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Quantification Errors Due to Inaccurate Use of Power Factor Definition

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ABSTRACT This article discusses the anachronism, insufficiency, and imprecision of the formulation and definitions of power factor (PF) in several regulatory texts. For consumer units in distribution networks, analyses are presented of how ANEEL defines this figure of merit. In the case of individual equipment, INMETRO's measurement procedures employ formulas that, depending on the tested device's operating principle, may yield technically erroneous results. For example, the results of LED luminaires, which are supposedly designed to have a high power factor, are analyzed and it is concluded that the solution for the errors in single-phase case is straightforward, and are achieved by using the correct formulation of the power factor, defined as the ratio between active and apparent power, with a sufficiently high sampling rate to capture the possible high-frequency spectral components of the current. Modern digital measuring instruments can easily obtain such quantities and do not incur errors that may arise from using quantities such as distortion factors or fundamental displacement.

KEYWORDS Luminaires, Power Factor, Power Quality, Standards.

I. INTRODUCTION

Power Factor (PF) is a classic concept whose interpretation has been widely discussed. In its most accepted formulation, it represents the relationship between active power (P), given in Watt [W], and apparent power (S), given in Volt-Ampère [VA], related to the terminal voltages and currents of a device or equipment, regardless of the voltage and current waveforms, as long as both are periodic (with period T).

The concept can be extended to a set of loads in a consumer unit (CU), which is of interest to electricity distribution companies because it affects CU bills. However, as will be discussed, Brazilian legislation does not adopt the definition described above, preferring other ways of identifying the PF that are, at the very least, problematic, if not mistaken, and certainly anachronistic.

However, even when analyzing a simple electrical device, the results can differ strikingly depending on how power factor is defined. For example, this article presents test results for LED luminaires, which are tested by INMETRO.

A. HISTORICAL CONTEXT

In 1892, J. Fleming, in his article "Experimental Research on Alternating Current Transformers" [1], first used the expression "power factor." Fleming stated that if currents and voltages are sinusoidal functions, the power factor is the cosine of the phase shift angle between current and potential difference. For him, this definition was merely a measure of the transformer's no-load performance. With the advancement of electrification, and particularly the

increasing use of induction motors, it has become essential for electricity distributors to quantify the energy demand of such machines. In 1901, Browne described the principles of various types of electromagnetic meters for measuring active and reactive power, as well as current [2]. At the time, this was already a relevant problem for consumer pricing.

There was no consensus on this quantity and how it should be measured. The Power Factor was discussed in historical meetings for the definition of electrical quantities, such as the one held in 1920 by the American Institute of Electrical Engineers: AIEE Special Joint Committee, "Power factor in polyphase circuits" [3]. Several important aspects of these discussions were restated in [4]. One conclusion is that, despite some progress, no agreement has been reached on definitions and measurement methods, especially for the non-ideal three-phase case.

The Power Factor, in its current context, was defined in 1922 by Buchholz [5] and has since been applied and accepted for single-phase AC circuits. The concept was extended to any forms of voltage and current waves (periodic) by Fryze in 1933 [6] and continues in use, practically without change [7,8]: "The power factor can be interpreted as the ratio between the power transmitted to the load and the maximum power that could be transmitted, maintaining the losses in the supply line." The equality of losses implies that the same effective current value is obtained.

II. DEFINITIONS

A. POWER FACTOR

As mentioned earlier, Power Factor (PF) is defined as the ratio of the active power (P) to the apparent power (S), both expressed in watts [W] and volt-amperes [VA], respectively. The apparent power is the product of the rms value of the voltage, V_{ef} , and the rms value of the current, I_{ef} . The PF can be determined for a single device or an installation (such as a consumer unit). According to (1), its value is determined independently of the shapes of the voltage and current waves, as long as they are periodic (with period T).

$$PF = \frac{P}{S} = \frac{\frac{1}{T} \int_0^T v(t) \cdot i(t) \cdot dt}{V_{ef} \cdot I_{ef}}, \quad (1)$$

where

$$V_{ef} = \sqrt{\frac{1}{T} \int_0^T v(t)^2 \cdot dt} \quad \text{and} \quad I_{ef} = \sqrt{\frac{1}{T} \int_0^T i(t)^2 \cdot dt}. \quad (2)$$

Definition (1) applies to single-phase or balanced polyphase circuits based on time functions. In unbalanced cases, the very definition of effective value becomes a matter of controversy. The measurement procedure will be discussed below. For sinusoidal waves, the above equation becomes equal to the cosine of the phase shift ϕ between the voltage and the current:

$$PF_{sin} = \cos \phi. \quad (3)$$

The International Electrotechnical Commission - IEC 61000-4-30 [9] standard, adopted by ANEEL (the Brazilian National Agency of Electric Energy) for power quality analyzers (PQAs), establishes testing and measurement techniques for assessing power quality indices. This document defines the DPF (Displacement Power Factor) as the cosine of the phase shift between the fundamental voltage and the corresponding fundamental current. It also defines TPF (True Power Factor) as the ratio of active power to apparent power. When only the voltage is sinusoidal, the PF can be expressed as:

$$PF_{Vsin} = \frac{P_1}{S} = \frac{I_1}{I_{ef}} \cos \phi_1, \quad (4)$$

where I_1 is the effective value of the fundamental current and ϕ_1 is the phase shift between this component and the voltage wave. This definition is consistent with (1) and valid for balanced three-phase cases. The ratio between the currents is called the form factor, and the cosine term is called the fundamental displacement factor, which corresponds to the DPF. However, this PF calculation method suffers from a practical difficulty: extracting the fundamental component of the current and obtaining the phase shift. Note that the calculation by (1) does not require such values.

In order to provide the analysis of (4), the effective value of the current can be expressed in terms of the coefficients of the Fourier series that describes the time function $i(t)$:

$$I_{ef} = \sqrt{I_1^2 + \sum_{h=2}^{\infty} I_h^2}. \quad (5)$$

The Total Harmonic Distortion (THD) is defined as the ratio between the effective value of the harmonic components and that of the fundamental (6). Note that (5) and (6) indicate a sum of infinite spectral components, which, in practice, is unfeasible.

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}, \quad (6)$$

Then, according to (4), (5), and (6), the PF can be rewritten as (7).

$$PF_{Vsin} = \frac{\cos \phi_1}{\sqrt{1 + THD_i^2}} \quad (7)$$

The relationship between PF and current distortion becomes evident. Standards regulate the maximum values of current harmonics that a device or equipment can inject into the power line [10] or that result from a set of loads in a CU [11]. These standards also specify the number of harmonics that should be quantified. For example, the IEC indicates measurement up to the 40th order. The IEEE indicates measurements up to the 50th harmonic. However, new procedures have advanced up to the 100th order, as indicated by companies in the United Kingdom [12].

In this context, an important question arises: how to define the harmonic order limit for correctly determining the quantities indicated in (5) and (6) and, consequently, define the value of the power factor (7)?

B. POWER FACTOR IN BRAZILIAN REGULATIONS

The aspects discussed here do not refer to how the valuation of non-active power consumption is determined, but only how the PF is defined, which, ultimately, is the parameter adopted in the country to quantify this portion of apparent power.

The PF value for a consumer unit, according to ANEEL [13], must be calculated from the recorded values of active and reactive powers (P , Q) or the respective energies (Ea , Er) using the following formulas:

$$PF = \frac{P}{\sqrt{P^2 + Q^2}}, \quad \text{or} \quad (8)$$

$$PF = \frac{Ea}{\sqrt{Ea^2 + Er^2}}. \quad (9)$$

Equation (8) differs from the concepts embedded in the definition of PF resulting from (1) by including the "reactive power", which lacks a consensual and consistent definition in situations where the waveforms are not sinusoidal. These situations are increasingly common, especially in low-voltage distribution networks, due to the high presence of non-linear loads.

The ANEEL distribution procedures (PRODIST) define the power factor as a function of reactive power or reactive energy, but do not specify how these quantities should be measured, which poses problems for non-sinusoidal waveforms and for three-phase cases with unbalance.

ANEEL defines reactive electrical energy as “that which circulates between the various electric and magnetic fields of an alternating current system, without producing work, expressed in kilovolt-ampere-reactive-hour (kvarh).” However, to be consistent, Er should be defined as “non-active energy”. In order for the determination of the PF to be correct using (8) or (9), the calculation of the corresponding power (Q) must consider all the spectral components of the current that are not present in the voltage, and also the portions of the current that are orthogonal to the spectral components existing in the voltage.

This is a problem of metrology. The quantities measured in each procedure, (1) or (8), in spite of being clearly defined, should not both be designed as “power factor”, since they are not the same [14]. As already said, historically and according to the IEC, the correct and valid definition for any periodic waveform is (1).

The ANEEL definitions (8) and (9) confuse a figure of merit, the Power Factor, with the method used to determine it before the advent of digital meters. Eq. (9) is just a way of calculating a value from data recorded in active (kWh) and “reactive” (kvarh) energy quantifiers and not a technically correct, consistent, and valid definition for non-sinusoidal currents.

In the three-phase case, calculations are more complex in unbalanced networks and in the presence of distortion. Although this discussion is highly relevant, it falls outside the objectives of this text and will therefore not be discussed in depth here. It is recommended that articles related to such studies be consulted [15-17].

The modernization of technology creates situations that require legislative adaptation, which do not always occur as quickly as desired. In situations that existed in the recent past, when consumers connected to distribution networks consumed energy from the network, and the currents were reasonably sinusoidal, the definitions given in (8) and (9) remained minimally adequate. However, as consumers began producing active power, it became necessary to review the use of PF as a figure of merit that could even unduly penalize consumers [18]. A relative figure of merit, such as PF, may indicate low values not due to an increase in reactive power, which would be a problem, but due to a reduction in active power, which, probably, is not a problem.

Recently, ANEEL banned the application of penalties for low PF to consumers in group B¹. However, the problem persists for consumers in Group A, as the conceptual issue defines the magnitude, not the type, of consumer [19].

From the grid's point of view, the interest is to preserve the quality of the supply voltage, which is affected by currents associated with reactive power. Such a deleterious effect, however, is related to the absolute value of such a portion of the current. Since many distribution codes impose penalties for excessive reactive demand [20-22], and this “excess” is determined from indicative PF or active power values, it is necessary to redefine the calculation method. It would be

better to directly define the maximum non-active power a CU can demand, which can be easily quantified by modern digital meters.

III. DIGITAL METERS

The anachronistic definitions for PF are linked to how this quantity was measured using electromechanical meters. In that case, it is necessary to contextualize how measurement technologies have evolved and how they currently enable, with much greater precision, the performance of voltage and current measurements and the subsequent calculation of electrical power components.

All modern electrical quantity meters use digital systems. This technology began in the 1980s [23-24] and was consolidated in the early 2000s when international standards established the current measurement procedures.

For example, the effective value of the periodic function $x(t)$, sampled uniformly with N values (x_i) contained in a period T , is defined by the square root of the mean square value of these N samples, that is:

$$X_{ef} = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2} \quad (10)$$

To determine the active power associated with the simultaneously sampled voltage and current values, the calculation is even simpler: simply multiply the sampled values, add them cumulatively until reaching the total number of samples in a period T , and divide the total by the number of samples.

$$P = \frac{1}{N} \sum_{i=1}^N v_i \cdot i_i \quad (11)$$

In the case that the number of samples is a power of 2 ($2^5 = 32$, $2^6 = 64$...), the division of the equivalent binary value is reduced to a simple right shift of that value by the amount of the exponent of the power of 2 (5, 6... in the example above, since each “shift” right represents division by 2).

According to the Nyquist-Shannon sampling theorem, a sampled signal can be used to identify a frequency if at least two samples per cycle are available. This imposes a limitation on the capacity of the Discrete Fourier Transform (DFT), or its Fast Fourier Transform (FFT) version, applicable when N is a power of 2, to identify spectral components of a signal. With few samples per cycle, although the frequency is identifiable, obtaining its amplitude is not very accurate. Nowadays, digital meters operate with hundreds or thousands of samples per cycle, which means sampling frequencies in the range of tens of kHz and the consequent possibility of spectral identification up to the order of hundreds of harmonics.

Thus, determining the values of active power (10) and apparent power with adequate precision becomes, from the algorithm's perspective, a trivial task. A very precise value

¹Group B: grouping composed of consumer units with supply at a voltage lower than 2.3 kV, characterized by the monomial tariff and subdivided into the following subgroups: a) subgroup B1 – residential; b) subgroup B2

– rural; c) subgroup B3 – other classes; and d) subgroup B4 – Public Lighting.

for the PF is obtained without resorting to other quantities, such as reactive power or the cosine of the phase shift between the fundamental components of voltage and current. When a digital meter indicates the DPF, the displayed value is determined by (3), which is based on the PF calculated in (1), the I_{ef} calculated in (10), and the value of I_1 obtained via numerical filtering or the DFT [25]. A similar procedure is used to indicate the reactive power value at the fundamental frequency, which is not directly measured.

IV. POWER FACTOR IN ELECTRONIC LOADS

The ABNT (Brazilian Association of Technical Standards) regulates the behavior of individual loads in Brazil, including the electrical aspects. As a member of the IEC, Brazil commonly adopts IEC standards. The few electronic devices that are regulated are those that, although they have low individual power, are widely used, such as luminaires.

A. POWER FACTOR IN LUMINARIES

For electronic luminaires, ABNT has defined performance standards since the 1990s, including restrictions on power factor. It was the first Brazilian regulation to establish a minimum PF value for an electronic device. For example, NBR 5170, from 1996 [26], indicated that the power factor measurement or calculation should be done with an instrument that considers harmonic distortion or calculates it using the relationship (1) between active power and apparent power.

Considering technological developments, ABNT NBR 14418 [27] establishes that $PF > 0.92$ and that the measurement must include harmonics. However, unlike the 1996 standard, the 2011 and subsequent versions no longer specify that the calculation is based on the ratio of active to apparent power. Only the use of (7) is indicated, and the analysis of the THD is limited to the fortieth harmonic. However, (7) is valid only if all the relevant current harmonics are included in the calculation. If spectral components are disregarded, the PF value will be incorrect. Considering the necessary consistency of definitions present in the set of IEC standards, which are the basis of the ABNT standards, for the calculation of the THD, the standards that define the spectral analysis of the quantities must be used. The measuring equipment requirements defined in [28] are those specified in IEC 61000-4-7 [29], utilizing the FFT.

To make the scenario even more confusing, ABNT NBR IEC 62612:2022 [28] specifies verification of the displacement factor, $\cos \phi_l$ (3), rather than using the PF. The measuring equipment does not directly measure the displacement between the voltage (supposedly sinusoidal) and the fundamental component of the current, but simply calculates it from other measured values. Note that the measuring equipment can indicate a displacement factor value from PF (P/S) measurements and THD calculations, which is correct in principle.

For solid-state lamps – SSL, or LED luminaires, the displacement factor is related to the lamp driver's input filter capacitance and may limit the filter's capacitance. However,

designers tend to minimize this component to save costs. In any case, this behavior is duly included in the PF value.

The EN 62612 standard [30], which is the origin of [28], contains the following text: “With a view to future regulations, EN 62612 defines - the displacement factor as a primary metric, as well as its measurement method and recommended values - instead of the power factor metric.” The use of the displacement factor as a quality indicator equivalent to the power factor occurs only in the hypothesis of sinusoidal current. Thus, the mention of a “future regulation” makes sense only if it imposes a power factor regulation for LED lamps that would approach unity.

In terms of roles, it would be expected that the ABNT defines, in the technical standards, the measurement methods, PF formulas, harmonic limits, etc. Complementary to this, the National Institute of Metrology - INMETRO ordinances should serve only as regulatory instruments and do not define metrological procedures themselves. However, this is not completely true.

According to INMETRO [31], the test procedures are defined for LED lamps with declared nominal power from 5 W to 25 W, $PF > 0.70$ must be achieved. A minimum power factor is not required for lamps with a power rating below 5 W. For lamps with nominal power greater than 25 W, $PF > 0.92$ must be achieved, and harmonic currents cannot exceed the limits shown in Table I.

The measurement must be done at 127 V, 220 V, or both. The $PF > 0.92$ must be achieved for LED tubular lamps, and harmonic currents must not exceed the limits shown in Table 1. For the measurement procedures, the INMETRO regulation refers to Illuminating Engineering Society rule IES-LM-79-08 [32]. This document specifies the required measurements of the active power, rms voltage, and rms current. It is not stated how to calculate the power factor, but it seems that (1) is implicit. The characteristics of the measurement devices are not defined.

The INMETRO regulation differs from that established in [28] in that it measures the power factor, rather than the displacement factor. Considering the current harmonic spectrum, the values in Table I reproduce those established in [10], although the IEC document explicitly states that this standard does not deal with loads with a power supply of less than 220 V (phase-neutral). Note that for the 3rd harmonic, the Table requires knowledge of the device power factor. The INMETRO document does not define how to determine the power factor, but it may be inferred that the method follows (1) as described in [32].

TABLE I. Harmonic current limits.

Harmonic order	Maximum allowed harmonic current, as a percentage of the input current at the fundamental frequency (%)
2	2
3	30λ
5	10
7	7
9	5
11 < n < 39 only odd orders	3
λ is the circuit power factor	

To further complicate this issue, regarding the indication of lamp characteristics, INMETRO allows marking "Power Factor (PF or $\cos \phi$)". So, the ABNT and INMETRO documents use conflicting definitions of Power Factor, displacement factor ($\cos \phi$), and fundamental displacement factor ($\cos \phi_1$), which are distinct concepts, clearly defined in the literature and in standards, but not in Brazilian documents.

B. POWER FACTOR CORRECTION IN LUMINARIES

Fig. 1 illustrates the internal power supply circuit of the LEDs, comprising a power factor correction circuit based on a buck converter [33] featuring a CLC filter (capacitor/inductor/capacitor) at the input, which minimizes the propagation of spectral components caused by the converter switching.



FIGURE 1. The internal circuit of the converter that powers an LED array (9W, 100~240V).

Fig. 2 shows a simplified power factor corrector (PFC) circuit based on the buck topology. The LED current is directly controlled by the transistor duty cycle. In discontinuous or critical current mode (considering the output inductor current), the power transistor operates with a constant conduction time, producing an input current that, after filtering, results in a high power factor. As shown in Fig. 3, when the input voltage is lower than the output capacitor voltage, the input current is zero. Even so, the resulting PF and THD may be good enough to comply with the standards.

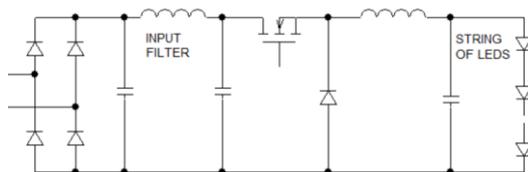


FIGURE 2. Simplified PFC scheme with buck converter.

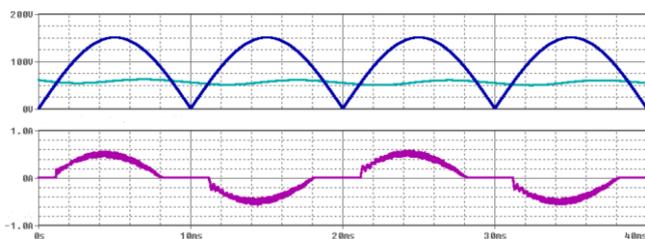


FIGURE 3. PFC waveforms. On top, rectified input voltage (dark blue) and output voltage (light blue). On the bottom, filtered input current.

The power factor, obtained through the average value of the input current calculated at each current switching cycle, is [34]:

$$PF = \frac{1 - \frac{2\varphi}{\pi} - \frac{2M\sqrt{1-M^2}}{\pi}}{\sqrt{(1+2M^2)\left(1 - \frac{2\varphi}{\pi}\right) - \frac{6M\sqrt{1-M^2}}{\pi}}}, \quad (12)$$

$$M = \frac{V_o}{V_p}, \quad \text{and} \quad \varphi = \sin^{-1}(M). \quad (13)$$

V_o is the average load voltage, V_p is the peak value of the AC input voltage.

As in Fig. 4, when the output voltage approaches zero, the power factor approaches unity, considering the filtered input current, i.e., disregarding the high-frequency components. As the output voltage increases, the angle φ increases, and the PF decreases. For the waveforms shown in Fig. 3, the results are DPF = 0.978, THD = 28.7%, and PF = 0.942. The harmonics comply with the limit given in Table I.

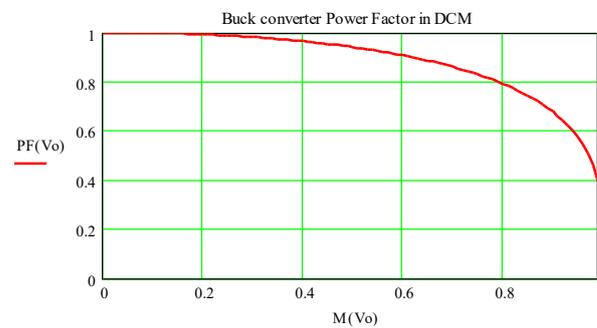


FIGURE 4. Buck-type PFC power factor, in discontinuous conduction mode, considering the filtered input current.

C. COMMERCIAL LED LUMINARIES

The next figures show the input current waveforms of commercial luminaries. Fig. 5 refers to a tubular lamp that operated according to the presented buck PFC. According to INMETRO rules, it must have $PF > 0.92$. At the side of the waveforms, a table shows quantities measured by the oscilloscope, where:

- TrPwr is the active power, according to (11);
- ApPwr is the apparent power, obtained by the product of rms voltage and current values;
- PF is the power factor, according to (1).

These three values are correctly measured and calculated. However, the reactive power (RePwr) and the Phase are incorrect values. RePwr and Phase values are determined using the "power triangle", which is valid only for sinusoidal current, which is not the case [35].

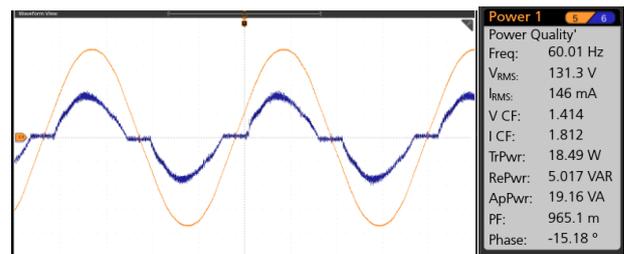


FIGURE 5. PFC waveforms: input voltage (orange) and filtered input current (blue).

Fig. 6 also refers to a tubular LED lamp. Probably intending to reduce the cost, this device eliminates the input CLC filter. Surprisingly, the product displays the information $PF > 0.92$. The oscilloscope-measured value yields $PF = 0.5659$, which is correctly calculated by equation (1). In this case, it is easy to verify the incorrect values calculated for $RePwr$ and Phase.

An important point to be discussed in the next section is: why can this lamp be sold as a high-power-factor device?

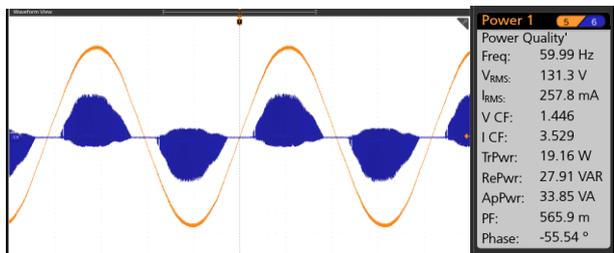


FIGURE 6. PFC waveforms: input voltage (orange) and unfiltered input current (blue).

Fig. 7 shows the waveforms of a residential 9 W screw-in lamp, which must have $PF > 0.7$ according to INMETRO rules. In this case, the integrated circuit that drives the lamp uses a constant-peak-current reference and operates in critical conduction mode. This operation mode results in a variable switching frequency. In this case, the input current is also unfiltered. The lamp is sold as having a $PF > 0.7$, while the actual PF is 0.53.

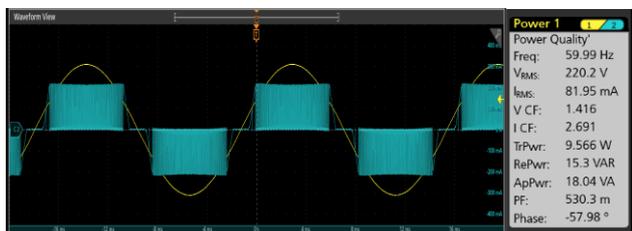


FIGURE 7. PFC waveforms: input voltage (yellow) and unfiltered input current (blue).

D. POWER FACTOR CALCULATION WITH DIFFERENT METERS

Although the unfiltered input current, as shown in Figs. 6 and 7, may be considered technically unacceptable, it is essential to understand how the LED lamps can indicate compliance with the INMETRO PF limits.

For this, it is necessary to consider the harmonic limits in Table I and the power factor calculated as in (7) [30]. Table I indicates that the harmonics should be measured only up to the 39th order. As said, there is no reference on which measurement apparatus to use.

The PF measurements shown in Figs. 5, 6, and 7, using (1), include the impact of the switching frequency components (in the range of tens of kHz), as the rms values are calculated using the oscilloscope's high sampling rate, which exceeds 1 MSa/s.

An alternative could be using a class-A power quality analyzer in compliance with [9], which, in principle, seems an adequate choice for measuring power factor. Usually

(although not mandatory), the PQA has an anti-aliasing filter input, designed to attenuate high-frequency spectral components above half of its sampling frequency.

Fig. 8 shows the voltage and current waveforms obtained with the class-A analyzer, Dranetz HDPQ Visa. The sampling frequency is 30.72 kHz, corresponding to 512 samples/cycle. Enabling the anti-aliasing filter minimizes high-frequency components in the processed current signal, making the current used in the calculations “clean”. These waveforms must be compared with the real forms shown in Fig. 6. Eliminating the high-frequency spectral components results in a calculated power factor of 0.972, with a THD = 16.6%. However, this is far from the current that the luminaire injects into the network.

Turning off the anti-aliasing filter significantly affects the current signal processed by the PQA, as shown in Fig. 9, exhibiting high-frequency behavior, but it remains distinct from the actual current. The shape of the current signal is affected by the sampling (at 30.72 kHz) of a signal with components in the range of 60 to 100 kHz [36]. It is from this deformed current signal that the PQA makes its calculations. Using the power method (1), the result is $PF = P/S = 0.76$. However, $THD_{255} = 81\%$ (including up to the harmonic of order 255, the analyzer’s limit), and $THD_{40} = 63\%$ (limit of [31]). The calculated displacement factor is $\cos \phi_1 = 0.997$.

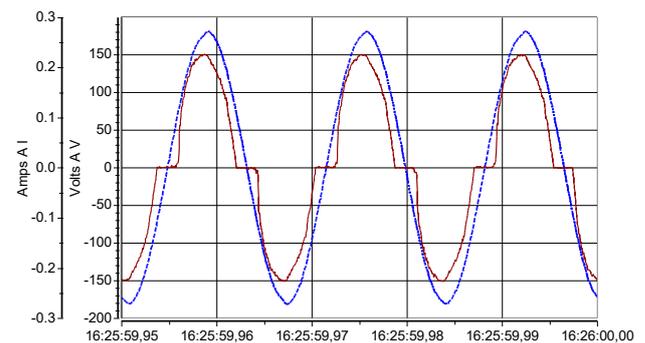


FIGURE 8. Filtered voltage (blue) and current (red) waveforms processed by the power analyzer using the anti-aliasing filter.

The PF value remains incorrect, even though it is closer to the correct value calculated by (1), since it includes all relevant spectral components. In any case, it would be sufficient to indicate that the luminaire associated with the Fig. 6 waveforms does not comply with the standard.

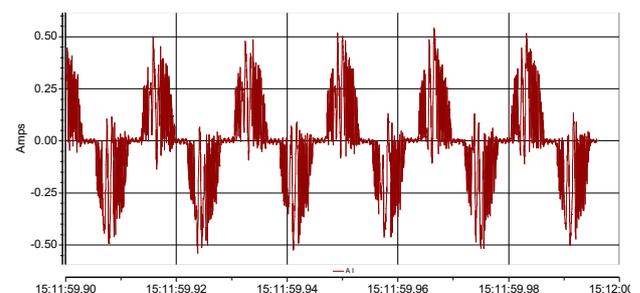


FIGURE 9. Current waveform processed by the PQA without the anti-aliasing filter.

Regarding the third luminaire (Fig. 7), the PQA measurements are shown in Figs. 10 and 11. As expected, the

anti-aliasing filter eliminates the switching-frequency components. The filtered current is far from sinusoidal; however, the PF is 0.84. Many harmonics exceed the limits in Table I. Removing the anti-aliasing filter, the resulting waveforms are shown in Fig. 11. High-frequency components are present in the current signal but are altered by the sampling process. This results in PF = 0.57, which is near to the value measured in Fig. 7 and does not comply with [30].

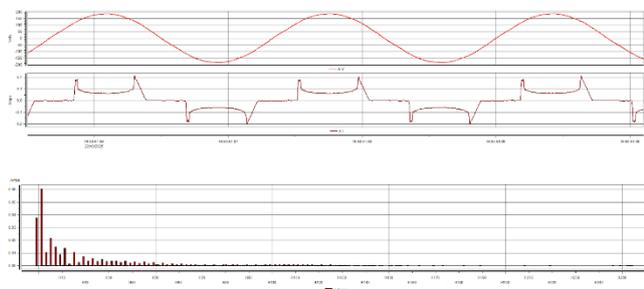


FIGURE 10. Above, filtered voltage and current waveforms processed by the power analyzer using the *anti-aliasing filter*. Below, the spectrum of the current.

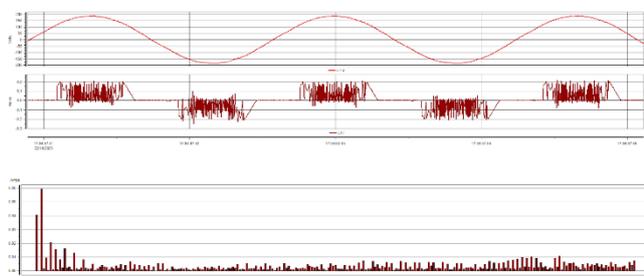


FIGURE 11. Above, voltage and unfiltered current waveforms processed by the power analyzer without the *anti-aliasing filter*. Below, the spectrum of the current.

Measurements of luminaries without high-frequency filtering using the class-A PQA are unreliable, as they eliminate or modify the spectral components produced by the lamp driver.

From the perspective of conducted electromagnetic interference (EMI), the frequency range is defined by NBR IEC CISPR 15 [37], which establishes procedures for measuring conducted EMI from 9 kHz to 30 MHz. The INMETRO ordinance states that this is one of the safety tests required to certify the luminaire. However, the eventual fulfillment of the limitations imposed by the EMI test does not alter the conclusion that the power factor indicated by the manufacturers of the presented second and third luminaires is conceptually incorrect.

E. THE SOURCE OF THE MISLEADING PROCEDURES

The reasons why the measurement procedure defined by INMETRO is inappropriate for accurately determining the PF of luminaires without an input filter are described in IEC Technical Report [7], “*Power factor in single-phase systems under non-sinusoidal conditions*”. This document, which serves as a reference for all standards regarding harmonics measurement, clearly states in Section 6 that the PF

calculation according to (7) is valid only if the current contains harmonics (voltages are supposed sinusoidal). As this is not the case with the problematic luminaires, the measurement procedure should not be used.

In fact, the current unfiltered switching components are not harmonics, since they do not depend on the line Frequency. If the measurement device had a sampling rate high enough to resolve the spectral switching components, the estimated PF value would be close to the correct one.

The same section of the IEC Technical Report states that the rms value of the total spectral components can be determined using the total rms current and extracting only the fundamental component (14):

$$I_H = \sqrt{I_{ef}^2 - I_1^2}. \quad (14)$$

Using the data from Fig. 6, $I_H = 212$ mA, and the total distortion (not only the harmonics) results in 145%. Considering, by inspection of the waveforms, that the DPF ≈ 1 , the power factor, as expected, is as low as 0.57.

However, it is necessary to use the rms value of the current, including the spectral components related to the unfiltered switching frequency. This calculation can be performed using a simple, high-quality ammeter. To extract the fundamental, since the active power comes exclusively from the fundamental (clean) voltage, and the driver guarantees a very low phase displacement between the current and the voltage, it is sufficient to divide the measured active power by the rms voltage.

V. CONCLUSION

This article discussed possible errors in the calculation of the power factor due to two aspects: the lack of a consistent formal definition of PF and the technological limitations of measuring instruments in the face of unforeseen behaviors of electronic loads.

In the first case, formal and methodological consistency would be expected between the performance specifications in a technical standard and the procedures for verifying compliance with it. However, using LED luminaires as an example, it was shown that there are discrepancies between what is established by the ABNT/IEC standard and what is determined by INMETRO/IES for PF measurement.

It is important to note that all IEC documents are consistent in terms of definitions of quantities and measurement procedures, regardless of whether they are standards, measurement procedures, or technical reports.

While ABNT and INMETRO deal with individual electrical and electronic equipment, ANEEL deals with Consumer Units, that is, aggregates of loads inside an installation.

For the ANEEL definitions present in PRODIST, the problem is more serious, as the definitions used are anachronistic and incapable of correctly quantifying PF even in the presence of common phenomena, such as current distortion.

When considering the measuring equipment, the question that arises is the possible inability of the meter to correctly measure voltages, currents, and power and, in this way, calculate the PF. This situation was exemplified by the

analysis of LED luminaires with a large number of high-frequency spectral components, beyond the device's measurement capacity, resulting in incorrect PF values.

Today, the use of electronic meters, which replace electromechanical energy recorders, enables very precise quantification of both active power and rms voltage and current values, and consequently, the precise determination of apparent power. This enables the immediate determination of the correct PF value without resorting to other, more complex quantities, such as THD and DPF.

These are correct statements as long as the measurement procedure is able to identify all the relevant spectral components of the voltage and current, providing correct rms values and, consequently, allowing the correct indication of PF.

It was also shown that the PF, calculated as the ratio of active to apparent power, provides reliable values and can be easily obtained using electronic meters.

If the measurement equipment has a limited spectral band response, the electronic load, as an SSL, must ensure adequate AC filtering to remove high-frequency components produced by the converter powering the LEDs. If there are high-frequency components in the current, the measured values are unlikely to reflect the device's actual PF.

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AUTHOR'S CONTRIBUTIONS

J.A.POMILIO: Conceptualization, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Validation, Writing – Review & Editing. **S.M.DECKMANN:** Conceptualization, Formal Analysis, Methodology, Writing – Original Draft, Writing – Review & Editing. **J.C.U.PEÑA:** Data Curation, Investigation, Writing – Review & Editing. **M.P.DIAS:** Data Curation, Investigation.

PLAGIARISM POLICY

This article was submitted to the similarity system provided by Crossref and powered by iThenticate – Similarity Check.

DATA AVAILABILITY

The data used in this research is available in the body of the document.

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