thirdly, the proposed indices give greater

$$ITDDW_{3\phi} = \sqrt{ITHDW_{L1}^2 \frac{I_{L11}^2}{I_e^2} + ITHDW_{L2}^2 \frac{I_{L21}^2}{I_e^2} + ITHDW_{L3}^2 \frac{I_{L31}^2}{I_e^2} + ITHDW_{L4}^2 \frac{I_{L41}^2}{I_e^2}} \quad (20)$$

weight in the responsibility for power quality deterioration, to those single-phase loads with higher power consumption.

Finally, several ways are presented to describe the data registered during the studied period statistically, i.e. the 95th percentile and the histogram. The presented distortion and unbalance evaluation indices are applied to measurements obtained from a low voltage installation over a week and the data are presented statistically.

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