VOLTAGE FLUCTUATION IMPACT ON EQUIPMENT PERFORMANCE: EXPERIMENTAL ANALYSIS BASED ON UIE/IEC FLICKER INDEXES

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***Abstract* – the aim of the paper is to present experimental results related to the impact of voltage fluctuation phenomenon upon representative residential, commercial and industrial equipment performance. The voltage fluctuation is represented by a periodic rectangular type, which is characterized by its frequency and magnitude level. These parameters are related to the flicker index by simulating the UIE/IEC flickermeter model. Laboratory tests of representative loads are then carried out to study their dependence upon flicker limits. The results obtained are useful to support the present flicker limits adopted in Brazil, and also to delineate a discussion about the possibility of making them more versatile.**

KEYWORDS

Voltage fluctuation, flicker indicators, equipment performance, power quality.

I. INTRODUCTION

Many phenomena in voltage and/or current signals in deviation of ideal conditions can be denoted as an Electrical Power Quality problem. Among them, voltage fluctuation is pointed out as an important matter because it has an intermittent and/or steady state behavior, and can propagate throughout the electric system, reaching many consumers. This phenomenon can be defined as voltage magnitude variations in RMS or peak value, in the range of 0.9 to 1.1 pu and frequencies up to 35 Hz [1].

Since incandescent lamps are extremely sensitive appliances to voltage oscillations, flicker was historically the most well known outcome caused by voltage fluctuation. In this sense, it is defined as the sensation experienced by human visual system when subjected to luminance variations [1], [2]. Flicker is used to evaluate the disturbance in the voltage even today.

Nowadays, many countries in the world, including Brazil, have been adopted the international UIE/IEC method to estimate voltage fluctuation by means of flicker.

As stated by UIE and IEC [3], [4] the method and its associated flickermeter takes into account various aspects of the voltage fluctuation, such as: magnitude, frequency, waveform shape and duration of the phenomena. The strategy consists in simulating the interaction of this voltage signal with the nonlinear combined lamp-eye-brain chain effect.

Furthermore, it performs a suitable statistical analysis. From this results the basic flicker indicator, the so-called *Short-Term Flicker Severity, P_{ST}*.

Otherwise, quite a large number of loads with different sensitivity degrees are present in modern electrical systems and they may experience some dependence with the power quality problem here considered.

In addition, incandescent lamps (reference of UIE/IEC method) are becoming less important, due to the increasing use of compact fluorescent lamps. It should also be noticed that this subject has been considered in some researches, but usually they just mention the problem, without deep inquiries.

These considerations motivate the following questions: Are current standard flicker limits suitable for modern equipment? From which P_{ST} value can any other prejudicial effect be observed on equipment performance?

The aim of this paper is to investigate the relationship between equipment behavior and voltage fluctuation associated with the P_{ST} index.

The relationship between voltage variation parameters and P_{ST} can be derived from simulation of the UIE/IEC flickermeter model, which was previously implemented by the authors on the MATLAB program [5].

From laboratory studies testing, different representative equipment is tested and its performance observed. The results are useful to support a discussion about flicker limits in Brazil, and the possibility of making them more versatile.

II. REMARKS

A. Voltage Fluctuations

Voltage fluctuation, as defined before, is mainly caused by variable demanding loads. These include electric arc furnaces, welders, rolling mills, large motor loads like saws, crushers, elevators, etc [4]. The varying current due to these loads leads to varying voltage drops on system components and thus voltage fluctuations. In a general way, they can be classified as periodic and random, depending on the load and its operation duty cycle.

Fig. 1 illustrates a periodic, rectangular voltage fluctuation, oscillating at frequency fm = 1/Tm. The magnitude of the fluctuation, ΔV, expresses the peak-to-peak voltage variation and V, is the fundamental voltage mean peak value. The relation $\Delta V/V\%$ expresses the relative voltage change.

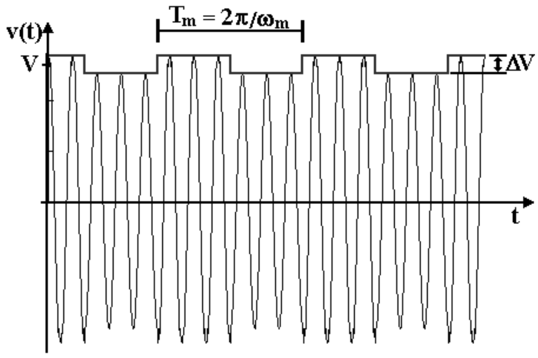

Fig. 1. Rectangular voltage fluctuation.

Fig. 2 illustrates a more realistic random voltage fluctuation, where many oscillating frequencies are involved.

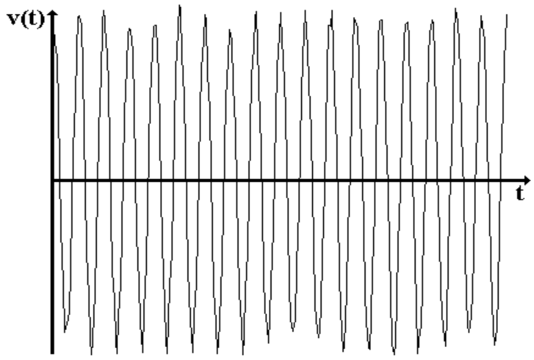

Fig. 2. Non-periodic voltage fluctuation.

For both well-defined and random voltage fluctuation, the UIE/IEC flickermeter can estimate the flicker effect due to voltage disturbance.

B. UIE/IEC Flickermeter and Flicker Indexes

For the purpose of this investigation, it is quite important to clearly understand the physical meaning of the flicker indicators. Therefore, this section presents a brief functional description of the flickermeter and its flicker indexes as stated by UIE/IEC [3], [4].

The architecture for UIE/IEC flickermeter has five blocks, as depicted in the simplified diagram of Fig. 3.

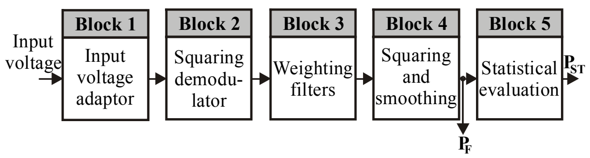

Fig. 3. The main blocks of the UIE/IEC flickermeter.

Where:

Block 1: normalizes the input voltage by the mean RMS value of the last minute, in order to establish an internal reference level for further calculations.

Block 2: is a quadratic demodulator. Its purpose is to extract the fluctuation voltage by squaring the scaled input voltage, thus simulating the behavior of an incandescent lamp.

Block 3: is composed by three filters connected in series. The first is a 1st order high-pass filter, used to eliminate the dc component. The second is a 6th order Butterworth low-pass filter, used to remove the component at twice the main frequency. The last filter provides a very specific weighting function band-pass response, within the range of interest between 0.05 and 35 Hz. The response is normalized for an 8.8 Hz sinusoidal modulation.

Block 4: simulates the nonlinear eye-brain perception through the squaring of weight flicker signal. Also, it implements a sliding mean operator with 300 ms time constant to simulate the storage effect in the brain. This signal is normalized, so that, Block 4 output unitary value corresponds to the reference human flicker perceptibility threshold. In other words, this signal represents the visual perception of the average human observer and it is called *Instantaneous Flicker Perception, $P_F(t)$.*

Block 5: performs a statistical analysis of the flicker signal $P_F(t)$, which yields the basic flicker index, the *Short-Term Flicker Severity, P_{ST}.* A period of 10 minutes (short interval) is usually chosen to accomplish this task. P_{ST} is calculated according to the expression:

$$P_{ST} = 0.1\sqrt{3.14P_{0.1} + 5.25P_{1s} + 6.57P_{3s} + 28P_{10s} + 8P_{50s}} \quad (1)$$

Where: $P_{0.1}$, P_{1s}, P_{3s}, P_{10s} and P_{50s} are the flicker levels that have been exceeded for 0.1, 1, 3, 10 and 50% of observation period. These percentiles are obtained from the statistical analysis. The suffix "s" indicates that smoothed value should be used [3].

It should be emphasized that P_{ST} indicator has the significance of annoyance, with P_{ST} = 1 pu meaning the threshold of the irritability.

It should also be noted that the weighting filter (Block 3) has a dependence on the reference lamp and power system frequency considered, thus, influencing the computation of P_F and P_{ST}. Fig. 4 shows the P_{ST} = 1 pu curves for rectangular fluctuation (120 changes/minute = 1 Hz oscillating frequency). The curves are associated with 230 V/60 W and 120 V/60 W incandescent lamps [4].

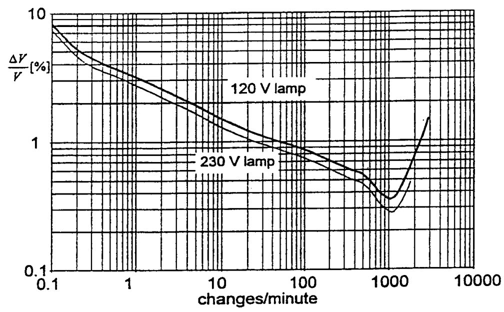

Fig. 4. P_{ST} = 1 pu curves for rectangular fluctuations.

From Fig. 4, it can be noted for a fixed frequency, that the less sensitive the lamp the higher the relative voltage change to the same P_{ST} value.

To take into consideration long period voltage fluctuations, a *Long-Term Flicker Severity, P_{LT},* is derived over a two-hour interval. This is calculated as the cube root of the mean of the cubes of 12 consecutive P_{ST} values.

Moreover, IEC recommends at least 1,008 short intervals, corresponding to seven days of continuous flicker measurement, and 84 P_{LT} values when considering 10 minutes short interval. The P_{ST} and P_{LT} measured values are then analyzed and representative indexes can be compared to the limits established by standards.

III. EQUIPMENT AND STUDIED CASES

The following devices are to be considered for the analysis:

a) Type 1 single-phase switched source: as found at the input of personal microcomputers and peripherals such as printers, video displays, etc. The variables monitored are the +5V and +12 V regulated voltage supplies.

b)Type 2 Single-phase switched source: as for the input of programmable logic controllers (PLCs) used mainly in industry. The quantities observed are the +5V and +24V regulated voltage.

c) Single-phase linear source: to supply TV sets, CD players, etc. Again, the regulated output voltage that feeds the main internal circuits will be examined.

d) Single-phase motor: representing appliances such as refrigerators and air-conditioners. For this device, the total current demanded by the motor is focused.

e) Three-phase induction motor (3 hp): for general application. The line currents will be observed.

f) Three-phase PWM-VSI frequency converter (3 kVA/380 V): feeding a three-phase induction motor. The ac output voltage and motor line currents will be observed.

Each device was investigated under seven distinct operating conditions as given by Table I. Case 1 (or Base Case) corresponds to an ideal constant and balanced (for three-phase loads) supply voltage. Cases 2 to 7 are also balanced and represent different degrees of frequency and voltage variation. In all cases the test time was at least 10 minutes. In Table I P_{ST} value ≥ 2 pu was chosen, because it is related to the superior limit in the Brazilian recommendations for systems < 69 kV [6]. The reference lamp chosen was the 120 V/60 W type, to take into account major values for $\Delta V/V\%$ (conservative).

TABLE I
P_{ST} values for experimental cases.

Case	1	2	3	4	5	6	7
f_m (Hz)	-	3	10	20	3	10	20
$\Delta V/V\%$	-	1,20	0,76	2,22	2,41	1,51	4,43
P_{ST}	0	2			4		

IV. LABORATORY ARRANGEMENT

The rectangular voltage fluctuation necessary to provide the required flicker level was generated by a programmable voltage source. Fig. 5 illustrates the laboratory arrangement for the tests.

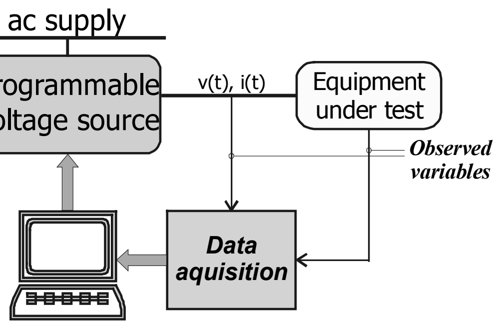

Fig. 5. Lab arrangements for tests.

Fig. 6 illustrates supply voltage conditions for Cases 1 and 7. It should be noted that last case has the highest $\Delta V/V\%$.

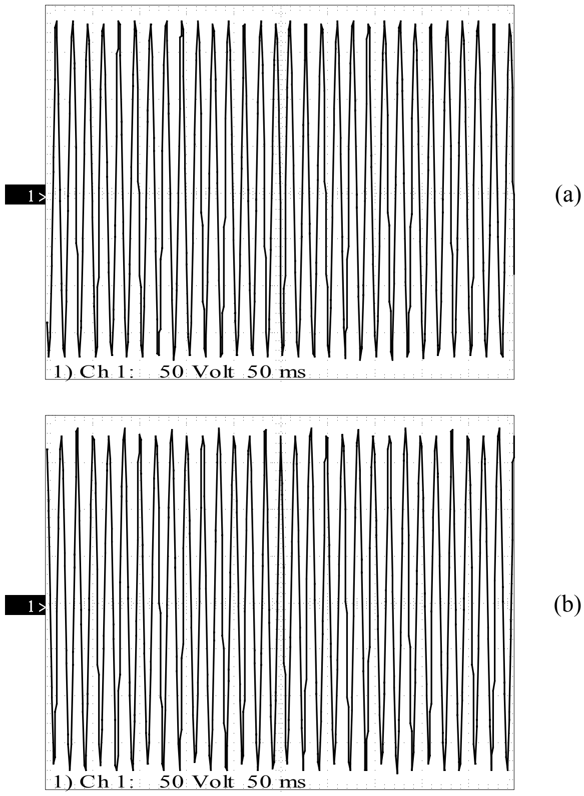

Fig. 6. Supply voltage: (a) Base Case; (b) Case 7.

V. EXPERIMENTAL RESULTS

A. Type 1 switched source

A microcomputer source was used to perform the tests. As previously mentioned the +5V and +12V regulated voltage are the focused signals. By increasing the fluctuation applied to the supply, the tests were carried out by considering common user tasks such as accessing hard disk (reading and saving), internet, CD-ROM, diskette drive and using text processor. No problem was detected for all cases. Fig 7 shows the corresponding results for Cases 1 and 7.

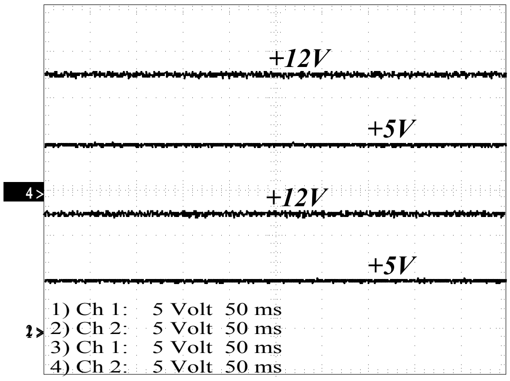

Fig. 7. Computer source output, +5 V and +12V output:
(a) Ideal Case; (b) Case 7.

The other tests provided similar results and were, therefore, omitted.

It should be noted the waveforms depicted were purposely shifted on the vertical axis to make easy the visualization. In other words, the references are not the same to both cases. This procedure also was adopted to exhibit next waveforms.

B. Type 2 switched source

Two devices from different manufacturers were tested. They were previously programmed to switch on and off all the output relays simultaneously. As stated, the +5V and +24V regulated voltage were observed. Again, no operational deviation from the expected performance was found under Cases 1 to 7 for both devices.

Fig. 8 presents the results obtained for Cases 1 and 7. Once again, the other situations lead to quite similar results and thus, the corresponding waveforms were omitted.

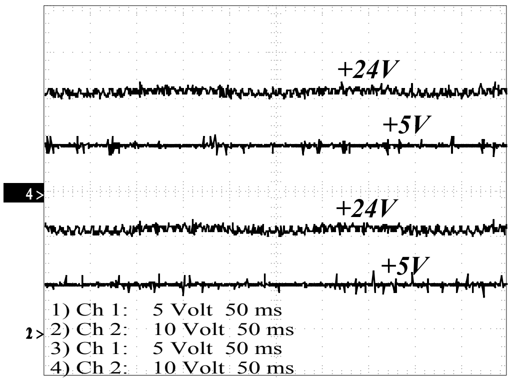

Fig. 8. PLC source output, +5 V and +24V output:
(a) Ideal Case; (b) Case 7.

C. Single-phase linear source

A domestic micro-system type was used to the investigations. The results presented are referenced to two DC regulated output voltage (+5 V and +10 V). These feeders supply the main equipment internal circuits. The tests comprised normal use of the device such as radio mode, CD and tape being recorded by CD.

Fig. 9 exhibits the results related to Cases 1 and 7. As can be seen, there is no perceptible difference on the waveforms. Besides, the equipment has not shown any prejudicial effect on its performance.

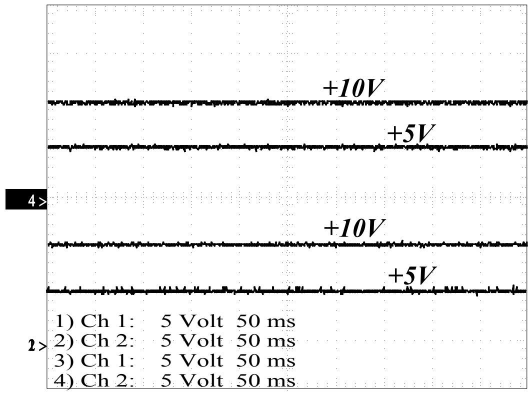

Fig. 9. Linear source, +5V e +10V regulated voltage:
(a) Ideal Case; (b) Case 7.

D. Single-phase motor

The equipment tested corresponds to a domestic refrigerator. Fig. 10 presents the input current demanded for Cases 1 and 7.

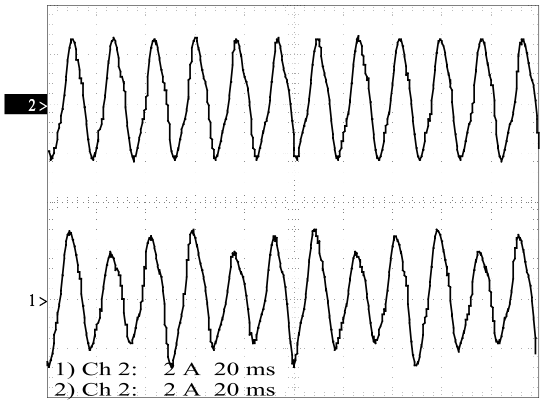

Fig. 10. Refrigerator, current demanded:
(a) Ideal Case; (b) Case 7.

The results are clear enough to emphasize the current variations with the supply voltage oscillation. Due to this, further analysis for the RMS value was carried out. In this way, Fig. 11 illustrates the results for Cases 1 to 7.

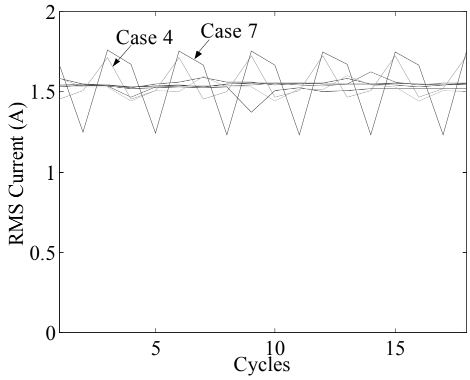

Fig. 11. Refrigerator: RMS input current variations.

As can be observed in Fig. 11, the current variations for Cases 2 to 7 oscillates around the constant RMS related to

Case 1. The major oscillations are associated to Cases 4 and 7. For the disturbance situations, torque and speed variations are expected, although not any abnormal effect on the motor was perceived during the experiments.

E. *Three-phase induction motor*

As already stated, the tested motor is a small 3 hp induction motor, 220 V, delta connection, supplying 75% of its rated mechanical load with constant torque.

Fig. 12 shows line A current for Cases 1 and 7 (the other line currents have experimented similar behavior).

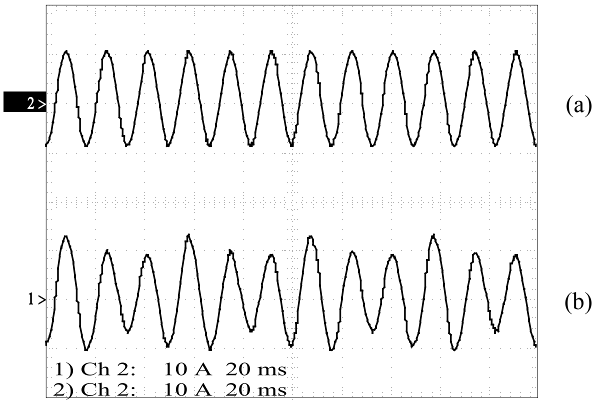

Fig. 12. Three-phase induction motor, line A current: (a) Ideal Case; (b) Case 7.

Fig. 13 presents the motor RMS current variations.

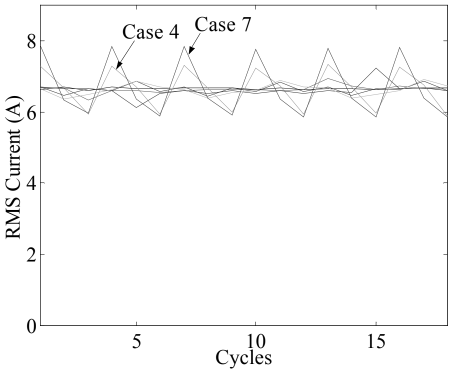

Fig. 13. Three-phase motor, RMS line A current oscillations: Cases 1 to 7.

Again, the studied device showed to be more sensitivity to the situations 4 and 7. During all the above tests no mechanical vibration or other unusual behavior were noticed.

F. Three-phase PWM-VSI frequency converter

This experiment used the same motor (380 V / Y isolated connection) and mechanical load previously tested, supplied by the specified frequency converter. Fig. 14 gives the line-to-line Vac output voltage for Cases 1 and 7.

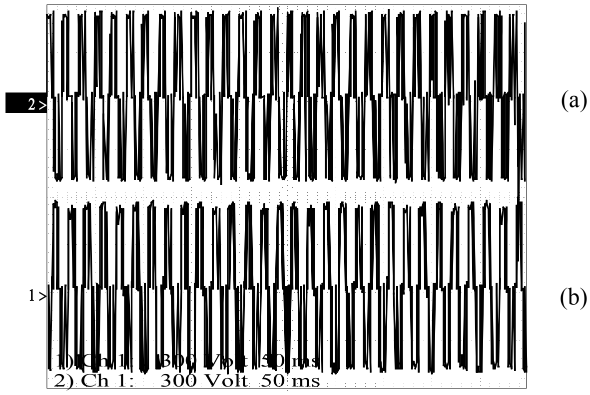

Fig. 14. Three-phase converter, Vac output voltage: (a) Ideal Case; (b) Case 7.

Observing Fig. 14(b) it can be seen the converter input voltage variations are proportionally transferred to the output voltage. It occurs because the DC link, present in this device, does not have the ability of suppressing the voltage fluctuations imposed.

Fig. 15 displays the line A current that feeds the motor (lines B and C provide similar waveforms).

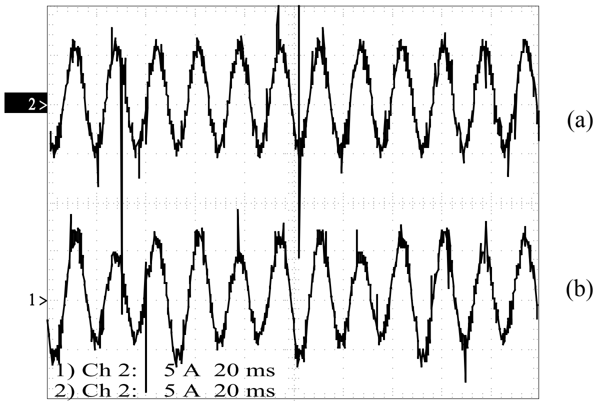

Fig. 15. Three-phase converter, line A output current: (a) Ideal Case; (b) Case 7.

As found before, it can be observed a 20 Hz motor current modulation.

Fig. 16 shows the RMS line A motor current variations related to Cases 1 to 7.

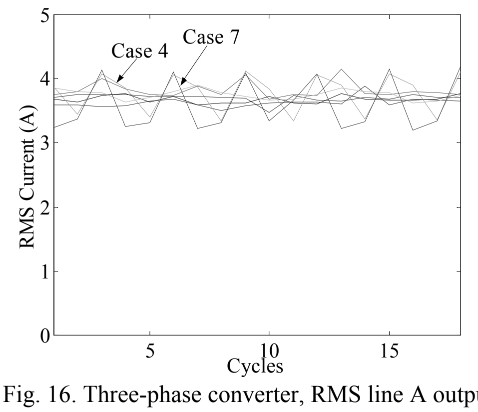

Fig. 16. Three-phase converter, RMS line A output current variations: Cases 1 to 7.

Again, the current oscillations were more intense for Cases 4 and 7. Of course, oscillating torque and speed will occur due these current variations, although visual or auditive effects were not perceived.

VI. ANALYSIS

Despite the flicker effect upon incandescent lamps, the interaction between P_{ST} and typical electrical loads does not seem to be very significant on their final performance. Additionally, it must be emphasized the studies were carried out for a single rectangular voltage modulation amplitude and frequency. However, for practical situations, voltage fluctuation usually has a random behavior. In these conditions, a frequency spectrum up to 35 Hz would be found. Thus, to match the same P_{ST} values, the voltage change magnitudes ($\Delta V/V\%$) involved would be lower than those given by Table I. This implies the performed tests were stricter than general real situations.

Another relevant aspect is that the use of conventional fluorescent lamps, as well as compact fluorescent lamps (CFLs), is becoming dominant in many residential, commercial and industrial installations. To save energy, incandescent lamps are being replaced by CFLs, which are, according to [7], [8], less sensitive to voltage fluctuation than the first ones. Under this new situation the flicker standard should be reconsidered in order to allow for P_{ST} flexibility. This is reinforced by the fact that flicker mitigation strategies for most disturbing loads are generally based on costly investments [9]-[11].

VII. CONCLUSIONS

Equipment behavior when submitted to voltage fluctuation constitutes the primary contribution of this research.

Excepted for motors and frequency converter, other equipment have shown high level of immunity to voltage fluctuation.

As for the above more sensitive devices, besides the input current and output voltage variations, no further effects were found. This underlines the strong relationship between P_{ST} standards to incandescent lamps is still the basis for establishing the usual limits.

The results and considerations, as stated above, provide an initial discussion point for questioning flicker limits relaxation, aimed at cost reduction and other drawbacks associated with compensation needs.

Further research on this subject should seek for:

a) Laboratory tests with other electrical devices.
b) Use of more realistic voltage fluctuations.
c) Field investigations about equipment behavior (and consumer complaints) on the presence of the voltage disturbance here considered, associated to P_{ST} and P_{LT} indexes.
d) Life expectance analysis.

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