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Abstract: This paper presents an analysis of the effect of the sampling rate on the calculation by a digital flickermeter of the flicker severity caused by phase jumps. The new edition of the IEC 61000-4-15 standard includes an innovative test aimed at verifying that a flickermeter works properly during a phase jump event. Since phase jumps are rapid angle changes, it seems that a high sampling rate should be used by a digital instrument. This requirement could be too demanding, so we have studied this hypothesis by defining three analytical signal models. One is based on the characterization of ideal phase jump sequences and the other two are based on the definition of realistic band-limited signals containing phase jumps. We found that the minimum sampling rate necessary to pass that test is not as demanding as expected. Practical experiments made by an actual generation and acquisition system confirm this conclusion. A typical sampling rate of 3200 S/s, usually used in commercial flickermeters, becomes clearly sufficient to pass the test. However, we give notice that passing this test could not guarantee accurate results when the phase jumps are different from those specified by the standard.

Keywords: Flicker, IEC flickermeter, phase jumps, power quality (PQ), P_{st}.

Effect of the Sampling Rate on the Assessment of Flicker Severity Due to Phase Jumps

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***Abstract*—This paper presents an analysis of the effect of the sampling rate on the calculation by a digital flickermeter of the flicker severity caused by phase jumps. The new edition of the IEC 61000-4-15 standard includes an innovative test aimed at verifying that a flickermeter works properly during a phase jump event. As phase jumps are rapid angle changes, it seems that a high sampling rate should be used by a digital instrument. This requirement could be too demanding, so we have studied this hypothesis by defining three analytical signal models. One is based on the characterization of ideal phase jump sequences and the other two are based on the definition of realistic band-limited signals containing phase jumps. We found that the minimum sampling rate necessary to pass that test is not as demanding as expected. Practical experiments made by an actual generation and acquisition system confirm this conclusion. A typical sampling rate of 3200 $\frac{S}{s}$, usually used in commercial flickermeters, becomes clearly sufficient to pass the test. However, we give notice that passing this test could not guarantee accurate results when the phase jumps are different from those specified by the standard.**

***Index Terms*—Power quality, Flicker, IEC flickermeter, Phase jumps, $\mathbf{P_{st}}$.**

I. INTRODUCTION

THE voltage of the electrical grid may change under the influence of load variations or the generation system. When the voltage variations are sudden and repetitive, they are called voltage fluctuations and cause flicker phenomena in lighting equipment. Flicker is understood as the sensation experienced by the human visual system due to changes in the illumination intensity of light sources caused by the voltage fluctuations. A persistently varying illumination can cause irritation in people and may lead to complaints. Therefore, flicker is a perception problem and consequently it is difficult to quantify. A flickermeter quantifies the discomfort suffered by the human eye when subjected to a luminous fluctuation of a reference incandescent lamp. The IEC 61000-4-15 standard [1] establishes the functional and design specifications for a flickermeter, and defines the short-term flicker severity P_{st} as the fundamental parameter used to evaluate the discomfort.

Actually, the implementation of an accurate IEC flickermeter is not an easy task and has recently generated a large number of research works [2]–[4]. The IEC 61000-4-15 standard includes a performance testing section to evaluate the implementation of the flickermeter. However, several works showed that different commercial flickermeters, designed according to the IEC standard, provide different measurements for the same input signal [5]. The CIGRE/CIRED WG2 on voltage quality defined a protocol [6] based on a previous work [7] to test the design in order to obtain reproducible results in every flickermeter. From that protocol, the TF1 group belonging to the WG2 (voltage fluctuations and other low-frequency phenomena) of the IEC SC77A subcommittee has recently been working to update the IEC 61000-4-15 standard. The new IEC standard has been approved and is due for publication in 2010 [8]. This new standard requires more exhaustive operational tests to guarantee a consistent design and obtain reproducible results in every implemented flickermeter.

One of the new tests is intended to verify that the flickermeter functions properly during a phase jump event. Phase jumps can appear during the operation of an AC arc furnace; at the switching of the power source and also due to a fault in the feeder [6]. According to this new test, the flickermeter should be tested with a sequence of phase jumps. As phase jumps are rapid angle changes, a proper phase resolution, and therefore a high sampling rate, seem to be unavoidable features for a digital flickermeter. There are several previous works analyzing the influence of the phase jumps on flicker [9], [10]. However, the sampling rate has not been a key factor in those studies. Only a recent publication [11], used as the reference work for this new test, established a minimum sampling rate of 36$\frac{kS}{s}$ for 230 V/50 Hz systems in order to provide an accurate P_{st} measurement for flicker caused by phase jumps.

In view of the publication of the new edition of the IEC standard, it is relevant to explore the sampling rate required by the phase jump test for a commercial IEC flickermeter. The current work details the minimum sampling rate needed to obtain accurate results for this test. The results were analytically and experimentally obtained. We used an analytical band-limited signal model for the sequence of phase jumps that characterized the actual signals that a calibrator could use in a very accurate way. From this model, the minimum sampling frequency required for this new test is not as demanding as essentially defined by [11] for flicker caused by phase jumps. Nevertheless, when the minimum sampling rate provided by our work is used for phase jump events different from those specified by the standard, the results are not so consistent.

In the remainder of this paper, Section II briefly introduces the IEC standard [1] and the definition of the new operational tests, detailing the main specifications and requirements for the phase jump test. This section also describes the imple-

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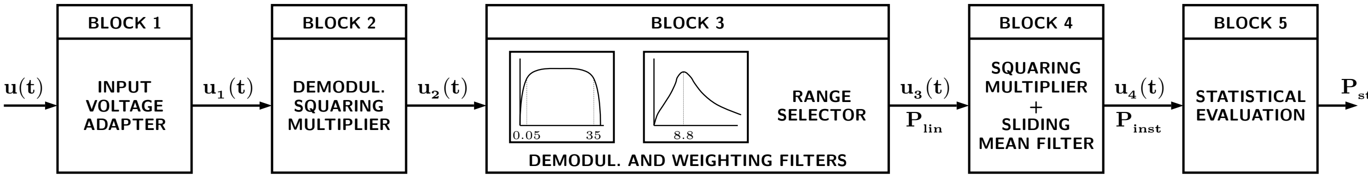

Fig. 1. Block diagram of the IEC flickermeter according to IEC 61000-4-15 [1].

mentation of the reference flickermeter used in this study. Section III presents the need for using a band-limited model for the sequence of phase jumps and details our simulations for analytically generated signals based on that model. Section IV confirms the previously simulated results through experiments made with an actual generation and data acquisition system. Section V contains a critical discussion of the results, with conclusions being stated in Section VI.

II. Description of the IEC flickermeter

This section introduces the specifications of the instrument defined by the IEC standard [1] and describes the implementation of the reference flickermeter used for the simulations and experiments. Another subsection briefly defines the new operational tests, detailing the main requirements for the phase jump test.

A. Implementation of a reference IEC flickermeter

Fig. 1 shows a block diagram of the IEC flickermeter according to the standard IEC 61000-4-15 [1]. In Block 1, the input voltage $u(t)$ is scaled to an internal reference value to make flicker measurements independent of input voltage level.

In Block 2, the scaled input voltage $u_1(t)$ is demodulated by means of a squaring multiplier. Block 3 comprises three cascaded filters. The first two filters complete the demodulation process and consist of a 1^{st}-order high-pass filter (3 dB cut-off frequency f_{co} = 0.05 Hz) and a 6^{th}-order low-pass Butterworth filter (3 dB cut-off frequency $f_{co,50}$ = 35 Hz for 50 Hz systems and $f_{co,60}$ = 42 Hz for 60 Hz systems). The third filter is a band-pass filter that models the behavior of the lamp–eye system. The analog response of this filter is given in the standard for both 230 V and 120 V reference lamps. The output of Block 3 is $u_3(t)$, which represents the weighted demodulated voltage-change signal P_{lin}.

Block 4 implements an eye–brain model. It includes a squaring multiplier followed by a sliding mean filter, having the transfer function of a 1^{st}-order low-pass resistance–capacitance filter with a time constant of 300 ms. The output of Block 4, $u_4(t)$, represents the instantaneous flicker sensation P_{inst}. A unit output from Block 4 corresponds to the reference human flicker perceptibility threshold. In Block 5, P_{st} is calculated by performing a statistical classification of P_{inst} over a short period of time (usually 10 min). The method for obtaining the P_{st} value is a multipoint algorithm that uses the percentiles obtained from the cumulative probability distribution of P_{inst}.

For the measurements performed in this work, we have implemented a highly accurate IEC flickermeter. This reference flickermeter is a complete digital MatLab implementation previously used in other studies [12]. Its three main features are: (a) it uses input sampling rates f_s from 800 to 180000 $\frac{S}{s}$; (b) it performs a decimation process at the output of the low-pass demodulation filter to allow a constant sampling rate f_p around 1000 $\frac{S}{s}$ in the following blocks, independent of the input sampling rate; and (c) the reference flickermeter does not classify the P_{inst} signal to avoid errors caused by the classification process of Block 5, in terms of the number of classes, type of classification, or type of interpolation. Instead, it stores the samples of P_{inst} during the 10 min short-term period and calculates the percentiles for the P_{st} formula in a precise way.

TABLE I
Summary of the IEC Flickermeter Tests.

Test	Test Voltage Characteristics	Intention	Value used for test	Flickermeter Classes		
1	Sinusoidal/rectangular voltage changes	Filters and scaling parameters	$P_{inst,max}$ [1]	F1	F2	F3
2	Rectangular voltage changes and performance testing	Classifier and statistical evaluation algorithms	P_{st}	F1	F2	F3
3	Frequency changes	Measuring circuit	$P_{inst,max}$	F1		
4	Distorted voltage with multiple zero crossings	Stability of the input control circuit	$P_{inst,max}$	F1		
5	Harmonics with side band	Input bandwidth	$P_{inst,max}$	F1		
6	**Phase jumps**	Stability of the input control circuit, input bandwidth and the classifier	P_{st}	F1		
7	Rectangular voltage changes with duty ratio	Classifier and statistical evaluation algorithms	P_{st}	F1	F2	
8	d_c, d_{max}, $d(t)$	Performance per IEC-61000-3-3		F1	F2	

[1] $P_{inst,max}$: maximum value of the output of Block 4, P_{inst}

B. IEC flickermeter tests

The IEC 61000-4-15 standard 2003 edition defines the way to test the accuracy of the output of a flickermeter. The standard provides tables of both sinusoidal and rectangular fluctuations to characterize the overall analog response from the instrument input to the output of Block 4. Furthermore, a performance test details a set of rectangular fluctuations of different frequencies and amplitudes for which a $P_{st} = 1$ should be measured. The meters are expected to give P_{st} results with an accuracy of 5%.

However, several studies have shown that different commercial flickermeters, designed according to the IEC standard, provide different measurements for the same input signal [5]. To solve this problem, the new IEC 61000-4-15 standard 2010 edition [8] defines six new tests, configuring three classes of flickermeters: (a) Class F1 general purpose flickermeters, suitable for power quality monitoring as well as compliance testing; (b) Class F2 flickermeters, intended for product compliance testing to IEC 61000-3-3 [13] or IEC 61000-3-11 [14]; and (c) Class F3 flickermeters compliant with IEC 61000-4-15 standard 2003 edition [1].

The tests are summarized in Table I. The first two tests are quite similar to the existing tests in the 2003 edition. The others are completely new and are intended for checking several important features of the flickermeters.

Test 6 is oriented to class F1 flickermeters and is specifically innovative; the flickermeter shall be tested with a sequence of phase jumps. Each phase jump shall occur at the positive zero crossing after 1, 3, 5, 7 and 9 min (± 10 s) after the beginning of a 10 min observation period. The test must be repeated for phase jump angles of $\Delta\beta^o = \pm 30°$ and $\pm 45°$, considering lamps of 230 and 120 V and systems of 50 and 60 Hz. The observed 10 min P_{st} has to be according to Table II with a tolerance of ± 5% or ± 0.05, whichever is larger. The transition time for each phase jump shall be less than 0.5 ms.

TABLE II
TEST SPECIFICATION FOR PHASE JUMPS.

Phase Jump $\Delta\beta^o$	230 V/50 Hz $P_{st,ref}$	120 V/60 Hz $P_{st,ref}$	120 V/50 Hz $P_{st,ref}$	230 V/60 Hz $P_{st,ref}$
±30°	0.913	0.587	0.706	0.760
±45°	1.060	0.681	0.819	0.882

Fig. 2 shows a fragment of the input voltage waveform $u(t)$ for both positive phase jumps $\Delta\beta^o = +30°$ and $+45°$, corresponding to 230 V/50 Hz systems.

III. SIMULATIONS WITH THE REFERENCE IEC FLICKERMETER

We made several simulations by calculating P_{st} for the excitations defined in Test 6. For this purpose, we constructed three different models of the input voltage signal. We calculated from them the values provided by the reference IEC flickermeter for the test points defined by the standard. The final aim was to obtain the minimum sampling frequency needed to characterize accurately the P_{st} produced by these sequences of phase jumps.

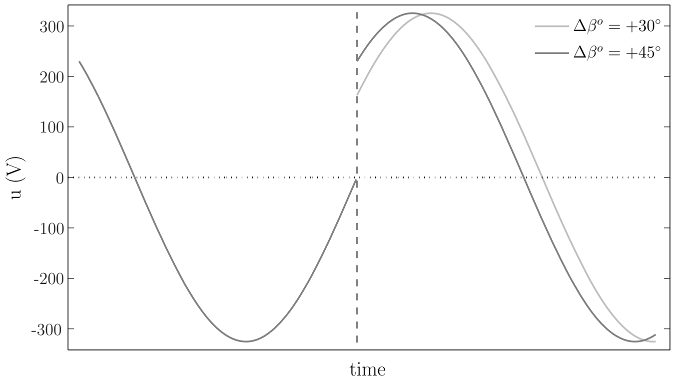

Fig. 2. A detail of the waveform corresponding to 230 V/50 Hz systems, for both positive phase jumps, $\Delta\beta^o = +30°$ and $+45°$.

A. Generation of the analytical input signal

The input signal $u(t)$ used for the simulations was analytically generated according to three different models:

– Model A: Ideal input signal

The first model consists of an input signal $u(t)$ characterized by an ideal phase jump with nil transition time producing a discontinuity on the waveform, such as the one shown in Fig. 2.

Considering $u(t)$ as a periodic signal of period $T_0 \approx 120$ s:

$$u(t) = \sum_{l=-\infty}^{\infty} u_b(t - lT_0) \quad \text{for } l \in \mathbb{Z}, \tag{1}$$

the waveform $u_b(t)$ of one period of $u(t)$ is represented in Fig. 3.

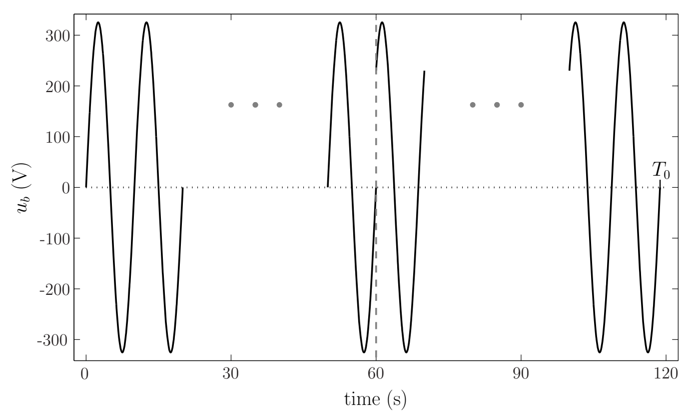

Fig. 3. Basic signal $u_b(t)$ corresponding to one period T_0 of the input excitation $u(t)$ for 230 V/50 Hz systems, for $\Delta\beta^o = +45°$ at positive zero crossing after 1 min.

The analytical expression corresponding to this waveform is:

$$u_b(t) = \begin{cases} V \cdot \sin(\omega_p t + \beta_0) & 0 \le t < 60 \\ V \cdot \sin(\omega_p t + \beta_0 + \Delta\beta) & 60 \le t < T_0, \end{cases} \tag{2}$$

where V is the amplitude of the 50/60 Hz mains frequency, β_0 is the initial angle in radians of the mains frequency and $\Delta\beta$ is the phase jump in radians occurring at odd minutes of the 10 min observation period. The period of the excitation is defined as $T_0 = 120 - T_p \frac{\Delta\beta}{2\pi}$; $T_p = \frac{2\pi}{\omega_p}$ is the period corresponding to 50/60 Hz. The input signal $u(t)$ to the IEC digital flickermeter is the repetition of $u_b(t)$ with period T_0, sampled at f_s. For instance, in the case of a $45°$ phase jump, corresponding to a 50 Hz system, the period would be T_0 = 119.9975 s. In order to obtain the 10 min signal containing 5 phase jumps it would be necessary to aggregate 6 times $u_b(t)$. Because $u_b(t)$ presents a discontinuity in 60 s, $u(t)$ is not a band-limited signal. Therefore, the sampling operation will be always affected by the aliasing. This effect decreases as the sampling rate increases.

– Model B: Band-limited signal
The previous model is an idealization of the actual characterization of a phase jump. Actually, a digital flickermeter processes band-limited input signals, due to the necessary antialiasing filtering stage of the data acquisition.
Considering the cut-off frequency $f_c = \frac{f_s}{2}$ of the antialiasing filters, we set out a band-limited analytical model through the cosine Fourier series, namely:

$$u_{BL}(t) = A_0 + \sum_{k=1}^{k_{max}} A_k \cdot \cos(k\omega_0 t + \theta_k) \quad \text{for } k \in \mathbb{N}, \tag{3}$$

where $\omega_0 = \frac{2\pi}{T_0}$ and k_{max} is the maximum order of the Fourier coefficients satisfying $k_{max} \cdot \frac{1}{T_0} \leq f_c$. The Appendix details the calculation of the amplitudes A_k and phases θ_k of every spectral component.
From this analytical band-limited model, Fig. 4 shows the waveforms produced by both positive phase jumps, $\Delta\beta^o = 30°$ and $45°$, corresponding to 230 V/50 Hz systems and working with f_c = 1600 Hz, resulting k_{max} = 191996.
The main differences regarding Fig. 2 are the small overshoots appearing around the phase jump, due to the behavior of the Fourier series at a discontinuity of a continuously differentiable periodic function (Gibbs phenomenon) [15], [16]. On the other hand, when sampling at f_s, $u_{BL}(t)$ does not produce aliasing.

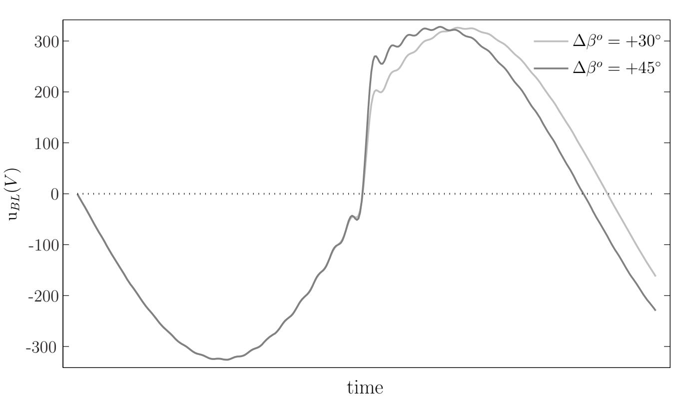

Fig. 4. A detail of the waveform of $u_{BL}(t)$ from model B, corresponding to 230 V/50 Hz systems, for both positive phase jumps, $\Delta\beta^o = +30°$ and $+45°$, with f_c = 1600 Hz.

– Model C: Filtered signal
The previous model generates a band-limited signal through an ideal filter with a cut-off frequency $f_c = \frac{f_s}{2}$. To obtain an analytical model approaching more realistic conditions, we set out a third model considering the band limitation produced by a 5^{th}-order low-pass Butterworth filter over the ideal model A. This type of filter has similar characteristics to those typically used by commercial power quality meters. The filter has been designed to verify $H(\frac{\omega_s}{2}) \approx 0$, where $H(\omega)$ is the frequency response of the filter. In this case, the band-limited model can be expressed as follows:

$$u_{BLB}(t) = B_0 + \sum_{k=1}^{k_{max}} B_k \cdot \cos(k\omega_0 t + \phi_k) \quad \text{for } k \in \mathbb{N}, \tag{4}$$

where $B_0 = A_0 \cdot H(0)$, $B_k = A_k \cdot |H(k\omega_0)|$, $\phi_k = \theta_k + \angle H(k\omega_0)$.

B. Simulation results

We used the three models to analyze the behavior of the digital IEC flickermeter subjected to Test 6. As the phase jumps are located at positive zero crossings, $\beta_0^o = 0°$ for all the test points of Table II. Every model was simulated by generating the corresponding discrete signal at a sampling rate f_s and processed by the reference IEC flickermeter for all the test points defined in the standard.

Fig. 5 shows the P_{st} values obtained for one point of Test 6 in terms of several sampling frequencies (from 1200 to 144000 $\frac{S}{s}$ in logarithmic scale) for input voltage signals corresponding to models A and B. The results corresponding to model C were not shown because they were slightly higher than those from model B and become superimposed. The P_{st} values have been calculated for a 230 V/50 Hz system and $\Delta\beta^o = \pm 45°$, plotting the results for model A in dashed lines and for model B in solid lines. The values from both models progress to the reference value defined by the standard ($P_{st,ref}$ = 1.060) as the sampling frequency increases.

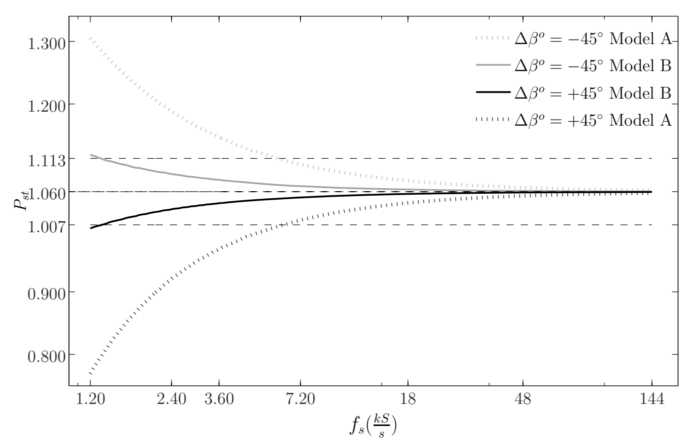

Fig. 5. P_{st} values for 230 V/50 Hz systems and different sampling rates in logarithmic scale, $\beta_0^o = 0°$ and $\Delta\beta^o = \pm 45°$ using the band-limited and ideal signal models.

A symmetrical convergence around the reference value between the values produced by the pair of angles $\Delta\beta^o = \pm 45°$ can also be observed. However, the convergence is not equally fast for both models. The P_{st} values provided by model B are always closer to the reference value. This entails that the minimum sampling frequency $f_{s,min}$ needed to get values within the required tolerance (P_{st} between 1.113 and 1.007) was clearly different between both models. The minimum sampling rate was 6150 $\frac{S}{s}$ for model A, but fell to 1350 $\frac{S}{s}$ for model B signals. The spectral components over the cut-off frequency (Nyquist frequency) generate aliases located inside the influential band for flicker. As the sampling frequency becomes larger, those aliases have less weight on the P_{st} value and the deviation becomes smaller. When using model B, the potential aliases are completely removed and the deviation is drastically reduced. This leads to a lower $f_{s,min}$ for both angles.

We also calculated the minimum sampling frequency for all the points defined in Test 6 for the three models. Table III details the values of $f_{s,min}$ considering a tolerance of 5%, calculated in terms of the $P_{st,ref}$ values of Table II, namely:

$$\frac{\Delta P_{st}}{P_{st}}(\%) = 100 \cdot \frac{P_{st}-P_{st,ref}}{P_{st,ref}} = 5\%. \tag{5}$$

TABLE III
MINIMUM SAMPLING RATE FOR TEST 6.

Phase Jump $\Delta\beta^o$	Signal model	230 V/50 Hz $f_{s,min}$ [1]	120 V/60 Hz $f_{s,min}$	120 V/50 Hz $f_{s,min}$	230 V/60 Hz $f_{s,min}$
	A [2]	6000	7150	6050	7100
$-45°$	B [3]	**1350**	**1600**	**1350**	1550
	C [4]	1300	1600	1350	1600
	A	**6150**	**7600**	**6150**	**7600**
$+45°$	B	**1350**	**1600**	**1350**	**1600**
	C	**1400**	**1850**	**1400**	**1850**
	A	3350	4100	3350	4050
$-30°$	B	800	950	800	950
	C	750	900	750	850
	A	3700	4450	3750	4500
$+30°$	B	850	1000	850	950
	C	850	1050	850	1100

[1] $f_{s,min}$: minimum sampling rate, expressed in $\frac{S}{s}$.
[2] A: Model A: ideal signals.
[3] B: Model B: band-limited signals.
[4] C: Model C: filtered signals.

Table III shows the important differences between the minimum sampling frequencies for models A and B. For every angle and electrical system, $f_{s,min}$ is clearly higher for model A. For 60 Hz systems, the dominant minimum sampling frequency that is valid for all the test points (marked in bold font) is 7600 $\frac{S}{s}$ in the case of model A. However, for model B, the predominant $f_{s,min}$ is 1600 $\frac{S}{s}$. For 50 Hz systems, those values are slightly smaller: 6150 $\frac{S}{s}$ for model A and 1350 $\frac{S}{s}$ for model B signals.

The results for input signals corresponding to model C are similar to those obtained for model B. It can be observed how the minimum sampling frequency values are again smaller than those obtained from model A. However, they are also larger than those obtained from model B (1400 $\frac{S}{s}$ for 50 Hz systems and 1850 $\frac{S}{s}$ for 60 Hz systems). This small increase in $f_{s,min}$ is due to the nonideal characteristic of the 5^{th}-order Butterworth filter.

It is important to note how those predominant minimum sampling frequencies are associated in every electrical system to the phase angle of $+45°$. This confirms the results presented in previous works [11], where this angle produced the highest P_{st} value and consequently the most demanding flicker conditions.

IV. EXPERIMENTAL RESULTS

Previous results confirm the importance of the antialiasing filtering to reduce the minimum sampling frequency needed to assess accurately the flicker produced by phase jumps. As we are dealing with a normative test, designed for the calibration and certification of commercial flickermeters, we reproduced the previous study, developed for the analytical model C, but by using actual analog signals in the laboratory.

In order to reproduce the analytical model C, we generate an analog signal by applying a D/A conversion, at a rate of 180 $\frac{kS}{s}$, to the samples obtained from the ideal model A. The output of this process is a 90 kHz band-limited signal, corresponding to model B. However, the cut-off frequency is so large that model A and B are almost coincident in practice.

To measure the flicker, the analog signal is filtered by a 5^{th}-order low-pass Butterworth filter to avoid aliasing. This is the same filtering characteristic used for the implementation of the analytical model C. After filtering, the analog signal is sampled by an A/D converter, working at a sampling rate f_s. The obtained signal is an actual analog version of the analytical model C.

Fig. 6 shows the physical layout of the signal generation system. The system consisted basically of four modules:

1) Management module. This is a software tool based on a PC for the control of the tests. Its main functions are:
   a) generation of the discrete analytical signals and control of the digital-to-analog conversion;
   b) recording of the flickermeter input signals and control of the analog-to-digital conversion;
   c) calculation of the P_{st} by means of the reference IEC flickermeter;
2) D/A conversion module. This uses the 16 bit USB-6211 National Instruments card for analog generation of the discrete signals.
3) Amplifying module. This uses the Krohne Hite 7500 amplifier, with a bandwidth of 1 MHz and 75 W for a voltage of 120 V_{rms}, and a 120 V_{AC} / 230 V_{AC} transformer to amplify the generated signal.
4) Conditioning and A/D conversion module. All the generated signals were acquired by means of our own registering system, SAC-2 (see reference [17] for more details). This system used 5^{th}-order low-pass switched-capacitor Butterworth anti-aliasing filters (MAX7420) and a 6062E National Instruments A/D card for the acquisition. The A/D system worked at several sampling frequencies, namely 1280, 1600, 2560, 3200, 5120, 6400, 20480 and 25600 $\frac{S}{s}$.

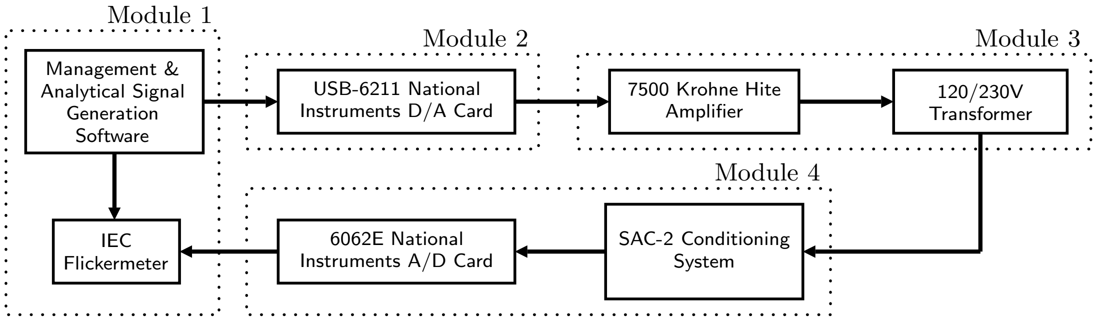

Fig. 6. Description of the signal generation system.

For every test point of Table II, we carried out the following tasks:

- Generation of the analytical discrete signal according to model A, at a high sampling rate of over 180000 $\frac{S}{s}$.
- Analog conversion by module 2 and amplification by module 3.
- Recording by module 4 at eight different sampling rates, from 1280 to 25600 $\frac{S}{s}$.

Fig. 7 shows the P_{st} values obtained for one point of test 6 in terms of the sampling frequencies (from 1280 to 25600 $\frac{S}{s}$, in logarithmic scale). The excitations were obtained from the signal generation system. The P_{st} values correspond to a 230 V/50 Hz system and $\Delta\beta^o = \pm 45°$.

As with the analytical models, the values from both phase jumps progress to the reference value defined by the standard ($P_{st,ref}$ = 1.060) as the sampling frequency increases. The convergence is also symmetrical around the reference value between the values produced by both phase jumps. However, the P_{st} values come into the admissible region for a higher sampling frequency (1600 $\frac{S}{s} < f_s <$ 2560 $\frac{S}{s}$) than in the case of the analytical models.

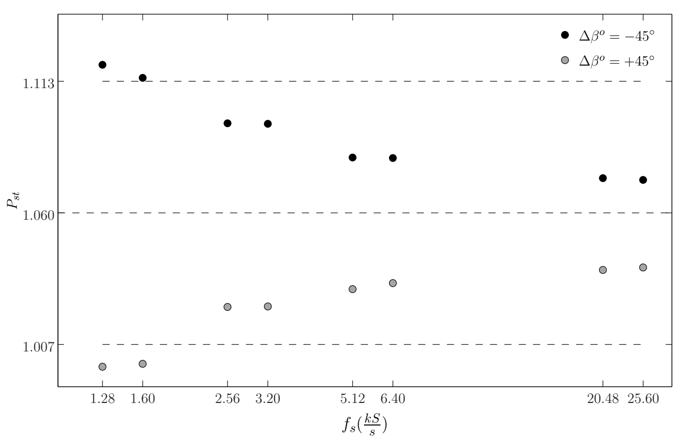

Fig. 7. P_{st} values for 230 V/50 Hz systems and different sampling rates in logarithmic scale, $\beta_0^o = 0°$ and $\Delta\beta^o = \pm 45°$ using registers obtained from the signal generation system.

Table IV details the $f_{s,min}$ range including the 5% deviation from the $P_{st,ref}$ values. The figures confirm the results obtained from the previous simulations. The phase jump corresponding to $\Delta\beta = +45°$ is again the most demanding test point. The dominant $f_{s,min}$ for 50 Hz systems is in the range from 1600 to 2560 $\frac{S}{s}$, biasing to 1600 $\frac{S}{s}$. For 60 Hz systems, the range is a little higher, from 2560 to 3200 $\frac{S}{s}$, with a tendency to 2560 $\frac{S}{s}$. Both values are not far from the simulated dominant $f_{s,min}$, 1400 $\frac{S}{s}$ for 50 Hz systems and 1850 $\frac{S}{s}$ for 60 Hz systems (Table III), obtained by means of model C.

TABLE IV
MINIMUM SAMPLING RATE FOR TEST 6 WITH ACTUAL SIGNALS.

Phase Jump $\Delta\beta^o$		**230 V/50 Hz**	**120 V/60 Hz**	**120 V/50 Hz**	**230 V/60 Hz**
$-45°$	$\mathbf{\Delta}$ [1]	5.13/3.14	6.58/4.76	5.19/3.48	6.34/4.71
	$\mathbf{f_{s,min}}$ [2]	**1600/2560**	1600/2560	**1600/2560**	1600/2560
$+45°$	$\mathbf{\Delta}$	-5.73/-3.57	-5.2/-3.73	-5.65/-3.6	-5.23/-3.79
	$\mathbf{f_{s,min}}$	**1600/2560**	**2560/3200**	**1600/2560**	**2560/3200**
$-30°$	$\mathbf{\Delta}$	3.62	5.31/3.56	3.62	4.87
	$\mathbf{f_{s,min}}$	$<$1280	1280/3200	$<$1280	$<$1280
$+30°$	$\mathbf{\Delta}$	-2.20	-2.67	-2.20	-3.16
	$\mathbf{f_{s,min}}$	$<$1280	$<$1280	$<$1280	$<$1280

[1] $\Delta = \frac{\Delta P_{st}}{P_{st}}$: deviation range from the reference value, expressed in %.
[2] $f_{s,min}$: range of sampling rates, expressed in $\frac{S}{s}$.

V. DISCUSSION OF THE RESULTS

Test 6 is one of the most innovative tests of the new 2010 edition of the IEC 61000-4-15 standard. The characterization of the P_{st} produced by phase jumps is not an easy task due to the unpredictable behavior of the IEC flickermeter when subject to discontinuous waveforms produced by the phase jumps. It seems logical to consider the sequence of phase jumps as one of the most demanding tests of the standard. In fact, previous works have considered a high sampling rate (over 36000 $\frac{S}{s}$) for adequate phase resolution and to provide a highly precise evaluation of the P_{st} [11]. Our work proved how the use of an ideal analytical signal similar to model A for the sequence of phase jumps requires a high sampling rate due to the influence of the aliasing spectral components. When using a more realistic model, based on band-limited signals similar to models B or C, the sampling rate for the same accuracy was drastically reduced (under 2000 $\frac{S}{s}$).

However, it seems questionable that a proper behavior in this test will mean that the instrument is ready for the accurate characterization of the P_{st} produced by any other kind of phase jumps. We made the same experiments for values of β_0^o and $\Delta\beta^o$ different from those specified by the standard.

For instance, in the case of $\beta_0^o = +15^\circ$ and $\Delta\beta^o = +210^\circ$, the reference value should be $P_{st,ref}$=0.5373, obtained at a reference sampling rate of $f_{s,ref}$ = 180 $\frac{kS}{s}$ for a 230 V/50 Hz system. Considering a sampling rate of 3200 $\frac{S}{s}$, corresponding to the worst cases obtained from the experimental results, the value provided by the IEC flickermeter working with model C at a sampling rate of 3200 $\frac{S}{s}$ is P_{st}=0.4966, resulting in a deviation of –7.57%. More impressive figures correspond to phase jumps starting at $\beta_0^o = +15^\circ$ with $\Delta\beta^o = +245^\circ$, considering the same electrical system and sampling rate. The reference value at $f_{s,ref}$ = 180 $\frac{kS}{s}$ is $P_{st,ref}$=0.3075 and the value at 3200 $\frac{S}{s}$ is P_{st}=0.3523, resulting in a deviation of 14.55%.

The improvement and extension of the calibration tests and functional requirements should involve more reproducible measurements by the commercial IEC flickermeters. In this sense, Test 6 is actually essential because it is a useful tool to determine the input bandwidth of the instrument. However, a better calibration of the IEC flickermeters subject to phase jumps does not guarantee accurate results when the phase jumps are different to those specified by Test 6. It seems necessary to make a deeper study about the actual effect of phase jumps on the P_{st} and the optimal way to characterize them.

VI. Conclusions

We gave a full analysis of the influence of the sampling rate on the P_{st} values provided by a digital IEC flickermeter when subject to the phase jump sequences defined in the new edition of the standard. The study was carried out by simulating the behavior of a highly accurate IEC flickermeter excited by ideal and band-limited phase jump sequences. Moreover, the simulations were confirmed by experiments made with actual signals. In spite of previous works suggesting a sampling rate over 30 $\frac{kS}{s}$ for an accurate characterization of the P_{st} produced by phase jumps, this work demonstrated that the minimum sampling rate necessary to fulfill the standard requirements is not so demanding. A typical sampling frequency of 3200$\frac{S}{s}$ became a conservative minimum limit to pass the phase jump test.

However, fulfilling the requirements of this test could not guarantee accurate results when the phase jumps are different from those specified by the standard. The results of this work could be used by the manufacturers and calibrators of IEC flickermeters to improve their implementations of the new edition of the standard.

Appendix

In this section we detail the calculation of the Fourier coefficients for the analytical models B and C.

Considering the periodic input signal u(t), with period $T_0 \approx 120$ s:

$$u(t) = \sum_{l=-\infty}^{\infty} u_b(t - lT_0) \quad \text{for } l \in \mathbb{Z},$$

$u_b(t)$ can be expressed as:

$$u_b(t) = \begin{cases} V \cdot \sin(\omega_p t + \beta_0) & 0 \le t < 60 \\ V \cdot \sin(\omega_p t + \beta_0 + \Delta\beta) & 60 \le t < T_0, \end{cases}$$

where V is the amplitude of the 50/60 Hz mains frequency, β_0 is the initial angle in radians of the mains frequency and $\Delta\beta$ is the phase jump in radians. The period of the excitation is defined as $T_0 = 120 - T_p \frac{\Delta\beta}{2\pi}$; $T_p = \frac{2\pi}{\omega_p}$ is the period corresponding to 50/60 Hz.

The periodic input signal $u(t)$ can be also expressed in terms of the Fourier series, namely:

$$u(t) = \sum_{k=-\infty}^{\infty} a_k \cdot e^{jk\omega_0 t} \quad \text{for } k \in \mathbb{Z},$$

where a_k are the coefficients of the Fourier series and $\omega_0 = \frac{2\pi}{T_0}$. The Fourier coefficients a_k can be obtained from:

$$\begin{aligned} a_k &= \tfrac{1}{T_0} \int_0^{T_0} u_b(t) \cdot e^{-jk\omega_0 t} dt \\ &= \tfrac{1}{T_0} \left[\int_0^{60} V \cdot \sin(\omega_p t + \beta_0) \cdot e^{-jk\omega_0 t} dt \right. \\ &\left. + \int_{60}^{T_0} V \cdot \sin(\omega_p t + \beta_0 + \Delta\beta) \cdot e^{-jk\omega_0 t} dt \right], \end{aligned}$$

obtaining:

$$\begin{aligned} a_k &= \tfrac{V}{2\pi} \cdot \sin(\tfrac{\Delta\beta}{2}) \cdot e^{j\phi_1} \left[\frac{e^{j\phi_2}}{\frac{T_0}{T_p} - k} + \frac{e^{-j\phi_2}}{\frac{T_0}{T_p} + k} \right] \\ \phi_1 &= -k \tfrac{2\pi}{T_0} 60 \\ \phi_2 &= \beta_0 + \tfrac{\Delta\beta}{2} + \tfrac{\pi}{2} \end{aligned}$$

Finally, since the excitation is a real signal, $u(t)$ can be also expressed in terms of the cosine Fourier series, namely:

$$\begin{aligned} u(t) &= A_0 + \sum_{k=1}^{\infty} A_k \cdot \cos(k\omega_0 t + \theta_k) \quad \text{for } k \in \mathbb{N} \\ A_0 &= a_0 \\ A_k &= 2|a_k| \\ \theta_k &= \angle a_k \end{aligned}$$

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