A New Alternative for the Input-Voltage Adaptor of the IEC Flickermeter

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***Abstract*—In this paper, we present a study of the linearity of the International Electrotechnical Commission (IEC) 61000-4-15 flickermeter when subject to rectangular fluctuations of different amplitude. We show, both analytically and through simulation, how the scaling in Block 1 causes the nonlinear response of the flickermeter. While the standard proposes scaling methods based on the rms value of the input voltage, we introduce an alternative method based on the mean value of the rectified input voltage. The measured P_{st} using the new scaling method has a linear relationship to the amplitude of the voltage fluctuations.**

***Index Terms*—Disturbance, flickermeter, linearity, power quality, voltage fluctuation.**

I. Introduction

FLICKER is an important low-frequency disturbance [1]. The International Electrotechnical Commission (IEC) flickermeter reproduces the malaise suffered by the human eye when subject to light fluctuations from a 230-V/50-Hz or 120-V/60-Hz incandescent reference lamp. The IEC 61000-4-15 standard [2] establishes the functional and design specifications for the flickermeter and defines the short-term flicker severity (P_{st}) as the fundamental parameter used to evaluate the malaise. The initial design of the standard involved power systems in Europe, but by 1997, an extended measurement for 120-V lamps was added [3]. There is a high correlation between end-user complaints and the values provided by flickermeters based on the standard [4], [5]. The standard also serves as a reference in flicker mitigation [6].

The performance-testing section of the standard requires that every flickermeter be tested for seven series of rectangular fluctuations at different frequencies. For those frequencies, the standard specifies the amplitude of the fluctuation $(\Delta V/V)$ that produces $P_{\mathrm{st}} = 1$. Flickermeters conforming to the standard should measure $P_{\mathrm{st}} = 1$ with an error under 5%.

For the case of rectangular fluctuations, the standard presumes that the measured P_{st} is proportional to the amplitude of the fluctuation, i.e., if $\Delta V/V$ should double, then the resulting P_{st} value must also double. This is the reason why the standard requires that, for each of the seven series specified in the performance-testing section, the range of $\Delta V/V$ providing the P_{st} measurement with an error under 5% is determined. In fact, the Working Group on Power Quality is developing a test protocol for the IEC flickermeter [7], which has already been used in various research [8]–[10]. This protocol includes a test specifically designed to prove the proportionality of the measured P_{st} with $\Delta V/V$ for the case of rectangular fluctuations. A linear response for the P_{st} from about 0.2–20 is desirable for a class-3 instrument [7]. The linearity test shows whether the measured P_{st} has a linear relationship to the amplitude of the voltage fluctuation for values of the P_{st} ranging from 0.2 to 20.

We have studied the relationship between the P_{st} and the $\Delta V/V$ for the IEC flickermeter when subject to rectangular fluctuations. These magnitudes are not proportionally related. We have analyzed the different blocks of the IEC flickermeter in depth. The conclusion is that the lack of proportionality is due to Block 1 of the flickermeter, which scales the input-voltage level. Furthermore, the lack of proportionality depends on the frequency of the fluctuation.

The IEC 61000-4-15 standard suggests two scaling methods. The first method is based on the rms value of the input voltage, calculated over a 60-s interval. The second method is a linear system with a response time (10%–90% of the final value) to a step variation in the rms-input value that is equal to 1 min.

We have theoretically analyzed both methods, concluding that the maximum error due to the scaling process is always under 3.4% for $\Delta V/V$ in the 0.5%–20% range. This error is within the 5% accuracy margin of IEC flickermeter; we nevertheless think that it is important to clarify its origin and to quantify its value. We theoretically demonstrate that the use of a new scaling method based on the mean value of the rectified input voltage provides better results. The theoretical results are then confirmed by computer simulations using an offline version of the IEC flickermeter that is subjected to analytically generated rectangular fluctuations. Finally, we have conducted field trials to analyze the influence of the scaling of the input voltage in field measurements. In Section VI, we provide a summary of field measurements using the IEC flickermeter for a range of the P_{st} values from 0.2 to 17 when the different scaling methods are used. The results show that the new method is a valid alternative for measuring flicker that conforms to the IEC standard.

II. P_{st} as a Function of $\Delta V/V$ in the Case of Rectangular Fluctuations

Fig. 1 shows the block diagram of the IEC flickermeter. We will conduct the analysis of the blocks for a carrier voltage of frequency f_{o} and rms amplitude A, modulated by a rectangular fluctuation of frequency f_{m} and peak-to-peak amplitude $\Delta V/V$. The modulating rectangular fluctuation $g_{\mathrm{m}}(t)$ is shown in Fig. 2.

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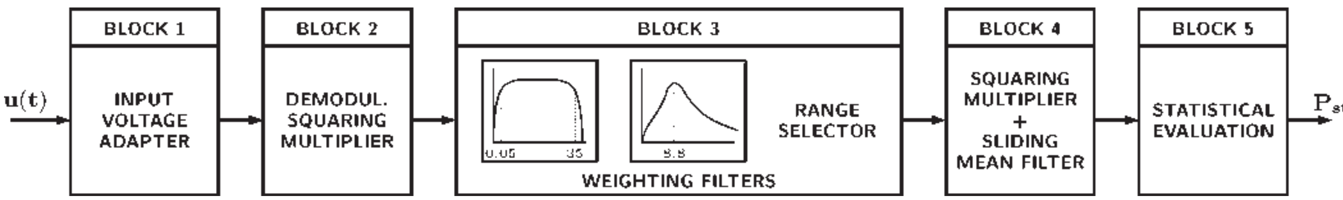

Fig. 1. Block diagram of the IEC flickermeter.

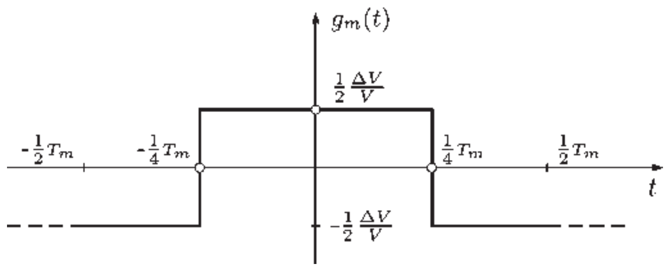

Fig. 2. Modulating rectangular fluctuation: $g_{\mathrm{m}}(t)$.

The flickermeter input signal for a rectangular fluctuation $u(t)$ is then written as

$$u(t) = \sqrt{2}A\,(1 + g_{\mathrm{m}}(t))\cos(\omega_{\mathrm{o}}t).$$

A. Input-Voltage Adaptor

Block 1 of the flickermeter scales the input-voltage level down to an internal reference value V_{ref}. The objective of this block is to make flicker measurements independent of the input-voltage level. This goal can be achieved by an analog block that automatically adjusts its gain to an average value of the input voltage V_{sc}. The time constant of this block must significantly be longer than the response time needed to correctly reproduce the voltage changes relevant for flicker [11].

The IEC 61400-4-15 standard proposes a system with a 1-min response time to a step variation in the rms-input value. This is sufficient to follow the slowest variations of the fluctuation, namely $f_{\mathrm{m}} = 1$ c/min (changes per minute). In fact, digital versions of the flickermeter implement this block using the rms value of the input voltage, averaged over 1 min.

The input to Block 2 is then given by

$$u_1(t) = \sqrt{2}V_{\mathrm{ref}}\left(\frac{A}{V_{\mathrm{sc}}}\right)(1 + g_{\mathrm{m}}(t))\cos(\omega_{\mathrm{o}}t).$$

B. Quadratic Demodulator

Block 2 recovers the voltage fluctuation by squaring the scaled input voltage, simulating the behavior of an incandescent lamp.

In the case of a rectangular fluctuation, $g_{\mathrm{m}}^2(t) = 1/4(\Delta V/V)^2$ is an dc component. The output of the squaring module is

$$u_1^2(t) = V_{\mathrm{ref}}^2\left(\frac{A}{V_{\mathrm{sc}}}\right)^2\left[1+\frac{1}{4}\left(\frac{\Delta V}{V}\right)^2 + 2g_{\mathrm{m}}(t)\right](1+\cos(2\omega_{\mathrm{o}}t)).$$

C. Weighting Filters

Block 3 of the flickermeter is composed of two cascaded filters followed by a range selector that determines the sensitivity of the device. The first filter is the demodulation filter for Block 2. The second filter models the frequency response of the human eye and is therefore experimentally determined for an average observer. These filters eliminate the dc component and strongly attenuate (by more than 90 dB) the frequency components above $2f_{\mathrm{o}}$. The input to Block 3 can be decomposed into two terms. The first one consists exclusively of dc and $2f_{\mathrm{o}}$ components, which will be suppressed by the filters. It is the second term alone that produces the measured flicker

$$V_{\mathrm{ref}}^2\left(\frac{A}{V_{\mathrm{sc}}}\right)^2\left[\overbrace{\left(1+\frac{1}{4}\left(\frac{\Delta V}{V}\right)^2\right)(1+\cos(2\omega_{\mathrm{o}}t))}^{\text{eliminated by filters}} + \underbrace{2g_{\mathrm{m}}(t)\,(1+\cos(2\omega_{\mathrm{o}}t))}_{\text{component producing } P_{\mathrm{st}}}\right].$$

The input of Block 3 that ultimately produces the P_{st} value is therefore proportional to $g_{\mathrm{m}}(t)$, i.e., to $\Delta V/V$

$$V_{\mathrm{ref}}^2\left(\frac{A}{V_{\mathrm{sc}}}\right)^2 2g_{\mathrm{m}}(t)\,(1+\cos(2\omega_{\mathrm{o}}t))\,. \tag{1}$$

In fact, since all the subsystems of Block 3 are linear, the output of this block must also be proportional to $\Delta V/V$.

D. Nonlinear Eye–Brain Response and the Statistical Classifier

Block 4 of the flickermeter completes the eye–brain response model by including a squaring multiplier that simulates the nonlinear eye–brain response, followed by a low-pass filter that accounts for the perceptual storage effects in the brain. The low-pass filter is specified to be a sliding mean filter with a 300-ms time constant. The output of Block 4 represents the instantaneous flicker sensation.

Block 5 performs the statistical classification of the instantaneous-flicker-sensation output from Block 4. The instantaneous flicker sensation is sampled with a sampling rate of at least 50 Hz. The amplitude of these samples is classified within an adequate number of classes. Each sample increments the counter corresponding to one such class; the result is the cumulative probability distribution of the amplitude of the instantaneous flicker sensation.

The cumulative probability distribution is characterized in terms of a set of percentiles and weighted percentiles: $\mathsf{P}_{0.1}$, P_{1s}, P_{3s}, P_{10s}, and P_{50s}. The short-term flicker severity is then defined as the expression shown at the bottom of the page.

Blocks 4 and 5 are nonlinear, but their combination verifies the homogeneity property. Let the input of Block 4 be multiplied by a constant C. The output of Block 4, and consequently all the percentiles, is proportional to C^2. The square-root operation involved in the calculation of the P_{st} produces a value proportional to C.

Since the input of Block 4 was indeed proportional to $\Delta V/V$, then the P_{st} must also be proportional to $\Delta V/V$.

III. Input-Voltage Adaptor

We have shown in the previous section that if the input of Block 3 producing the P_{st}, namely (1), is proportional to $\Delta V/V$, then the P_{st} must also be proportional to $\Delta V/V$. The term $2g_{\mathrm{m}}(t)(1+\cos(2\omega_{\mathrm{o}}t))$ in (1) is directly proportional to $\Delta V/V$. The lack of proportionality can therefore only be due to the scaling factor V_{sc}, which, instead of being constant, depends on $\Delta V/V$. We will now analyze the different methods proposed by the standard in evaluating the scale factor.

A. RMS Value of the Input Voltage Over a 60-s Interval

This method computes the scaling factor as the rms value of the input voltage $u(t)$, which is calculated over the previous 60 s, i.e.,

$$V_{\mathrm{sc}} = \sqrt{\frac{1}{T}\int_T u^2(t)dt}, \qquad T = 60 \text{ s}.$$

In order to obtain a closed-form expression for V_{sc}, we expand the integrand as

$$u^2(t) = A^2\left[1+\frac{1}{4}\left(\frac{\Delta V}{V}\right)^2 + 2g_{\mathrm{m}}(t)\right](1+\cos(2\omega_{\mathrm{o}}t)).$$

The ideal rectangular fluctuation, as shown in Fig. 2, is an even function and can therefore be expressed as a cosine Fourier series

$$g_{\mathrm{m}}(t) = \sum_{n=0}^{\infty} c_{2n+1}\cos((2n+1)\omega_{\mathrm{m}}t)$$
$$c_{2n+1} = \frac{\Delta V}{V}\frac{2(-1)^n}{(2n+1)\pi}. \tag{2}$$

The term $g_{\mathrm{m}}(t)$ produces odd harmonics of f_{m}, while the product $g_{\mathrm{m}}(t)\cos(2\omega_{\mathrm{o}}t)$ produces harmonics of frequency $(2n+1)f_{\mathrm{m}} \pm 2f_{\mathrm{o}}$. Writing these frequencies in terms of changes per minute ($f_0 = 50$ Hz $\equiv 6000$ c/min), the harmonics are $(2n+1)f_{\mathrm{m}}$ and $(2n+1)f_{\mathrm{m}} \pm 12\,000$, which are all integer numbers. All the harmonics have an integer number of periods in the observation interval. This means that their integral vanishes, and the only component contributing to the V_{sc} value is the dc component of $u^2(t)$. For a particular set of f_{m} frequencies, there is an additional dc component originating in one of the harmonics in $g_{\mathrm{m}}(t)\cos(2\omega_{\mathrm{o}}t)$, namely

$$(2n+1)f_m - 12\,000 = 0 \quad \Rightarrow \quad f_{\mathrm{m}} = \frac{12\,000}{2n+1} \in \mathbb{N}$$

whose value is the corresponding Fourier coefficient c_{2n+1}. The scaling value can therefore be written as follows:

$$V_{\mathrm{sc}} = \begin{cases} A\sqrt{1+\frac{1}{4}\left(\frac{\Delta V}{V}\right)^2}, & f_{\mathrm{m}} \neq \frac{12\,000}{2n+1} \\ A\sqrt{1+\frac{1}{4}\left(\frac{\Delta V}{V}\right)^2 + 2\frac{\Delta V}{V}\frac{(-1)^n}{(2n+1)\pi}}, & f_{\mathrm{m}} = \frac{12\,000}{2n+1} \end{cases} \tag{3}$$

which is not independent of the amplitude of the fluctuation. Block 1 of the flickermeter scales the input signal by V_{sc}, so the P_{st} value will be inversely proportional to V_{sc}^2. The theoretical dependence of the P_{st} on $\Delta V/V$ is then

$$P_{\mathrm{st}} \propto \begin{cases} \frac{\Delta V}{V}\left[1+\frac{1}{4}\left(\frac{\Delta V}{V}\right)^2\right]^{-1}, & f_{\mathrm{m}} \neq \frac{12\,000}{2n+1} \\ \frac{\Delta V}{V}\left[1+\frac{1}{4}\left(\frac{\Delta V}{V}\right)^2 + 2\frac{\Delta V}{V}\frac{(-1)^n}{(2n+1)\pi}\right]^{-1}, & f_{\mathrm{m}} = \frac{12\,000}{2n+1}. \end{cases} \tag{4}$$

The theoretical results summarized in (4) show a deviation from the expected proportionality. The maximum value of $\Delta V/V$ specified in the flickermeter linearity test [7] is 20%. This amplitude produces a 1% error in the general case, namely $f_{\mathrm{m}} \neq 12\,000/2n+1$. The frequencies containing an additional term have higher errors: $f_{\mathrm{m}} = 2400$ c/min $(n=2)$[1] is the worst case, with a 3.4% error for $\Delta V/V = 20\%$.

B. System With a 1-min Step Response Time

Often, this type of system is implemented by calculating V_{sc} as the first-order low-pass filtered output of $u^2(t)$; thus, the filter-transfer function is

$$H(f) = \frac{1}{1+\frac{jf}{f_{\mathrm{c}}}}$$

where f_{c} represents the 3-dB cutoff frequency of the filter. The calculation of f_{c} assures a 1-min response time for a step variation in the input rms value, namely $f_{\mathrm{c}} = 0.00583$ Hz.

The minimum frequency component in $u^2(t)$ is 1 c/min $(1/120 = 0.0083$ Hz). All the frequency components are above the cutoff frequency of the filter. The steady-state output of the

[1]For $f_{\mathrm{m}} = 4000$ $(n=1)$, the additional contribution compensates for the effect of the $1/4(\Delta V/V)^2$ term.

$$P_{\mathrm{st}} = \sqrt{0.0314\cdot \mathsf{P}_{0.1} + 0.0525\cdot \mathsf{P}_{1s} + 0.0657\cdot \mathsf{P}_{3s} + 0.28\cdot \mathsf{P}_{10s} + 0.08\cdot \mathsf{P}_{50s}}$$

filter for a $u^2(t)$ input voltage is approximately the dc component of $u^2(t)$. Therefore, (3) and (4) are good approximations in the present case. This scaling method will also produce a P_{st} that is not proportional to the $\Delta V/V$.

IV. New Scaling Value: Mean Value of the Rectified Signal Over a 60-s Interval

The results of the previous section indicate the necessity for an alternative scaling value: one that is less dependent on the amplitude of the fluctuations. We propose the use of the mean value of the rectified input signal as the scaling value.

Using the mean value of the rectified input signal as the reference value, we obtain

$$V_{\mathrm{sc}} = \frac{1}{T}\int_T |u(t)|\,dt, \qquad T = 60\ \mathrm{s}.$$

We expand the integrand in order to obtain a closed-form expression for the reference value. Since the amplitude of the fluctuations can never be greater than the carrier, the $1 + g_{\mathrm{m}}(t)$ term is always positive. The integrand reads

$$|u(t)| = A\sqrt{2}\,(1 + g_{\mathrm{m}}(t))\,|\cos(\omega_{\mathrm{o}} t)|\,.$$

The scaling value is then

$$V_{\mathrm{sc}} = \frac{A\sqrt{2}}{T}\left[\int_T |\cos(\omega_{\mathrm{o}} t)|\,dt + \int_T g_{\mathrm{m}}(t)\,|\cos(\omega_{\mathrm{o}} t)|\,dt\right].$$

The first term in the integrand can easily be computed and is the mean value of a full-wave rectified sinusoid

$$\int_T |\cos(\omega_{\mathrm{o}} t)|\,dt = \frac{2}{\pi}T.$$

In order to calculate the second term, we will use the Fourier cosine series expansion of the even functions $g_{\mathrm{m}}(t)$ and $|\cos(\omega_{\mathrm{o}} t)|$. The series expansion of the rectangular fluctuation is given by (2). For the second function, we have

$$|\cos(\omega_{\mathrm{o}} t)| = \sum_{\ell=0}^{\infty} a_\ell \cos(2\ell\omega_{\mathrm{o}} t), \quad a_\ell = \frac{4}{\pi}\frac{(-1)^{\ell+1}}{4\ell^2 - 1}. \tag{5}$$

The product can now be written in terms of the harmonics as

$$g_{\mathrm{m}}(t)\,|\cos(\omega_{\mathrm{o}} t)| = \sum_{\ell,n} a_\ell c_{2n+1} \cos(2\ell\omega_{\mathrm{o}} t)\cos((2n+1)\omega_{\mathrm{m}} t)\,.$$

The frequencies of the harmonics are now $12\,000\ell \pm (2n + 1)f_{\mathrm{m}}$, which again correspond to integer values. Integration over a $T = 60$-s period will yield the dc value alone. Only those frequencies meeting the following condition have an additional dc component:

$$f_{\mathrm{m}} = \frac{12\,000}{2n+1}\ell. \tag{6}$$

The closed expression for the dc component is cumbersome, since many combinations of the (ℓ, n) values produce a dc component for a particular f_{m}. Let us analyze the general and the worst cases, namely those corresponding to the lower harmonic values.

A. General Case

Those frequencies not satisfying the condition expressed in (6) will not have an additional dc component in V_{sc}. In this case, the scaling value is constant

$$V_{\mathrm{sc}} = A\frac{2\sqrt{2}}{\pi}.$$

In the general case, the P_{st} is proportional to the $\Delta V/V$, which is an improvement over the previous methods.

B. $f_{\mathrm{m}} = 4000$ c/min

This frequency corresponds to $(\ell, n) = (1, 1)$, which is the lowest harmonic number, and, therefore, produces the largest additional dc component. Mombauer [12] indicated the importance of this frequency, which is now one of the significant frequencies mentioned in the last amendment to the standard. In this case, the relation between the harmonic numbers producing a dc component is given by

$$12\,000\ell - (2n+1)4000 = 0 \quad \Rightarrow \quad 2n + 1 = 3\ell.$$

Therefore, there are dc components for the following harmonic number pairs:

$$(\ell, 2n+1) = \{(1,3)\ (3,9)\ (5,15), \ldots, (2k+1, 6k+3), \ldots\}\,.$$

The dc component is computed in terms of the Fourier coefficients given in (2) and (5) as

$$\frac{1}{2}\sum_{k=0}^{\infty} c_{6k+3}a_{2k+1} = \frac{4}{\pi^2}\frac{\Delta V}{V}\sum_{k=0}^{\infty}\frac{(-1)^{k+1}}{(6k+3)\,(4(2k+1)^2 - 1)}$$
$$= -\frac{2}{\pi}\frac{\Delta V}{V}0.0690.$$

The scaling value can now be written as

$$V_{\mathrm{sc}} = A\frac{2\sqrt{2}}{\pi}\left(1 + k_{\mathrm{sc}}\frac{\Delta V}{V}\right), \qquad k_{\mathrm{sc}} = -0.0690.$$

P_{st} will therefore be proportional to

$$P_{\mathrm{st}} \propto \frac{\Delta V}{V}\left(1 + k_{\mathrm{sc}}\frac{\Delta V}{V}\right)^{-2}, \qquad k_{\mathrm{sc}} = -0.0690. \tag{7}$$

For $\Delta V/V = 20\%$, the error is 2.8%, which is less than the worst-case error analyzed for the rms value.

The functional form obtained for the P_{st} applies for all the frequencies showing an additional dc term. The difficulty lies in obtaining a general form for the constant k_{sc}.

C. $f_{\mathrm{m}} = 2400$ *c/min*

The improvement obtained for the worst case, namely $f_{\mathrm{m}} = 4000$ c/min, is not conclusive. Therefore, we analyze the next-to-worst case to finally prove the better linearity when scaling by the mean value of the rectified signal. This case corresponds to the next-to-highest harmonic $f_{\mathrm{m}} = 2400$ c/min$((\ell, n) = (1,2))$

$$12\,000\ell - (2n+1)2400 = 0 \quad \Rightarrow \quad 2n+1 = 5\ell.$$

Following the procedure outlined earlier, the additional dc component is currently

$$\frac{1}{2}\sum_{k=0}^{\infty} c_{10k+5}a_{2k+1} = \frac{4}{\pi^2}\frac{\Delta V}{V}\sum_{k=0}^{\infty}\frac{(-1)^k}{(10k+5)\,(4(2k+1)^2-1)} = \frac{2}{\pi}\frac{\Delta V}{V}\,0.0414.$$

The constant is now $k_{\mathrm{sc}} = 0.0414$, which produces a 1.6% error for $\Delta V/V = 20\%$.

V. Simulations With a MATLAB IEC Flickermeter

The theoretical analysis of the previous section provides closed-form expressions for the dependence of the P_{st} on the amplitude of the fluctuation. We have developed a high-precision MATLAB version of the flickermeter to check the validity of these results. The flickermeter is compliant with the IEC 61000-4-15 standard and is as accurate as the well-known implementation presented by Mombauer [13], which has been used in previous works [7], [9]. Using analytically generated rectangular fluctuations as input to our flickermeter, we have measured the P_{st} for the $\Delta V/V$ values proportional to those providing the $P_{\mathrm{st}} = 1$ curve, i.e.,

$$\frac{\Delta V}{V} = K \cdot \left.\frac{\Delta V}{V}\right|_{P_{st}=1}.$$

The values of K that were used correspond to $\Delta V/V$ in the 0.5%–20% range.

Our results show a slight deviation from the theoretical predictions for very low values of amplitude. This slight deviation occurs because the filters in Block 3 of the flickermeter do not completely remove the $2f_{\mathrm{o}}$ component. This component produces a nonzero P_{st} in the absence of fluctuation, i.e., for a purely sinusoidal input. In our MATLAB version of the flickermeter, the value of this residual value (P_{sto}) is

$$P_{\mathrm{sto}} = 0.0096.$$

A better approximation[2] to the P_{st} is then obtained by quadratic addition of this residual value and the theoretical expressions obtained in the previous section

$$P_{\mathrm{st}}^{*} \approx \sqrt{P_{\mathrm{st}}^2 + P_{\mathrm{sto}}^2}. \tag{8}$$

We have analyzed the different scaling methods by considering three frequencies. The first frequency $(f_{\mathrm{m}} = 1620$ c/min$)$ is used in the testing protocol and corresponds to the general-case formulas. The other two frequencies are the two particular cases showing the greatest deviation from the expected proportionality, namely $f_{\mathrm{m}} = 4000$ c/min and $f_{\mathrm{m}} = 2400$ c/min. Figs. 3 and 4 show the relative deviation of a P_{st}^{*} from linear behavior. Initially, we calculate the theoretical value of the P_{st} using (4) or (7), depending on the scaling method under analysis. The theoretical value is then corrected using (8).

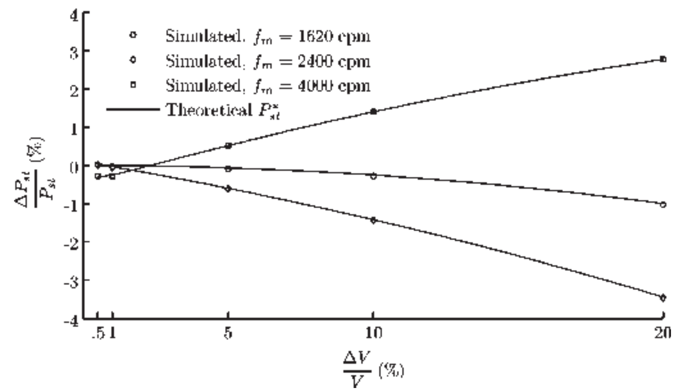

Fig. 3. Relative deviation from the linear behavior of P_{st} when the rms value is used as the scaling method. For a fluctuation of a frequency that meets the general-case criterion $(f_{\mathrm{m}} = 1620$ c/min$)$, the error is nonzero. For the two worst frequencies, namely $f_{\mathrm{m}} = 2400$ c/min and $f_{\mathrm{m}} = 4000$ c/min, the maximum error is above 3%.

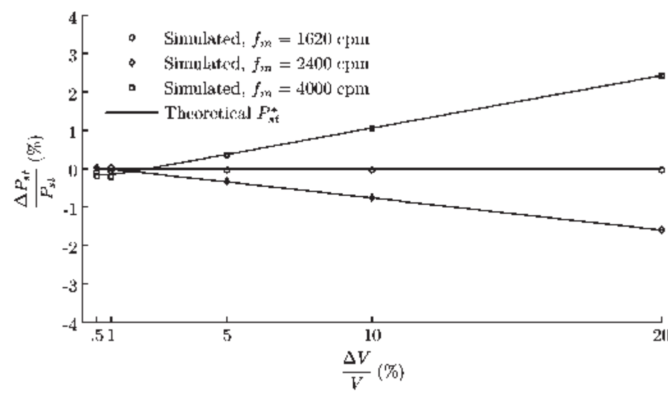

Fig. 4. Relative deviation from the linear behavior of P_{st} when the mean value of the rectified signal is used as the scaling method. For a fluctuation of a frequency that meets the general-case criterion $(f_{\mathrm{m}} = 1620$ c/min$)$, there is no error. For the two worst frequencies, namely $f_{\mathrm{m}} = 2400$ c/min and $f_{\mathrm{m}} = 4000$ c/min, the maximum error is below 3%.

We found an exact correspondence between the theoretically predicted values and those provided by the MATLAB version of the IEC flickermeter, with the differences being under 0.4%. The scaling method proposed in this paper ameliorates the lack of proportionality in the previous methods. In fact, the lack of proportionality is corrected in the general case, where the proposed method shows no deviation from the desired proportional behavior. For the two particular case frequencies showing the greatest deviation, the proposed method introduces a smaller error, namely, less than 3% in the worst case.

Fig. 5 shows the relative deviation of the MATLAB IEC flickermeter over the whole frequency range. The curves are calculated for $K = 10$, i.e., an expected value of $P_{\mathrm{st}} = 10$. We have considered two of the scaling methods discussed in this paper. When the new scaling method is used, there is no deviation over the whole frequency range. Only for the

[2]The error is under 1% for values of P_{st} above 0.07.

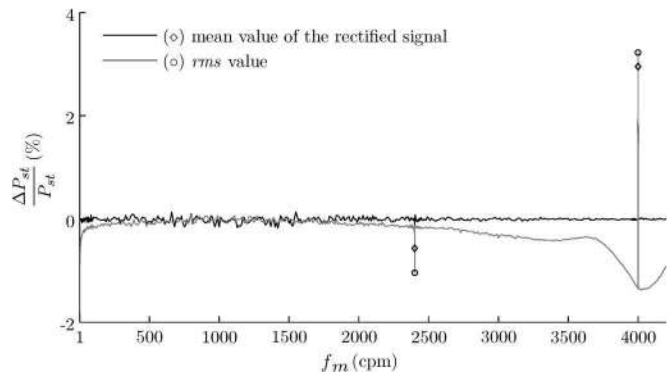

Fig. 5. Relative error in $P_{\rm st}$ as a function of the frequency of the fluctuation for $K = 10$. The mean value of the rectified signal is the scaling method that presents the lower deviation from the desired proportionality.

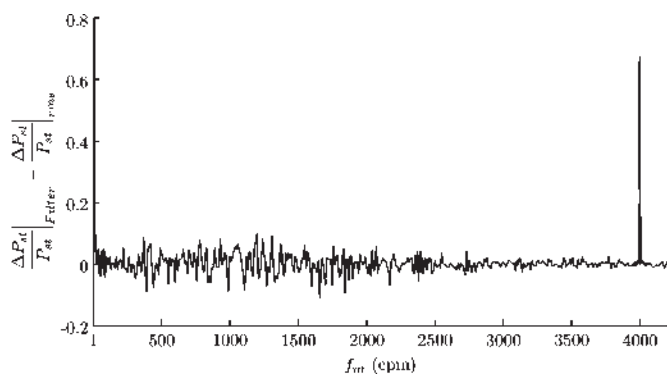

Fig. 6. Comparison of the deviations obtained when scaling by the rms value and by the filtered value of $u^2(t)$. The deviation is calculated over the whole frequency range for $K = 10$. Only for low frequencies, i.e., $f_{\rm m} \approx 1$ c/min, and for frequencies close to $f_{\rm m} \approx 4000$ c/min, there are slight deviations. These are due to very-low-frequency components in $u^2(t)$.

special-case frequencies, i.e., $f_{\rm m} = 4000$ c/min and $f_{\rm m} = 2400$ c/min, is there a significant deviation. When the scaling method based on the rms value is used, there is a significant deviation, particularly for the low and high frequencies. This is due to these frequencies having a bigger $\Delta V/V$ value for $P_{\rm st} = 1$.

We have not obtained a closed-form expression for the $P_{\rm st}$ when the low-pass filtered $u^2(t)$, namely method B in Section III, is used as the scaling method. We have indicated that this method yields approximately the same scaling value as the method based on the rms value. Fig. 6 shows that these two methods provide similar values for $P_{\rm st}$ over the whole frequency range. For $K = 10$, the difference in deviation is less than 1%, where the differences occur when $f_{\rm m} \approx 1$ c/min, and $f_{\rm m} \approx 4000$ c/min. In these cases, $u^2(t)$ has very-low-frequency components that are not properly filtered by the low-pass filter and that, consequently, contribute to $V_{\rm sc}$ when scaling by the low-pass filtered $u^2(t)$.

VI. Field Tests

The correspondence between the theoretical results and the values obtained using synthetic signals is very good. Nevertheless, the validity of the new method must be tested in a field environment, where the line voltage greatly differs from synthetically generated voltages. We do not intend to select the best scaling method because a commercial reference flickermeter does not exist. In fact, it is well known that different commercial implementations of IEC flickermeters provide different $P_{\rm st}$ measurements [14]. On the contrary, we have analyzed the differences between flicker measurements in the field when different scaling methods are used in Block 1 of the IEC flickermeter. We have recorded 24-h registers of line voltages which were then processed offline by the MATLAB flickermeter using the different scaling blocks analyzed in this paper. The voltage signals have been captured in three different locations in Spain, which have different flicker levels. The characteristics of these locations are summarized in Table I.

TABLE I
Locations and the $P_{\rm st}$ Characteristics for the Field Test

Location	Type of line	P_{st} range[1]
Medina del Campo	33 KV line	$0.2 - 0.3$
Bilbao	230 V line	$0.5 - 1$
Bergara	33 KV arc furnace	$1 - 15$

[1] expressed between 10^{th} and 90^{th} percentiles.

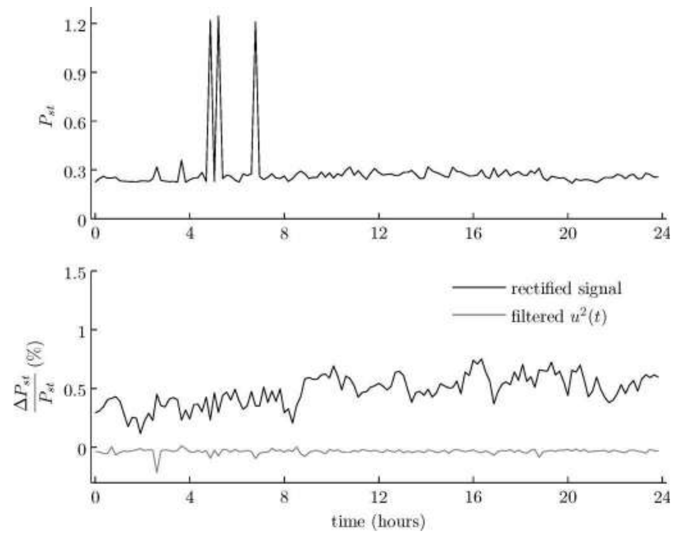

Fig. 7. $P_{\rm st}$ in a 33-kV line substation close to power generation (Medina del Campo). For low values of the $P_{\rm st}$ (average value under 0.3), the differences between the scaling methods are low.

Figs. 7–9 show the $P_{\rm st}$ values obtained for the three locations. In each figure, the upper graph shows $P_{\rm st}$ when evaluated using the scaling method based on the rms value. This method serves as a reference for the computation of the deviation in the $P_{\rm st}$ when the other two methods are used. These deviations are shown in the lower graph.

Fig. 7 shows $P_{\rm st}$ in a 33-kV line substation close to power generation. The $P_{\rm st}$ value is below 0.4, except for the three peaks caused by maintenance operations in the substation transformer. The deviations are very low; in fact, the values obtained when scaling by the low-pass filtered $u^2(t)$ show a deviation under 0.2% for all cases. The new scaling method has a mean deviation of 0.5%.

The results for a 230-V home line at the limit of an admissible disturbance are shown in Fig. 8. The mean recorded $P_{\rm st}$ is 0.72. The deviations are similar to those recorded at the previous site, with the new scaling method having a mean deviation of 0.6%.

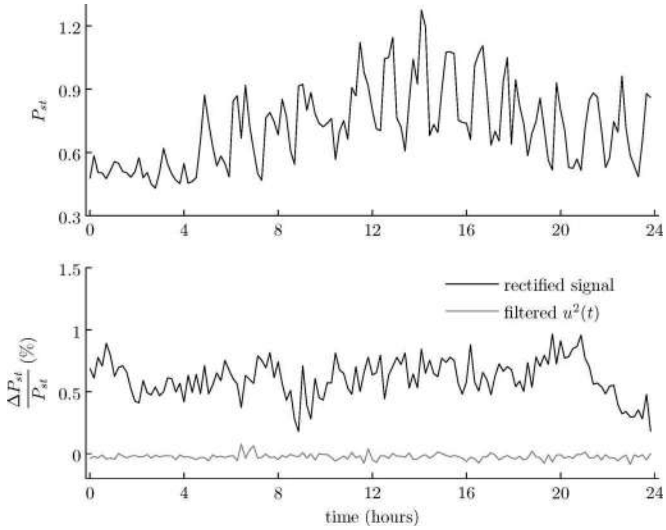

Fig. 8. $P_{\rm st}$ in a 230-V home line, at the limit of an admissible disturbance. For intermediate values of $P_{\rm st}$ (average value under 0.8), the differences between the scaling methods are still low.

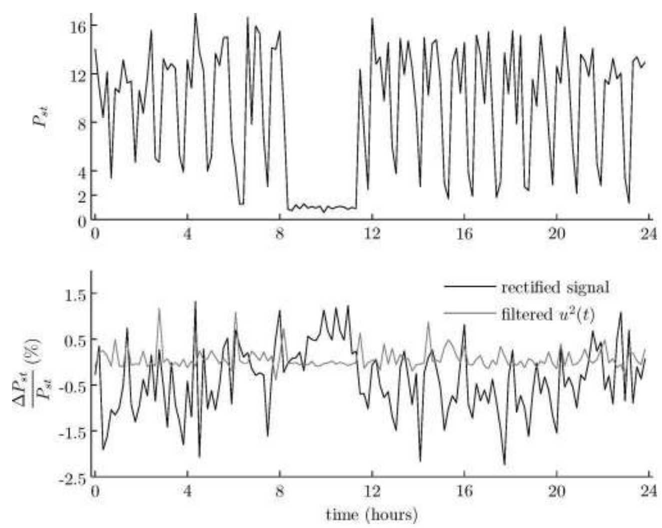

Fig. 9. $P_{\rm st}$ in an arc-furnace substation. The $P_{\rm st}$ values are high (3–17) during the operation cycles of the arc.

In the case of an arc-furnace substation, as shown in Fig. 9, the results greatly differ from those of the previous two sites. $P_{\rm st}$ is low for the periods when the furnace operation stops and rises to values between 3 and 17 during operating hours, where the periodicity in the smelting cycle is easily observable. The recorded line voltage is complex and very different from the rectangular fluctuations defined in the standard, particularly during the operating hours of the arc furnace. This produces bigger deviations among the three scaling methods. The mean deviation for the filtered $u^2(t)$ is practically zero, but in this case, there are peak deviations of 1.2%. The new method shows a low negative mean deviation, namely, -0.4%, but during the operation cycle of the furnace, the deviation is well below -1%, reaching values of -2.2%.

In short, the scaling method implemented in Block 1 of the IEC flickermeter has influence on the $P_{\rm st}$ values obtained in the field measurements. This influence is usually small for low values of the $P_{\rm st}$, but it can become significant as the $P_{\rm st}$ grows.

VII. Conclusion

This paper is the first detailed study on the lack of linearity of the IEC flickermeter when subject to rectangular fluctuations. We have shown that the lack of linearity is due to the scaling process implemented in Block 1 of the IEC flickermeter. We have analytically quantified the lack of linearity when the two scaling methods suggested by the IEC 61000-4-15 standard are used: a scaling block that is based on the rms value of the input voltage $u(t)$ and a scaling block that is based on the filtering of $u^2(t)$. The theoretical results are then confirmed through simulations. We propose a new scaling method based on the mean value of the rectified line voltage calculated over a 1-min interval. This method corrects, to a great extent, the lack of linearity. First, the correction is theoretically proven and is then confirmed through simulations. Finally, we have conducted field trials to validate the method in the presence of line voltages that differ greatly from those generated analytically. We report deviations from the expected linear behavior, which are generally small and are always below the 5% accuracy margin fixed by the IEC standard. We nevertheless think that it is important to know the source and magnitude of these deviations when an IEC flickermeter is built and tested. This is particularly applicable to test number six of the Cigré Test Protocol [7], which analyzes the linearity of the $P_{\rm st}$ in relation to the amplitude of the rectangular fluctuations.

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