ASSESSMENT OF POWER QUALITY INDICES OVER A DECADE OF CONTROL IN ARGENTINIAN DISTRIBUTION SYSTEM

Pedro Issouribehere, Juan Barbero, Gustavo Barbera, Fernando Issouribehere, *IEEE* Member, and Hugo Mayer

Abstract**—**The electricity distribution service in the Buenos Aires metropolitan area of Argentina, which was privatized in the early nineties, is carried out by three different Utilities and the control is performed by a Regulatory Agency (ENRE).

By the time this control began, the existing limits in IEC standards for Power Quality were adopted in order to obtain a starting point for the local regulation. In addition, the equipment employed to perform the measurements also meets IEC standards.

The aspects of Power Quality which are regulated, and therefore controlled, are voltage magnitude, voltage disturbances - harmonic distortion and flicker - , and long-term interruptions - 3 minutes or longer duration -. In every site in which the limits established for Power Quality are exceeded, the Utility is penalized.

The aim of the article is to show the results obtained over more than 10 years of permanent control. The carried out studies mainly consisted of processing the data collected since the beginning of the control in order to obtain: disturbance trends over the years, comparisons of the levels measured in different Utilities as well as disturbance behaviors throughout the day. In addition to this, the degree of fulfillment achieved by the Utilities is also assessed.

Index Terms**—** Flicker. Harmonics. Interruptions. Total Harmonic Distortion. Short-term flicker severity. Voltage Magnitude.

I. INTRODUCTION

The electricity distribution service in Buenos Aires – Argentina – is provided by three private companies and the control is carried out by the Regulatory Agency (ENRE). The IITREE of La Plata University provides technical assistance to the Regulatory Agency.

Table I summarizes information about each Utility, hereinafter named A, B and C.

Table I: Information of each Utility.

Utility	Customers	Supplied Energy [GWh per year]	Area [km^2]
A	300,000	2,600	5,700
B	2,200,000	16,600	3,300
C	2,500,000	17,900	4,600

Since the beginning of the privatization, extensive Monitoring Programs regarding Power Quality have been carried out.

The control of Power Quality, which is detailed in [1-2] began in the mid-nineties. For this reason, more than a decade of permanent control has been achieved so far.

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Firstly, regarding Voltage Magnitude control, the RMS value is recorded in 15-minute intervals. A large Monitoring Campaign is conducted performing 670 weekly measurements per month. If it is detected that in certain site the recorded values are not within the permitted band, the Utility will be penalized. The fine will be imposed until the Utility shows by a new measurement that the problem has been fixed.

Then, the control of harmonics requires measuring the THD (***Total Harmonic Distortion***) and all the individual harmonics up to the 40^{th}, as well. However, only the THD was used to assess harmonic behavior in several analyses carried out in the present article.

Regarding flicker control, the Pst (***Short-term Flicker Severity***) is employed. In all the studies carried out in the article concerning flicker phenomenon, the Pst parameter was used.

Each normalized weekly measurement consists of 1008 10-minute intervals. To represent each measurement, either the mean value or the Percentile 95 (P95) of all the 10-min intervals was employed. This P95 represents that value exceeded by only 5 % of all the 10-min intervals. This parameter is widely used in Argentinian regulations since it is the one to be compared to the established limits in order to determine whether a measurement is penalized or not.

Recent reports such as [3] of CIGRE/CIRED recommend using either P95 or P99 for each site in order to characterize the system. Since the P99 is not normally employed in Argentina, such a parameter was not used in this paper. Naturally, it would also be possible to represent the analyzed data by the P99 parameter.

The normalized equipment [4-5] is normally installed at the secondary of MV/LV transformers. These points are not randomly chosen but are selected from the results obtained through a previous, massive survey that leads to localize those sites of the network which are more likely to have high levels of disturbances. This previous survey is carried out by using a large number of low-cost disturbance recorders that only provide the THD and a parameter similar to the Pst.

And last but not least, Utilities must also comply with maximum supply interruption rates, for long-term interruptions (duration longer than 3 minutes) imposed by Franchise Agreements.

In case of transgression of the limits the Utility must compute discounts (bonus) to the customers. These computations require the estimation of non-supplied energy, and for this reason network contingencies must be recorded.

The control method applied since 1997 provides deterministic information about long-term interruptions obtained with event recorders.

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The main object of recorders installation is to detect interruptions in MV lines or higher voltage levels. To reach this objective the recorders are installed in couples, each one in a location (customer address) connected to the LV network and both located in the same MV line. In this way, interruptions on the monitored MV line or higher voltage levels, will be detected and recorded as coincident events in the installed recorders.

In this work the information obtained at customer level is employed to perform interruption statistics.

All the information processed comprises the period 1997-2008 for the three Utilities.

II. VOLTAGE MAGNITUDE

As regards Voltage Magnitude assessment, Utilities carry out 670 weekly measurements each month (70 Utility A, 300 Utility B and 300 Utility C).

Measurements are performed in different points of the LV-network, randomly selected.

The nominal voltage in Argentina is 220 V. When it comes to the permitted band, this depends on the type of network, i.e. for overhead lines the voltage measured must be within ± 8 % of the nominal values, while for underground lines the requirements are stricter as voltage must be within ± 5 % of the nominal voltage.

The previous conditions in each weekly measurement must be fulfilled for at least 97 % of the time. Otherwise, the measurement will be considered inappropriate and thus the Utility will be fined.

In general, it is believed that voltage magnitude follows a Gaussian distribution with average μ - coincident with the nominal voltage - and standard deviation σ [6].

Nevertheless, the results obtained from the Monitoring Campaign in Argentina did not actually follow that well-known law.

In Fig. 1 a histogram resulting of processing 1000 weekly measurements belonging to overhead line is shown (Utility A). The average value was 221.7 V (similar to the nominal voltage) whereas the standard deviation was 8.3 V. In the same figure, in continuous line, it has been also depicted the Normal distribution whose μ and σ are the same as the measurement results. By comparing both graphics it is possible to conclude that voltage behavior does not match a Gaussian distribution. The main difference lies in the fact that the real distribution is not symmetrical, but it decreases slowly towards the lowest values.

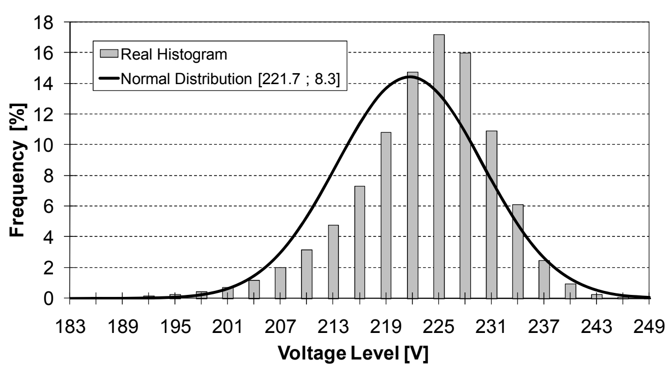

Fig. 1: Results of voltage magnitude assessment.

As far as the number of points with inadequate voltage magnitude is concerned, the conclusions drawn are almost the same for the three Utilities. If customers supplied by overhead lines are considered, the percentage of penalized points was as high as 18 % for Utilities A and B, and 24 % for Utility C.

As it was mentioned above, the permitted voltage band for those points supplied by underground network is narrower. For this reason, the results obtained in areas with underground distribution follow a narrower graph, as well. In Fig. 2 the probability density function for both types of networks in Utility B are depicted.

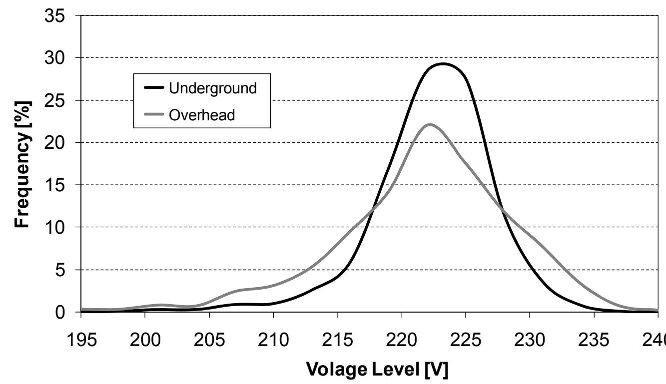

Fig. 2: Probability density functions for both types of networks.

As it can be seen, the stricter requirements resulted naturally in a better quality of voltage. The average value of both groups of measurements was similar, while the standard deviation of the underground group turned out to be smaller.

Finally, the results obtained in the three Utilities are compared. In Fig. 3, the three distribution functions for overhead areas are shown. The behavior of voltage magnitude in the different companies was similar. In the three functions the asymmetry previously commented is observed.

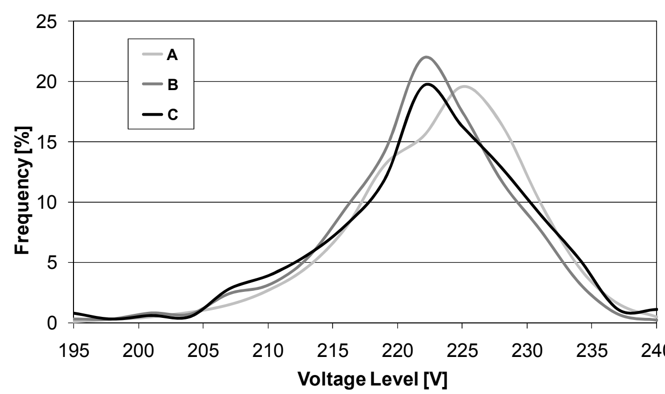

Fig. 3: Comparison of the Three Utilities.

III. HARMONICS AND FLICKER

According to Argentinian regulations it is the responsibility of Utilities and/or power system operators to ensure the electromagnetic compatibility (EMC) of the whole system and the equipment connected to it. In this respect compatibility levels have to be considered as reference values for the coordination of emission and immunity of equipment connected to the power network. The compatibility levels have to be considered on statistical basis, generally adopting

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the principle that the established limits will not be exceeded in both time and space with a 95% probability.

A summary of Flicker compatibility levels and planning levels for LV and MV networks is given in Table II.

Table II: Summary of IEC Flicker standards.

Standard		IEC 61000-3-7 [7]	IEC 61000-2-12 [8]
Purpose		Defines planning levels for controlling emissions	Defines compatibility levels for medium voltage networks
Objectives at LV-MV	P_{st}	0.9	1
	P_{lt}	0.7	0.8

For assessment purposes, the minimum period of observation should be one week, and the $P_{st99\%}$ and $P_{lt99\%}$ values resulting from the measurements should be compared with the allowed relevant 99% or 95% emission limits. The following relationships are considered:

$$P_{st99\%} = 1.25\, P_{st95\%}$$
$$P_{lt95\%} = 0.84\, P_{st95\%}$$

Regarding voltage harmonics, the reference levels to be met are those which should be guaranteed at each supply point. Transgression probability should not be above 5 % a week.

The adopted values for voltage harmonics depend on the voltage level. The reference levels according to Argentinian standard and IEEE-519 [9] standard are shown in Table III.

Table III: Summary of voltage harmonic limits.

	THD	H_2	H_3	H_4	H_5	H_7	H_9	H_{11}	H_{13}
ENRE Limits	8	2	5	1	6	5	1.5	3.5	3
IEEE Limits	5	3	3	3	3	3	3	3	3

II.1 Comparison of levels recorded in the three Utilities

In Fig. 4 a comparison of the THD levels recorded in the three Utilities is shown. The values were represented by both the average value and the P95 of all the weekly averages.

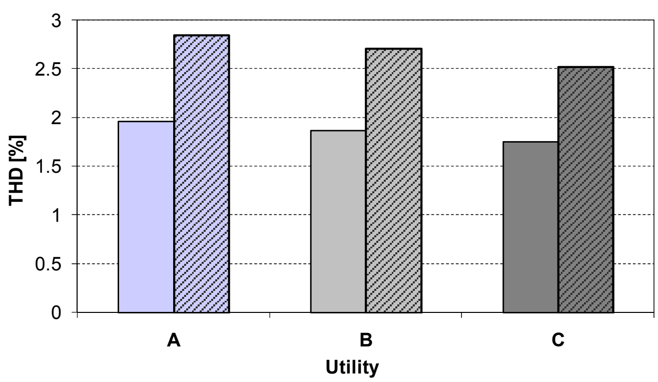

Fig. 4: Comparison of harmonic levels in the three Utilities.

The values reached in the three Utilities were quite similar. The highest levels were observed in Utility A, while the lowest ones were measured in Utility C.

Similarly to what was presented above for harmonics, the comparison of flicker levels is depicted in Fig. 5.

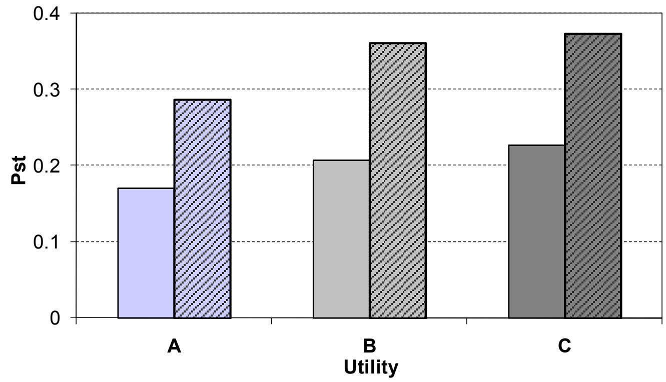

Fig. 5: Comparison of flicker levels in the three Utilities.

The values recorded in the three Utilities were also similar. Nevertheless, in this case the highest values were observed in Utility C whereas the lowest ones in Utility A. That is to say, the opposite to what occurred in harmonic control.

II.2 Disturbance behavior throughout the years

The trends of both disturbances over a decade were also obtained considering the results in the three Utilities.

The THD trend is illustrated in Fig. 6. This parameter was represented by the mean value and the Percentile 95 of the average values of all the weekly measurements belonging to each year.

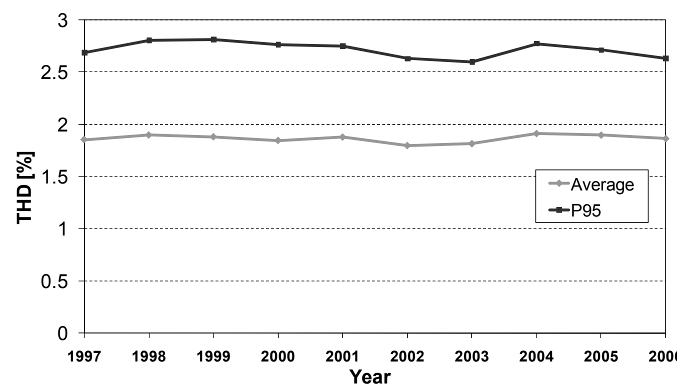

Fig. 6: THD trend throughout 10 years.

The trend did not show significant changes in different years. It is remarked the fact that the degree of fulfillment regarding harmonics was quite high.

As regards flicker behavior over the years, the trend appears in Fig. 7.

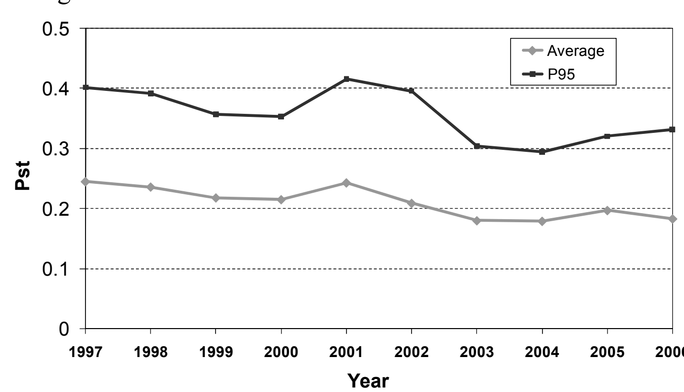

Fig. 7: Pst trend throughout 10 years.

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Although the levels recorded in different years were also similar, the trend showed a slight decrease. Probably, the reason of this issue lies in the fact that the fulfillment of flicker requirements was not as high as that for harmonics. Therefore, throughout all these years the Utilities have had to mitigate flicker in different points of the network. As a result, the system may have become more powerful and less sensitive to distorting loads.

II.3 Disturbance behavior in the different months

In order to obtain the behavior of disturbances throughout a typical year, all measurements were classified according to the month they belong to, regardless of the year in which they were carried out. Thus, the graph shown in Fig. 8 was obtained.

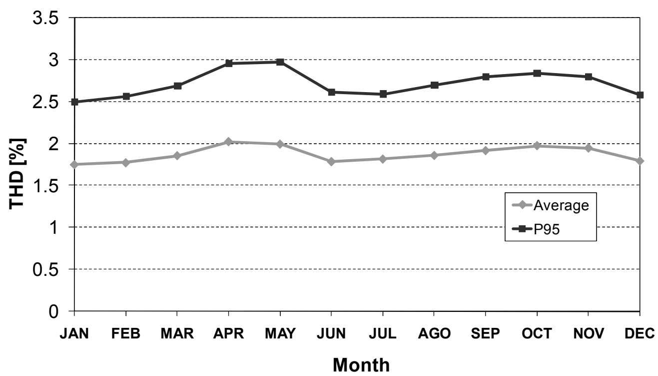

Fig. 8: THD behavior during the year.

Even though there were not significant differences in the THD values throughout the year, for both parameters – i.e. mean value and P95 – it was observed that the lowest levels of harmonics were reached in winter and summer. Since harmonic levels in the network depend heavily on customers' emissions, it would be worth correlating this harmonic trend with users' habits (use of diverse household appliances in different seasons, holidays, etc.).

When it comes to flicker behavior, the results are depicted in Fig. 9. As it can be observed, the Pst values have remained steady and therefore no correlation between this disturbance and the period of the year was achieved.

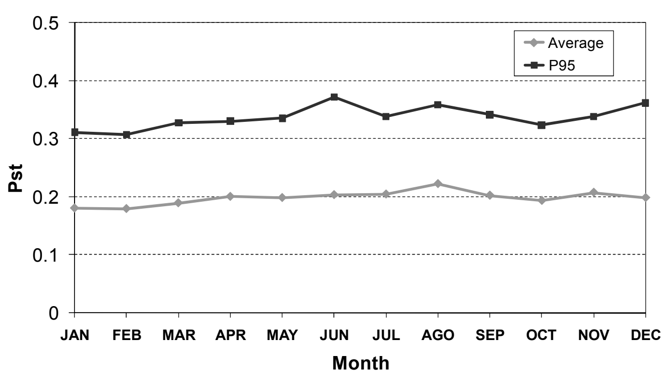

Fig. 9: Pst behavior during the year.

II.4 Disturbance behavior throughout the day

The profiles of both disturbances throughout the day were achieved. In order to do so, all the data gathered over a whole decade were divided into the 24 hours corresponding to a complete day.

The THD daily profile is illustrated in Fig. 10. This graph looks like the load curve of residential customers. For this reason, it was concluded that such customers are thought to be prone to cause harmonics.

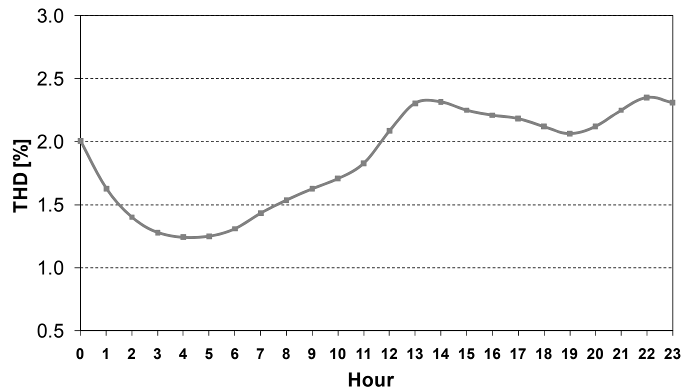

Fig. 10: THD behavior during the day.

On the other hand, the Pst daily profile is illustrated in Fig. 11. On this occasion, the graph was similar to the load curve of general customers. Consequently, these customers, who consist mainly of industrial and commercial users, appear to be in part responsible for the flicker existing in the distribution system.

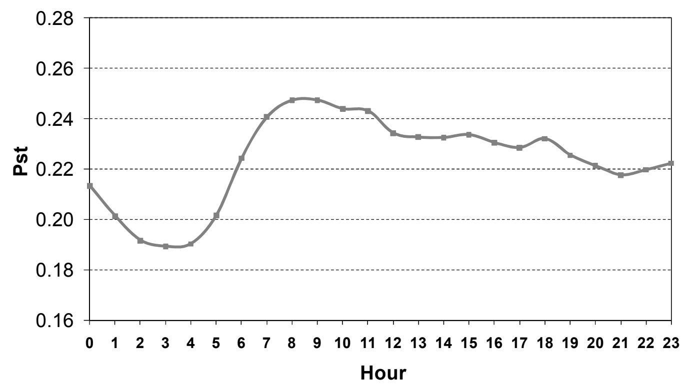

Fig. 11: Pst behavior during the day.

II.5 Degree of fulfillment in each Utility

A. Ordinary Monitoring Program

This section is about the assessment of the established disturbance limit fulfillment.

To begin with, the fulfillment of harmonic levels is discussed. In Fig. 12, a bar chart shows the percentage of penalized measurements in each Utility. As it can be observed, since the percentage of penalized sites was below 2 % in the three companies, it is concluded that the degree of fulfillment was high. Besides, the proportion of penalized sites in the three Utilities reached 1.2 %.

When it comes to which harmonics are more likely to appear in the distribution system, it was found that from the 2nd to the 14th all of them appeared with the same occurrence. In contrast, it was observed that practically in half of the penalized cases, the harmonic that was above the limits was the 15th.

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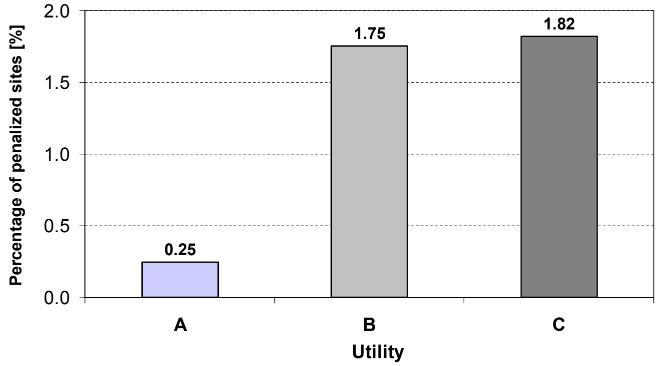

Fig. 12: Penalized sites for harmonics in each Utility.

The bar chart in Fig. 13 appears to be useful in order to compare the measurement results with the established limits. There, the P95 of all the P95s of each weekly measurement was represented for all the harmonics up to the 15th. This parameter is close to the maximum value to be found in the network.

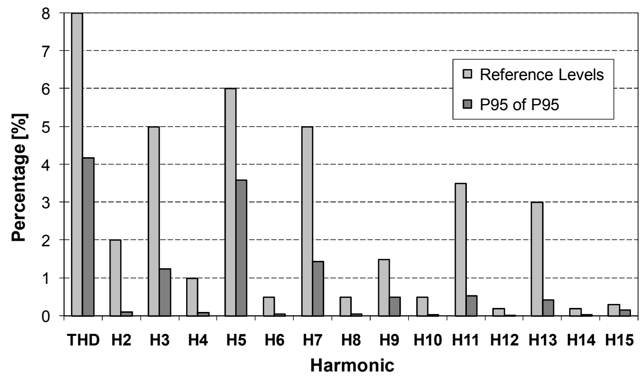

Fig. 13: Reference levels and measured values at different harmonics.

In the worst case (5th harmonic), this parameter was slightly higher than the half of the reference level. Therefore, it is concluded that the degree of fulfillment regarding harmonics was high. Nevertheless, it is important to point out the fact that the measurements are normally made at the point with highest short-circuit power of the whole LV network. This point has the maximum capacity of absorbing the disturbances present in the current and, consequently, the harmonics in the voltage waveform are supposed to be the lowest of the LV network.

In connection with the fulfillment of flicker levels, the results for each Utility appear in Fig. 14. On this occasion, the proportion of penalized sites is not as low as in the case of harmonics. The highest number of penalized measurements was reached in Utility B, in which more than 4 % of the sites resulted fined. Considering the three Utilities together, 2.5 % of all the flicker measurements were penalized.

The comment made above about the points where the measurements are normally made is also applicable here.

B. *Complaint treatment*

Apart from the ordinary monitoring program, whose results were discussed in the previous section, the Utilities are also required by the Regulatory Agency to deal with special cases. These cases are when customers complain about disturbances existing in the supplied voltage. In most of them, such complaints are connected with flicker phenomenon since customers notice some fluctuation in the luminance of their bulbs.

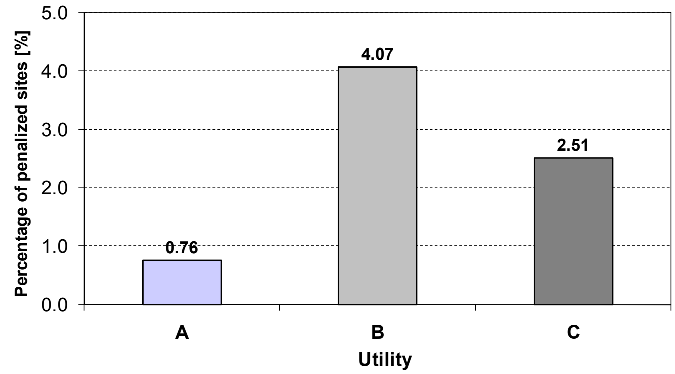

Fig. 14: Penalized sites for flicker in each Utility.

The same IEC normalized equipment is employed to assess the flicker level directly in the houses whose owners have claimed to notice the annoying fluctuation. So far, more than 300 complaints have been dealt with. Obviously, with the purpose of not affecting the results, these measurements were not included in all the previous analyses.

In this case, taking into account the three companies, almost 60 % of the analyzed complaints resulted in flicker levels above the established limits. That is to say, the results were completely different from those in the ordinary monitoring program; the flicker levels were far higher.

Finally, in Fig. 15 the histogram of Pst values – representing each measurement by its P95 – for all the complaint sites is depicted. The addition of all the bars with Pst values higher than 1 represents the proportion of penalized sites.

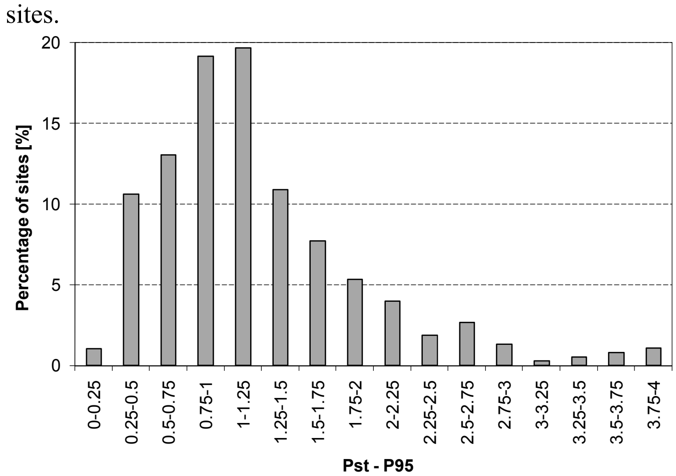

Fig. 15: Histogram of Pst values – Complaint cases.

From this parallel campaign it is possible to conclude that although the flicker levels measured at the secondary of MV/LV transformers were in general within the established limits, in certain points of the LV network – with less short-circuit power – the Quality of Service provided was not so satisfactory.

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IV. LONG INTERRUPTIONS

The interruption administration system employed by the Utilities is based on queries performed over both, the interruption data base and the data base which describes the Customer-Network connectivity. Transgressions to the established limits give rise to discounts to each user.

The control method applied today by the Regulatory Agency ENRE [10] includes interruption recording at supply points.

Some indicative indices of the present situation concerning long interruptions and obtained from the data recorded are presented here.

IV.1 Details of the data processed

The main object of the recorders installation is to detect interruptions on MV lines or higher voltage levels on the network. To reach this objective the recorders are installed in couples, each one in a location (customer address) supplied from different MV/LV transformers and both connected to the same MV line. In this way, interruptions on the monitored MV line or higher voltage levels, will be detected and recorded as coincident events in the installed recorders.

The information obtained at customer level was employed to perform the interruption statistics.

The information processed comprises the period January 1999 to December 2008 for the three Utilities A, B and C.

Table IV presents indicative numbers of the processed data and its representativeness.

Table IV. Details of the sampling made.

Utility	Stations	MV/LV Transformers	Sites	Months per site
A	9	331	1413	5.8
B	57	439	1666	5.7
C	61	450	1652	5.7

IV.2 Processing details

Statistical processing of interruptions was oriented to obtain indices expressed as average values by monitored location per year. The processing goals were to obtain indicative figures of the present situation after more than ten years of control and to compare their values with the older ones after the first three years of control.

Criteria to identify and suppress interruptions caused by customers (such as holidays, weekends, daily and periodic interruptions) were implemented and applied in order to minimize errors in statistics.

From the recorders, the following magnitudes for each Utility and for each monitored location were obtained:

D_i: Interruption duration [min].

N_{tot}:Total number of recorded interruptions.

Mi:Number of *months* that the location was monitored.

With that information the following indices were determined:

Interruption rate expressed in [interruption/year]**:**

$$\lambda = 12\,\frac{N_{tot}}{Mi} \qquad (1)$$

Restoration time expressed in [hour/interruption]**:**

$$r = \frac{\overline{D}}{5\,Mi} \qquad (2)$$

Unavailability expressed in [hour/year]**:**

$$Q = \frac{D_{tot}}{5\,Mi} \qquad (3)$$

where:

$$D_{tot} = \sum_{i=1}^{N_{tot}} D_i \qquad \overline{D} = \frac{1}{N_{tot}} \sum_{i=1}^{N_{tot}} D_i$$

Average values of indicators given by expressions (1) to (3), extended to the corresponding network level, are respectively the *System Average Interruption Frequency Index* (SAIFI), *Customer Average Interruption Duration Index* (CAIDI) and the *System Average Interruption Duration Index* (SAIDI). These indices are industry standard of electrical outages and are extensively used by Distribution Utilities.

IV.3 Processing results

Figs. 16 to 20 show statistics of the *interruption rate* λ, the *restoration time r* and the *unavailability Q* mean values computed at each location on a year basis from the data collected over the period January 1999 to December 2008.

The 50th-percentile of the mean values at each location for λ, *r* and *Q* are also indicated for each Utility, and according to [11] such values should respectively correspond to the SAIFI, CAIDI and SAIDI.

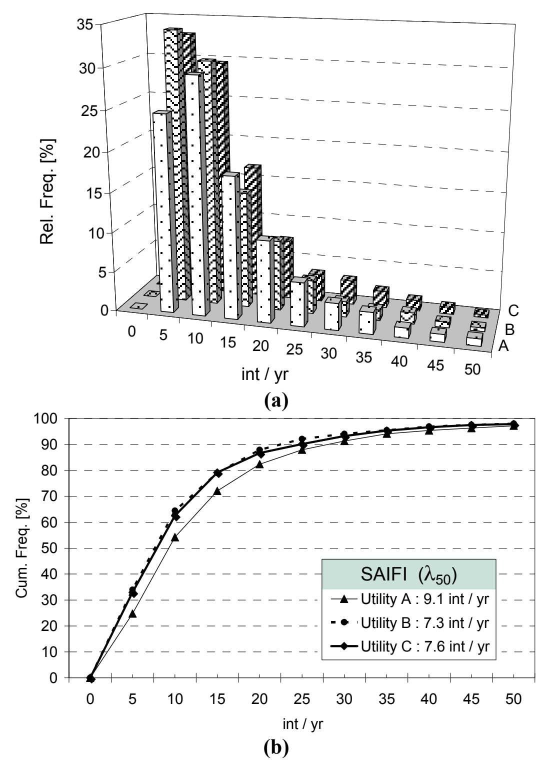

Fig. 16: Interruption rate λ. **(a)** Relative frequency histograms. **(b)** Cumulative frequency curves.

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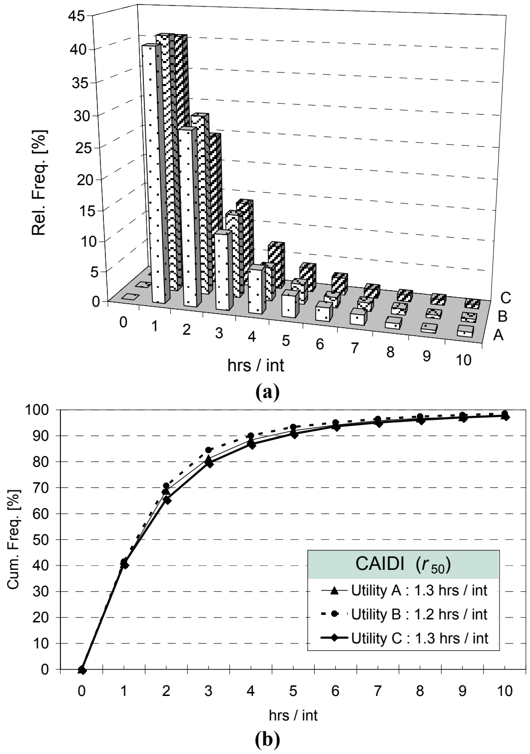

Fig. 17: Restoration time r. **(a)** Relative frequency histograms. **(b)** Cumulative frequency curves.

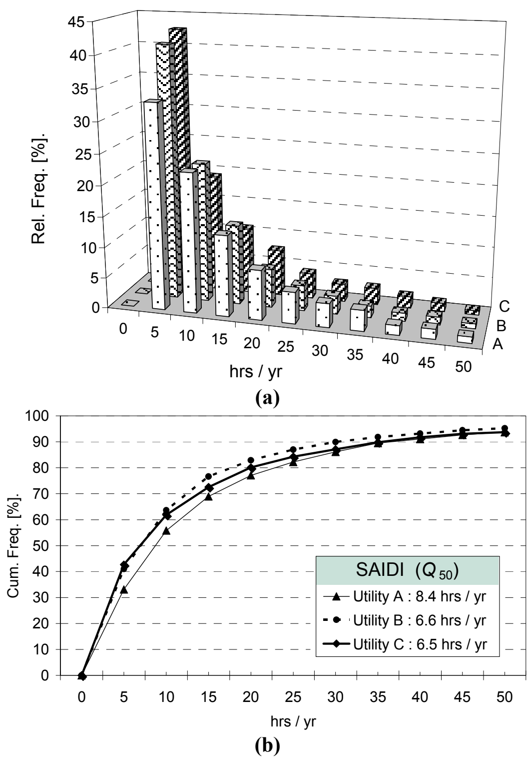

Fig. 18: Unavailability Q. **(a)** Relative frequency histograms. **(b)** Cumulative frequency curves.

Long-duration interruptions recorded during the last three years, over a *sample* of locations in the Buenos Aires metropolitan area, were processed to obtain reliability indices such as the *interruption rate* (λ), the *mean time to repair* (r) and the *unavailability* (Q). Table V summarizes the obtained results. The shown values for each index are the 50th-percentile of the mean values at each location.

Table V. Reliability indices.

Utility	Period	λ_{50} [int/yr]	r_{50} [hrs/int]	Q_{50} [hrs/yr]
A	Jul. 1997- Jun.2000	9.8	1.1	7.7
	Jan. 1999 – Dec. 2008	9.1	1.3	8.4
B	Jul. 1997- Jun.2000	8.0	0.9	5.1
	Jan. 1999 – Dec. 2008	7.3	1.2	6.6
C	Jul. 1997- Jun.2000	9.7	1.2	6.9
	Jan. 1999 – Dec. 2008	7.6	1.3	6.5

It is important to denote that the presented results were obtained from data recorded at locations supplied with a low power quality, because at present the Regulatory Agency (ENRE) gives priority to the validation of the interruptions reported each semester by the Utilities rather than the statistical evaluation of the quality and reliability indices.

Nevertheless according to [11] this fact does not invalidate the method employed here to evaluate the system reliability indices.

V. CONCLUSIONS

In Argentinian distribution system the voltage level does not match a Gaussian distribution due to the fact that the real distribution is not symmetrical, but it decreases slowly towards the lowest values.

Taking into account underground and overhead lines, the average of both groups of measurements was similar, while the standard deviation of the underground group turned out to be smaller.

Furthermore, the three distribution functions for overhead areas in the different companies were similar.

Concerning harmonic and flicker, the degree of fulfillment was high. In addition, in harmonics was higher than in flicker.

The disturbance levels recorded in the three Utilities were similar. However, the company with the highest levels of harmonics showed the lowest levels of flicker and vice versa.

The harmonic levels throughout 10 years have remained practically steady. Nevertheless, a slightly decreasing tendency has been observed in flicker levels.

The lowest levels of harmonics have taken place during the periods of the year in which residential customers are normally on holiday. In addition, no correlation between flicker levels and periods of the year has been found.

The harmonic daily profile was similar to the load curve of residential customers, whereas the flicker daily profile resembled the load curve of general customers.

The treatment of complaints about flicker led to the awareness of the presence of this phenomenon in the LV network.

Regarding long interruptions, it is possible to conclude that nowadays after ten years of control, SAIFI values are better for the three Utilities, but SAIDI and CAIDI values are almost the same or slightly worse.

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VI. ACKNOWLEDGEMENTS

The authors would like to thank the Investigation Project: “Sistemas de suministro de energía eléctrica. Operación y expansión. Compatibilidad electromagnética y calidad del suministro. Impacto ambiental y seguridad eléctrica”. Code: 11-I112 Effective date: 01-01-2006 to 31-12-2009, of “Programa Nacional Argentino de Incentivos a la Investigación y Docencia, Ministerio de Educación de la Nación”.

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